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Bottom-up method to derive cost curves for space heating savings in residential buildings for all European countries

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ABSTRACT

Space heating constitutes approximately a quarter of final energy consumption in the European Union. Aligned with the ambition of the European Green Deal for climate-neutrality by 2050, effective energy system modelling is crucial for shaping strategies. However, integrating energy efficiency within the building sector remains challenging due to limited methodologies and data on specific energy consumption, heated surfaces, and retrofit costs. This paper proposes a methodology that balances accuracy and implementation effort through clustering analysis and relies entirely on open data primarily from the Hotmaps project to compute country-specific cost curves for energy savings in building space heating for each of the EU-27 countries. The aim is to empower energy system modelers to better incorporate energy efficiency measures into scenarios, thus advancing strategies in line with the European Green Deal. Findings indicate that the retrofits considered – insulation of façade, roof, ground floor; windows replacement – can save 40–60 % of space heating energy demand in most countries but marginal costs range widely, from 2 to 180 Eurocents invested per kWh saved over the retrofit lifetime. Climate conditions and existing insulation levels significantly influence the cost-effectiveness of these retrofits. This research provides valuable insights for policymakers and stakeholders working towards climate-neutral objectives.

Acronyms

AB	Apartment Block
BPIE	Building Performance Institute Europe
BS	Building Stock
BSO	Building Stock Observatory
EPB	Energy Performance of Buildings
ESC	Energy Savings Cost
EU	European Union
GHG	Greenhouse gases
HDD	Heating Degree Days

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HRE	Heat Roadmap Europe
LCSE	Levelized Cost of Saved Energy
MAC	Marginal Abatement Cost
PCA	Principal Component Analysis
SFH	Single-Family House
MFH	Multi-Family House

Nomenclature

A^{wall}	External wall area
h	Room height
A^{floor}	Heated floor area
F^{w}	Window/floor factor
i	Index for building elements
s	Index for countries
c	Building category
p	Construction period
$U_{s,c,p}^{average}$	Average U-value referring to country n, building category c, and construction period p
$U_{s,c,p}^{i}$	U-value of building element i for country n, building category c, and construction period p
$A_{s,c,p}^{i}$	Surface area of building element i for country n, building category c, and construction period p
d	Index for day of year
T_d	Mean outdoor air temperature of day d
HD_d	Heating Degree of day d
HDD	HDD
$h_{c,e}, h_{r,e}, h_{c,i}, h_{r,i}$	Convective/radiative external/internal heat transfer coefficients
$Q(\varphi)$	Heating energy need calculated according to the standard for a constant air change rate of φ
n	Iteration step
φ_n	Air change rate at n-th iteration step
C	Total cost spread in equal annual payments
S	Total energy savings
CRF	Capital recovery factor
r	Discount rate
l	Retrofit lifetime

1. Introduction

In 2016, residential energy use contributed to 10 % of global greenhouse gas (GHG) emissions [1]. In 2019, households accounted for 26 % of final energy consumption in Europe [2]. The European Union (EU) envisions achieving a zero-emission building stock by 2050 [3] and aims to reduce GHG emissions by 55 % by 2030 compared to 1990 levels [4], ultimately striving for climate-neutrality by 2050 [5]. To tackle emissions in the building sector, the EU launched the Renovation Wave initiative [6], with the goal of doubling the annual energy renovation rate of buildings by 2030. Additionally, the EU has proposed transitioning from nearly zero-energy buildings to zero-emission buildings by 2030, introducing the ZEB standard, mandatory for all new buildings starting January 1, 2030 [7].

The EU's building stock is diverse but predominantly consists of residential buildings [8]. Moreover, reducing energy demand in residential buildings through external surface insulation and window replacement presents significant potential and an opportunity to stimulate the local economy [9].

To tap into this energy and emissions reduction potential, Lechtenböhmer and Schüring [10] estimated that approximately 80 % of residential buildings in European countries could undergo energy retrofitting within the next 20 years. Bettgenhäuser and Hidalgo [11] projected a potential 75 % reduction in final energy use for space heating and hot water in Europe by 2050 through building stock energy retrofitting. Zhong et al. [12] assessed material-related GHG emissions for residential and commercial buildings, along with their reduction potentials in 26 global regions by 2060. They concluded that with ambitious policies and technologies, material-related emissions could be reduced by 80–90 % compared to current levels.

The central question arising from this context is how to determine the most cost-effective energy demand level for retrofitting existing buildings, considering other options for heat supply or energy conservation measures in different sectors. A balanced approach that considers both cost efficiency and emission reduction is crucial to ensure effective resource allocation in pursuit of Europe's climate neutrality goals. In addressing this challenge, this article focuses on developing a methodology for generating cost curves for heat savings in the residential sector, utilising an open database of building stock data across all European countries. This will facilitate a more comprehensive understanding of the cost implications and potential benefits associated with various building retrofit strategies, ultimately supporting informed decision-making in energy efficiency and decarbonisation efforts.

Cost curves depict the relationship between heat savings achieved through different building retrofits and their associated costs. They serve as valuable tools in identifying the most cost-effective options for reducing heat demand in buildings and advancing the decarbonisation of the energy system. However, deriving cost curves for heat savings poses challenges due to the extensive building stock data required, including specific energy consumption, heated surfaces, and retrofit costs. Furthermore, it is essential to ensure consistency and comparability of data across countries. This paper presents a method for deriving cost curves for heat savings in buildings using open data sources, primarily leveraging findings from the Hotmaps project, which offers harmonised data on building stock characteristics and retrofit costs for each of the EU-27 countries [13,14]. The method is applied to generate national-level cost curves, allowing for comparisons encompassing the different building types and climatic zones. The objective is to create a tool to assist modellers of energy systems in integrating energy conservation measures into their processes for scenario development.

Such a tool for visualising the costs and potential of various energy efficiency and decarbonisation measures is given by Marginal Abatement Cost (MAC) curves, also known as Energy Savings Cost (ESC) curves. Hummel et al. [15] describe these curves as "a widely used methodology to prioritize political intervention according to costs and related potentials." These curves facilitate comparisons among different technologies or strategies, aiding policymakers and stakeholders in identifying the most cost-effective approaches for achieving emissions reductions and energy savings.

One of the main benefits of MAC curves lies in their simplicity, which aids in conveying complex information to a wide range of stakeholders. These curves offer a concise overview of potