Integrated Regression and Cluster Analysis for Cost Benefit Evaluation of Energy Retrofit Interventions in Hellenic Schools

Margarita Petroliagki [1], and *Sophia* Giannarou[1*]

[1]School of Applied Arts and Sustainable Design, Hellenic Open University, 26335, Patras, Greece

Abstract. This study introduces and explains a methodology that integrates regression and cluster analysis of Energy Performance Certificates data to evaluate the cost effectiveness of energy retrofit measures in Greek school buildings. These interventions have been supported by European funds and are scheduled to be implemented in schools across different climatic zones in accordance with the national Regulation of Energy Performance. The analysis first identified which architectural, economic and energy-related variables most significantly affect the cost-benefit ratio of interventions in schools located in warm and cold climatic zones. Cluster analysis then classified the school buildings into two homogeneous groups, one with larger, compact structures that initially exhibited reduced energy demands but required significant capital investment to achieve significant retrofit results and the other consisting of smaller, less compact buildings that demonstrated significant retrofit potential and energy savings related to the invested resources, despite their higher initial energy consumption. The study also identified representative building typologies to guide the optimization of retrofit strategies. The results indicate that balanced investments and targeted energy measures can lead to more sustainable and cost-effective educational buildings.

1 Introduction

In Greece, public buildings -especially educational institutions- are among the largest energy consumers, providing significant opportunities for energy savings through targeted retrofit interventions. However, this sector severely lacks dedicated research on adaptation of retrofit strategies to the Greek Mediterranean climate characteristics despite its critical need for improved energy efficiency (EE) [1], [2]. Most of the building stock was built before the implementation of thermal standards and the national Regulation of Energy Performance (K.Ev.A.K.). Thus, the school buildings often lack adequate thermal insulation and efficient technical systems, resulting in energy use intensities - averaging 203,90 kWh/m² for primary and 189,85 kWh/m² for secondary education schools- with substantial potential for improvement [3].

The architectural and energy design of Greek school buildings is significantly influenced by their operational characteristics and educational program requirements [6]. These buildings exhibit several distinctive functional features: (a) intermittent operation, with schools operating during specific hours over a nine-month period annually, although some facilities now provide afternoon childcare and community activities; (b) a variety of spaces, such as classrooms, multipurpose, and hygiene areas, each with unique thermal demands that affect energy performance and design; (c) high occupant density in classrooms which causes consistent internal heat gains, in contrast to variable natural lighting dependent on temporal and seasonal factors; (d) natural ventilation, crucial for hygiene, is responsible for 30–50% of thermal losses depending on insulation and climate; (e) extensive glazing that improves visual comfort but contributes to winter heat loss, summer overheating, and glare; (f) thermal comfort within classrooms influenced by occupant density, large glazed areas, and the sedentary cognitive activities performed by students.

The energy performance of school buildings is also influenced by a variety of broader factors, including economic, social, technical, and aging-related factors, as well as building typologies, management practices, and local climatic conditions [6]. These interrelated complexities contribute to high energy consumption, poor indoor air quality, and thermal, visual, and acoustic discomfort. Additionally, limited maintenance budgets often exacerbate these challenges making energy efficiency a complex issue that has a substantial impact on both education quality and environmental sustainability.

The European Union (EU) sets as primary objectives the reduction of carbon emissions and the achievement of climate neutrality by 2050 through specific strategies which include the renovation of public buildings including schools [3],[4]. The integration of renewable energy technologies such as photovoltaic systems, building envelope upgrades, and the modernization of HVAC systems, constitutes “green retrofitting” which demonstrates significant potential to reduce energy consumption and improve occupant comfort in Greek schools [2],[4].

Nevertheless, the economic evaluations of these interventions designed to address Greece’s aging school infrastructure remain underexplored, and high initial costs remain a major barrier to their implementation [4]. In Greece, policy frameworks increasingly support energy renovation through national action plans and funding programs, aiming to transform educational buildings into zero carbon footprint facilities and promote sustainable behaviors within educational communities [3],[5]. Therefore, retrofit strategies must be carefully designed to optimize cost-effectiveness and energy savings by addressing climatic conditions, typological diversity, and technical as well as socio-economic factors to accelerate the country's transition toward a decarbonized public building sector.

2 Methodology

2.1 Aim and objectives

The objective of this study is to develop and apply an integrated methodology which combines regression and cluster analysis for the assessment of the cost-benefit effectiveness of energy retrofit interventions in school buildings across different climatic zones in Greece. The research aims to identify representative building typologies and the key factors which influence both energy performance and retrofit outcomes. The results will provide practical insights to support decision making for the optimization of retrofit strategies.

To guide this investigation and achieve the study's objectives, the following questions will be addressed:

a. Which factors influence the cost benefit ratio of energy interventions in school buildings situated in different climatic zones?
b. How can regression and cluster analysis be integrated for the classification of school buildings into representative typologies based on their energy performance and retrofit cost benefit profiles?
c. What are the distinct cost-benefit patterns of energy retrofit interventions in warm and cold climatic zones?

2.2 Methods and material

2.2.1 Methodology

The methodology is systematically divided into three main steps:

a. Data acquisition and variable definition: The dataset of school buildings was selected from a sample of 498 Energy Performance Certificates which had been issued between 2011 – 2023 and submitted in Hellenic Ministry of Environment and Energy.
   Each record included geometric characteristics and details about the energy performance, financial metrics, and operational outcomes of the buildings. The dataset was filtered by target climatic zone, purged of missing or invalid values, and normalized using a global min–max scaler. For the protection of the model from leverage points, Cook's distance was used to remove global and cluster-wise outliers. Predictors with high multicollinearity (VIF ≥ 5) were excluded to ensure model stability and interpretability.
b. Regression analysis: An ordinary least squares regression model was applied to quantify the influence of each predictor (absolute coefficient). A LASSO regression, supported by SHAP analysis, provided a sparse, secondary variable ranking. PCA reduced dimensionality and the optimal number of components, and weighted K-means clustering identified building groups, unless an explicit domain split (e.g., volume threshold) overrides the algorithm.
c. Cluster validation: The quality of cluster analysis was assessed using the Silhouette score, Davies-Bouldin index, and RMSSTD. For both warm and cold climatic zones, individual clusters underwent regression analyses using diagnostic statistics (adjusted R^2, VIF, Durbin – Watson). Finally, centroids visualizations provided actionable interpretation of the main factors affecting the cost-benefit ratio of energy interventions.

2.2.2 Description of buildings' sample

After excluding missing or invalid data, the sample consisted of 240 school buildings distributed across climatic zones: 107 in the warm climatic zones (21 in A, 86 in B) and 134 in the cold ones (101 in C, 33 in D). According to Greek legislation, the sample includes 132 buildings of primary education (nursery and primary schools), and 108 for secondary education (gymnasium and lyceum).

The analysed sample consisted of educational buildings constructed before 2010, with 124 erected before 1980 and 116 between 1980 and 2010. Buildings built prior to 1960 exhibit neoclassical or interwar architectural styles having south-facing linear classrooms, single-glazed windows, wooden or concrete roofs, and thick stone or brick walls without thermal insulation [6]. Between 1960 and 1980, designs became standardized with classrooms arranged on both sides of a central corridor, thin non-insulated brick and concrete walls, metal frames and single glazing. After 1980, buildings comply with Thermal Insulation Regulation, incorporating thermal insulation in the building envelope; however, large, glazed areas still cause winter heat loss and summer overheating.

Following further analysis of the thermophysical properties of the building elements, the weighted average of the thermal transmittance coefficients (U-values) of the building components was calculated using the total surface area as the weighting factor and the results are presented in Table 1.

Table 1. Thermal transmittance values of building components before energy interventions.

Building Element	<1980 (W/m²·K)	1980 - 2010 (W/m²·K)
Walls	2.62	1.80
Windows	4.87	4.67
Roof	3.07	2.15
Floor	2.94	1.72
Pilotis	2.20	1.58

The school buildings also exhibit a total useful floor area ranging from 41 m² to 12,773 m², with heights varying between one and three stores. Two story buildings predominate within climatic zones B, C and D, whereas climatic zone A demonstrates a more uniform distribution across one to three story structures. The typical floor-to-ceiling height across all climatic zones ranges between three and four meters.

The analysis of the Surface to Volume ratio (SV) and Heat Loss Form Factor (HLFF) of the sample indicates that buildings situated in cold climatic regions exhibit lower SV and HLFF values compared to those in warm regions. This tendency signifies a more compact design with increased solar gains as well as higher thermal losses through vertical surfaces (Table 2). Buildings constructed between 1980 and 2010 demonstrated lower SV ratios (A: 0.52, B:0.48, C:0.46, D:0.40) compared to those built prior to 1980 (A: 0.72, B:0.48, C:0.44, D:0.36).

Table 2. Surface-to-Volume ratio and Heat Loss Factor (HLF) values of school buildings across different climatic zones.

Climatic zones		A	B	C	D
SV ratio	min	0,13	0,10	0,11	0,13
	max	2,84	2,00	1,71	1,11
	median	0,45	0,43	0,40	0,33
HLFF	min	0,46	0,41	0,36	0,51
	max	6,17	6,90	5,99	3,81
	median	1,9	1,57	1,46	1,17

Correspondingly, primary energy consumption data reveal that buildings erected before 1980 consume more energy (212.60 kWh/m²) than those built between 1980 and 2010 (161.45 kWh/m²), with heating constituting the largest share. Heating demands increase from warm to cold climatic zones (from 73,20 kWh/m^2 in A to 244,25 kWh/m^2 in D), while cooling demands decrease (from 2,80 kWh/m^2 in D to 15,60 kWh/m^2 in A), and lighting consumption remains relatively stable. Statistical analyses (Kolmogorov-Smirnov and Kruskal-Wallis tests) indicate that total and heating energy primary consumption present strong positive correlations for different use of school buildings, while the total primary energy consumption for heating, cooling, and lighting exhibit statistically significant differences between the climatic zones.

2.2.3 Cost framework and retrofit interventions

In Greece, the Partnership Agreement for the Development Framework (ESPA), co-financed by the European Structural and Investment Funds, supports the implementation of key energy efficiency and sustainability objectives through a variety of sectoral and regional operational programs. Notable initiatives such as the Operational Program Environment and Sustainable Development (EPPERAA), the "ILEKTRA" program, regional programs including "Sterea Ellada," "Crete," and "Epirus," as well as the transnational GRASPINNO project, have been instrumental in financing energy retrofit interventions in public buildings, including educational facilities.

These programs promote energy savings, renewable energy integration, and greenhouse gas emissions reduction, aligning with national and European objectives for sustainable development and climate change mitigation. In addition, renovated buildings are obliged to meet the highest energy performance standards for the building envelope and technical systems as they set forth by the national Regulation of Energy Performance of Buildings (K.Eν.A.K).

The analysis of energy retrofit interventions in school buildings across warm and cold climatic zones in Greece reveals that both the number of interventions and associated budgetary are notably varied (Fig. 1,2). Especially, most retrofits in warm climates underwent between one and three interventions and concentrated in the lowest budget category (0–150), with 61 buildings. In the higher budget categories (151-300 and above), there are fewer buildings with a wider number of interventions, including some with up to 7. Conversely, cold climatic zones exhibit most retrofits in the 0–150 budget range (73 buildings), but with a generally higher number of interventions per building, especially in the mid to high budget categories. Especially, in cold zones, more buildings received four or more interventions, particularly in the 151–300 and 451–600 budget ranges, indicating more comprehensive retrofit efforts as result of the increased energy demands.

Additionally, energy efficiency improvements in school buildings vary significantly depending on climatic conditions. In regions with a warm climate, improvements are often limited to minor, targeted measures, without requiring major investment. In cold zones, schools often require more comprehensive and expensive renovations. The increased heating demands and higher potential for energy savings in these areas drive this pattern [2],[3].

Thus, policymakers and program designers should acknowledge the climatic disparities between regions. The identical approach of all regions endangers resource allocation and overlooks opportunities for improvements in energy efficiency. According to reports from the European Commission and the International Energy Agency, interventions should be customized to each area's specific climate and needs in order to optimize overall benefits and attain cost-effective improvements [12],[13].

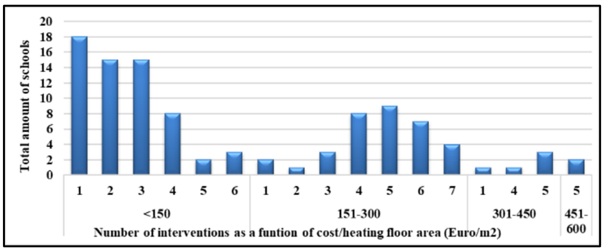

Fig. 1. Number of retrofit interventions as a function of cost/heating area (€/m^2) and total amount of school buildings in warm climatic zones.

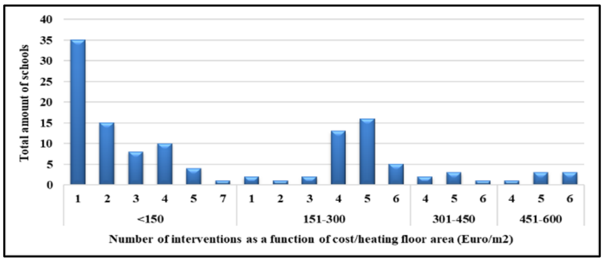

Fig. 2. Number of retrofit interventions as a function of cost/heating area (€/m^2) and total amount of school buildings in cold climatic zones.

According to this framework, the analysis of retrofit interventions in school building across Greece's diverse climatic zones reveals important trends that reflect both the country's energy policy priorities and its climate diversity. As illustrated in Figures 3 and 4, these interventions can be divided into:

a. thermal insulation of building envelope (vertical walls, roof)
b. replacement of windows
c. upgrade/replacement of heating, cooling, and lighting systems
d. installation of mechanical ventilation and control systems
e. deployment of renewable energy technologies (e.g. photovoltaics)

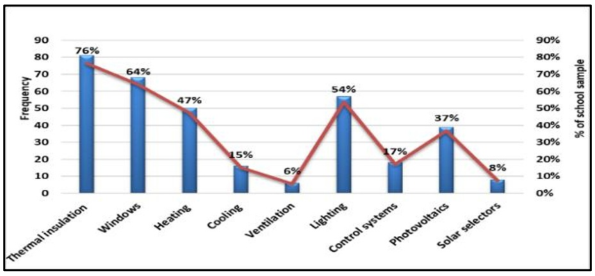

Fig. 3. Frequency distribution of retrofit interventions in warm climatic zones.

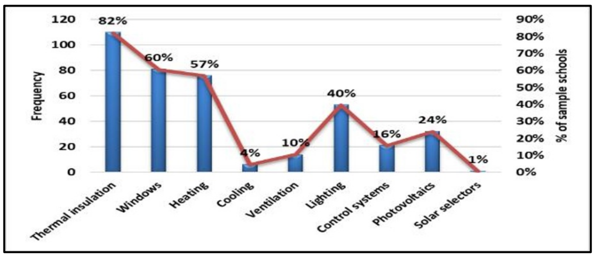

Fig. 4. Frequency distribution of retrofit interventions in cold climatic zones.

Thermal insulation of the building envelope underscores its critical role in balancing heating and cooling demands throughout Greece's diverse climatic regions, and it stands out as the most widely adopted measure in both zones (76% and 82% of sampled schools in warm and cold climatic zones). Replacement/upgrade of windows and heating systems are notably more common in cold zones (60% and 57%, respectively), whereas cooling systems as well as lighting interventions are preferred in warm zones (15% vs. 4% and 54% vs 40%), consistent with the distinct seasonal energy requirements of school buildings.

Similarly, due to the higher solar potential in southern Greece and the ongoing efforts to intergrade renewable energy technologies in building stock, photovoltaics is highly adopted in warm zones (37% vs. 24% and 8% vs. 1%). The relatively modest adoption of ventilation and control systems across both zones (6% - 10% and 16% - 17%) indicates a promising area for further development under the scope of improving the indoor air quality and advancing smart building management systems as part of Greece's green transition agenda.

In the context of the interventions, distinct patterns for CO_2 reduction are observed between the climatic zones in Greece (Fig. 5). In zones A and B, the percentage reduction of CO_2 emissions generally increases with the number of interventions, starting approximately at 10% for a single intervention and reaching a peak of 43% at five interventions, followed by a minor decline for six and seven interventions. This trend suggests that the returns will decrease after five interventions in these milder climates. Conversely, in the cold zones CO_2 reduction exhibits a more pronounced and consistent increase with additional interventions, starting at 16 % for one intervention and rising sharply to 76% with seven interventions. The critical significance of comprehensive retrofit strategies in these regions is underscored by the fact that reductions exceed 50% because of four interventions.

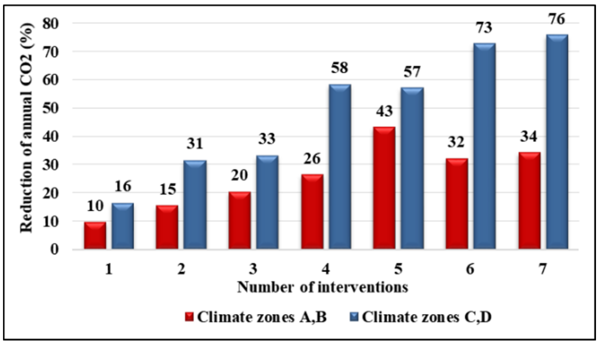

Fig. 5. Number of interventions versus the reduction of annual CO2 (%) in warm and cold climatic zones in Greece.

The major CO_2 reduction (~43%) in zones A and B, is achieved through interventions which include thermal insulation of building envelope, replacement of windows, upgrading of heating and lighting systems, and installation of photovoltaics. Integrating the above measures with the installation of cooling systems, mechanical ventilation and automated control systems, it is achieved the most substantial reductions in zones C and D. Thus, in the climate-sensitive retrofit planning, cold zones may benefit from more comprehensive intervention packages, while milder zones may achieve optimal CO_2 reductions with fewer, more targeted measures.

3 Results and discussion

The present study employs a clustering approach to analyze the cost benefit ratio of energy interventions on buildings across different climatic zones by grouping them based on architectural, economic and energy-related variables. The parameters selected for the cluster analysis were derived from the available literature and include:

- The surface volume ratio of the school buildings (SV ratio)
- The total useful volume (m^3) (V)
- The primary energy for heating/ total useful volume (kWh/m^3) (PE)
- Energy class jumps (J)
- Initial investment cost (€) (C)
- Specific energy savings/ total useful volume (kWh/m^3) (SEs)
- Cost-benefits ratio (€/kWh) (CBr)

This multidimensional parameter scheme aligns with recent reported methodologies that employ building clustering to improve energy simulations and retrofit planning [8],[9],[10]. The integration of architectural forms, energy consumption and economic performance facilitates the development of targeted strategies tailored to specific buildings archetypes and climatic conditions aiming to optimize investment allocation and advance energy efficiency objectives.

3.1 Integrated Regression and Clustering results

3.1.1 In warm climatic zones (A,B)

In climatic zones A and B, the cluster analysis identified two distinct groups composed of 50 and 56 school buildings respectively. Regression analysis demonstrated that clustering effectively captures underlying heterogeneity within the sample; the unclustered dataset (n = 106) yielded an adjusted R^2 of 0.543 ($p < 0.001$), whereas the adjusted R^2 values increased to 0.692 (n = 50) and 0.675 (n = 56) for clusters 1 and 2, respectively, both with highly significant p-values ($p < 0.001$) and DW value close to 2, indicating no autocorrelation in the residuals (Table 3). Both clusters exhibit statistically significant regression models explaining the cost-benefit ratio of energy interventions.

Table 3. R^2adj and p-values for Cluster 1 and 2 (zones A,B).

Clusters	R^2 adj	p-Value
No Clustering (106 samples)	0.543	0.0000
Cluster 1 (50 samples)	0.692	0.0000
Cluster 2 (56 samples)	0.675	0.0000

Additionally, the evaluation of clustering metrics suggests that a solution with two clusters provides best balance between cluster cohesion and separation, as the highest silhouette score is remarked 0.663 at k=2. This conclusion is further reinforced by the Davies–Bouldin index which reaches a relatively low value of 0.480 at k=2, indicating favourable cluster compactness and distinctness.

Cross-validation analyses confirm the stability of the two-cluster solution across different levels of explained variance in principal component analysis (PCA), as evidenced by high consistent silhouette scores (~0.692) and a low std. deviation (~0.014). Additionally, multicollinearity diagnostics indicate that the clustering parameters—surface-to-volume ratio (SV ratio), total useful volume (V), primary energy for heating per total useful volume (PE), energy class jumps (J), initial investment cost (C), specific energy savings (SEs), and cost-benefit ratio (CBr)-, do not exhibit problematic correlations, as all Variance Inflation Factor (VIF) values remain well below the commonly accepted threshold of five.

The mean values of the parameters corresponding to each cluster are represented by the centroid coordinates, as detailed in Table 4. The centroids summarize the typical characteristics of each cluster and facilitate the interpretation and comparison across the school buildings in warm climatic zones [14].

Table 4. The Centroids' coordinates for cluster 1 and 2 in warm climatic zones.

Predictors	Units	Cluster 1	Cluster 2
SV ratio	-	0.45	0.57
Total useful volume (m^3) (V)	m^3	7,705.77	2,559.12
Primary energy for heating/ total useful volume (PE)	kWh/m^3.year	18.76	27.28
Energy class jumps (J)	-	2.74	3.32
Initial invenstment cost (C)	€	279,565.52	93,273.36
Specific energy savings/ total useful volume (SEs)	kWh/m^3	19.23	29.02
Cost-benefits ratio (CBr)	€/kWh	1.92	1.60

The features of school buildings for Cluster 1 and 2 are represented in Table 5.

Table 5. Cluster 1 features (50 buildings) and Cluster 2 features (56 buildings) in warm climatic zones.

Variable	Units	Cluster 1 **min - max**	Cluster 2 **min - max**
SV ratio	-	0.22 – 1.04	0.13– 1.50
Tot. useful Vol. (V)	m^3	5,035.43 – 11,408.60	439.60 – 4,951.50
Prim. energy heat. (PE)	kWh/m^3.year	2.12 - 37.84	6.67-71.07
En. class jumps (J)	-	1.00 – 6.00	1.00– 6.00
Initial inv. cost (C)	€	3,000 – 877,148.00	8,000 – 372,926
Specific en. Savings (SEs)	kWh/m^3	1.13 – 47.13	1.89-83.38
Cost-benefits ratio (CBr)	€/kWh	0.10–3.90	0.2 – 4.40

Figure 6 represents the centroid coordinates for the normalized parameters of the two clusters identified in school buildings situated in warm climatic zones.

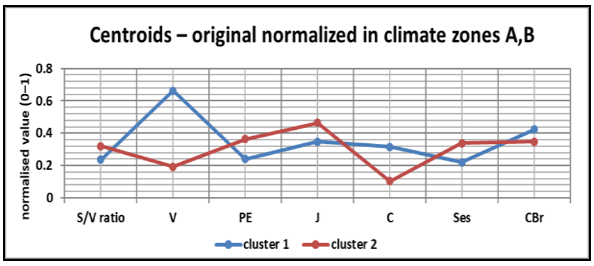

Fig. 6. Normalized coordinates of the centroids of Clusters 1 and 2 in warm climatic zones.

3.1.2 In cold climatic zones (C, D)

In climatic zones C and D, the cluster analysis classified the dataset into two distinct groups, comprising of 66 and 68 school buildings, respectively. Further, regression analysis confirmed that this classification improved the explanatory power of the models' ability to explain the data by capturing the inherent differences within the dataset. Specifically, the unclustered dataset (n = 134) yielded an adjusted R^2 of 0.635 ($p < 0.001$). In comparison, the models for clusters 1 (n = 66) and 2 (n = 68) showed better improved model fits, with adjusted R^2 values of 0.826 and 0.715, respectively (both $p < 0.001$). In addition, the Durbin-Watson value for both clusters were close to 2, indicating minimal autocorrelation (Table 6). These results suggest that the clustered models provide more accurate explanation of the variance in the cost-benefit ratio of energy interventions for the school buildings in cold climatic zones.

Table 6. R^2adj and p-values for Cluster 1 and 2.

Clusters	R^2 adj	p-Value
No Clustering (134 samples)	0.635	0.0000
Cluster 1 (66 samples)	0.826	0.0000
Cluster 2 (68 samples)	0.715	0.0000

Clustering evaluation metrics indicate that a two-cluster solution (k = 2 clusters), as in the warm climatic zones, provides the optimal balance between cluster cohesion and separation. The highest silhouette score of 0.691 at k=2 suggests the presence of well-defined and distinct clusters, whereas the silhouette scores decline for higher values of k. This finding is corroborated by the Davies–Bouldin index, which attains a relatively low value of 0.499 at k = 2, indicating favorable cluster compactness and distinctness.

Cross-validation analysis confirms the two-cluster solution's stability across PCA variance levels, as it is evident by the consistent silhouette scores (~ 0.692) with a low standard deviation (~0.014). There also no significant issues among the clustering variables, as all VIF values remain below the accepted threshold of five. The centroid coordinates, detailed in Table 7, effectively summarize the typical characteristics of each cluster within the cold climatic zones.

Table 7. The Centroids' coordinates for Cluster 1 and 2 in cold climatic zones

Predictors	Units	Cluster 1	Cluster 2
SV ratio	-	0.37	0.49
Tot. useful Vol. (V)	m^3	8,503.19	2,787.38
Prim. energy heat. (PE)	kWh/m^3.year	47.74	61.35
En. Class jumps (J)	-	4.38	4.91
Initial inv. cost (C)	€	243,435.51	132,531.23
Specific en. Savings (SEs)	kWh/m^3	36.37	50.66
Cost-benefits ratio (CBr)	€/kWh	0.81	1.08

The detailed characteristics of buildings within cluster 1 are summarized in Table 8.

Table 8. Cluster 1 features (66 buildings) and Cluster 2 features (68 buildings) in cold climatic zones

Variable	Units	Cluster 1 min - max	Cluster 2 min - max
SV ratio	-	0.11 – 0.78	0.13 – 1.46
Tot. useful Vol. (V)	m^3	5,012.71– 27,232.00	172.69 – 4,985.99
Prim. energy heat. (PE)	kWh/m^3.year	15.54 – 92.26	19.03 – 135.89
En. class jumps (J)	-	2.00 – 6.00	2.00 – 6.00
Initial inv. cost (C)	€	11,000.00– 850,000.00	6,799.80 – 717,239.00
Specific en. Savings (SEs)	kWh/m^3	4.72- 91.03	7.39- 140.60
Cost-benefits ratio (CBr)	€/kWh	0.10 – 2.90	0.10 – 3.00

Figure 7 illustrates the centroid coordinates of the normalized parameters for the two Clusters identified among school buildings located in cold climatic zones.

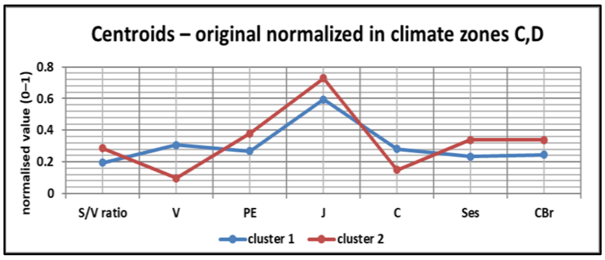

Fig. 7. Normalized coordinates of the centroids of Clusters 1 and 2 in cold climatic zones.

3.2 Detailed analysis of Clustering results

3.2.1 Building characteristics and energy performance

Cluster 1 buildings are characterized by their increased dimensions and greater compactness in warm climatic zones. They have a total useful volume of 7,705.77 m³ and a lower value of surface-to-volume (SV) ratio of 0.45. This compactness often diminishes heat exchange with the environment which results in reducing energy demands for heating and cooling. Buildings in Cluster 2 display reduced dimensions and looser spatial layout, characterized by a SV ratio of 0.57 and a total useful volume of 2,559.12 m³. These characteristics contribute to increased heat loss and higher energy consumption.

In cold climatic zones, buildings in Cluster 1 demonstrate a more compact form (SV ratio of 0.37) along with a significantly larger useful volume (8,503.19 m³) compared to those in Cluster 2 buildings (SV ratio 0.49, total useful volume of 2,787.38 m³). The lower value of SV ratio in Cluster 1 reduces heat losses, thereby improving the energy performance of building schools in cold climates.

These results emphasize the significant impact of building morphology on improving the energy performance of school buildings in various climatic zones [7],[11].

3.2.2 Energy Consumption and Retrofit Improvements

In warm climatic zones, Cluster 1 buildings demonstrate lower primary energy consumption for heating per unit volume (18.76 kWh/m³·year) compared to Cluster 2 (27.28 kWh/m³·year), indicating a better baseline energy efficiency. However, the buildings in Cluster 2 achieve a higher number of energy class jumps (3.32 versus 2.74), because of more ambitious retrofit initiatives on buildings with initially greater energy demands. In cold climatic zones, buildings appear greater total primary energy consumption for heating (in Cluster 1, 47.74 kWh/m³·year and in Cluster 2, 61.35 kWh/m³·year for). Cluster 2 buildings also have more energy class jumps (4.91 versus 4.38), aligning with the deeper retrofit interventions proposed in less efficient buildings.

3.2.3 Investment Costs and Economic Efficiency

Initial investment costs are substantially higher for Cluster 1 buildings in both warm (€279,565.52) and cold (€243,435.51) climatic zones than those for Cluster 2 (€93,273.36 and €132,531.23), indicating the increased scale and complexity associated with retrofitting bigger and more compact buildings. Despite these higher investments, Cluster 2 buildings achieve greater specific energy savings per unit volume—29.02 kWh/m³ in warm zones and 50.66 kWh/m³ in cold zones—compared to Cluster 1's 19.23 kWh/m³ and 36.37 kWh/m³, respectively, underscoring the retrofit potential of smaller, less efficient buildings. Buildings in Cluster 2 exhibit a more favorable cost benefit ratio in warm climates (1.60 €/kWh) than Cluster 1 (1.92 €/kWh), indicating more cost-effective energy savings. In contrast, Cluster 1 buildings demonstrate a better cost-benefit ratio in cold climates, (0.81 €/kWh versus 1.08 €/kWh), indicating that although retrofits incur higher costs, the economic returns per energy unit saved are more favorable.

3.3 Clusters Reference Building Assessment and energy performance analysis

After performing cluster analysis in warm and cold climatic zones, the Euclidean distances of all buildings from their respective centroids were calculated in both zones. Schools that are nearest to the centroids serve as reference buildings for their cluster, as their characteristics closely approximate the centroid coordinates [14].

3.3.1 In warm climatic zones

For Cluster 1, the lowest distance was identified for a school of secondary education (gymnasium and lyceum), located in climatic zone B in the region of Evia, constructed in 1987. The proposed interventions of this three-store building involved thermal insulation of the building envelope, window replacement, installation of heating, cooling, lighting systems, and photovoltaics. These retrofits increase the energy class from D to A at a cost of 3.2 /kWh per saved energy unit (Table 9). In Cluster 2, the reference building is a nursery school, located in climatic zone A in Crete, built before 1980. The proposed measures for this single store building concluded thermal insulation of building envelope, window replacement, installation of heating, cooling, systems, and photovoltaics. These interventions improved energy class from G to A at a cost of 1.6 €/kWh per saved energy unit (Table 9).

Table 9. Buildings closest to the centroid of Cluster 1 and 2 in warm climatic zones.

Predictors	**Units**	 **CLUSTER 1**	 **CLUSTER 2**
SV ratio	-	0.18	0.35
Tot. us. Vol. (V)	m³	8,936.3	1,3746.56
Prim. en. heat. (PE)	kWh/m³ .year	13.12	17.28
En. cl. jumps (J)	-	4	6
In. inv. cost (C)	€	563,087	59,388.9
Sp. en. sav. (SEs)	kWh/m³	19.52	26.87
Cost-benefits ratio (CBr)	€/kWh	3.2	1.6

3.3.2 In cold climatic zones

For Cluster 1, the lowest distance was identified for a school of secondary education (gymnasium), located in climatic zone C in the mountainous area of Arcadia, constructed in 1955. The proposed interventions of this two-store building involved thermal insulation of the building envelope, window replacement, installation of heating, improving the energy class from H to D at a cost of 0.7 €/kWh per saved energy unit (Table 9). In Cluster 2, the reference building is a primary education school (elementary school), located in climatic zone C in Thessalia, built in 1997. The proposed retrofit measures for this single store building concluded thermal insulation of the building envelope, window replacement, upgrade of heating, lighting systems, and installation of photovoltaics resulting in the improvement of energy class from Z to A at a cost of 1.0 €/kWh per saved energy unit (Table 10).

Table 10. Building closest to the centroid of Cluster 1 and 2 in cold climatic zones.

Predictors	**Units**	 **CLUSTER 1**	 **CLUSTER 2**
SV ratio	-	0.34	0.45
Tot. us. Vol. (V)	m^3	5354.28	2170
Prim. en. heat. (PE)	kWh/m^3 .year	56.62	70.72
En. cl. jumps (J)	-	3	6
In. inv. cost (C)	€	127,160	170,000
Sp. en. sav. (SEs)	kWh/m^3	36.39	78.72
Cost-benefits ratio (CBr)	€/kWh	0.7	1.0

4 Conclusion

The present study provides a detailed evaluation of energy retrofit interventions in school buildings located in warm and cold climatic zones in Greece, focusing on their cost-benefit effectiveness by integrating regression and cluster analysis. Initially, the analysis identified two main building groups for each category of climatic zones. The first group (Cluster 1) consisted of larger, compact structures that initially exhibited reduced energy demands but required significant capital investment to achieve significant retrofit results. The second group (Cluster 2) involved smaller, less compact buildings that demonstrated significant retrofit potential and energy savings related to the invested resources, despite their higher initial energy consumption. However, the economic efficiency of retrofits, as indicated by the cost-benefit ratio, tends to favor Cluster 1 in cold climates and Cluster 2 in warm climates, reflecting the complex interplay between building characteristics, climate, retrofit measures, and investment scale.

However, it is important to acknowledge certain constraints in the research process here. The study's initial reliance on clustering to categorize buildings might oversimplify the inherent diversity with each structure. This simplification, while methodologically robust, suggests the necessity of supplementary analyses that focus on specific local contexts and building features. Additionally, even though the research conducted using a substantial sample from Greece, it is still limited by the economic and climatic specificities of the region. Consequently, direct extrapolation to other geographic contexts should be approached cautiously, requiring adaptation to local conditions.

Regardless the considerations above, the energy intervention patterns in school buildings do reflect a pragmatic, climate-sensitive retrofit strategy that balances building envelope improvements, renewable energy integration, as well as automatic system controls, which also aligns with Greece's national and EU energy efficiency policies, supporting the country's path towards a more sustainable and resilient building stock, capable of addressing both current and future climatic challenges.

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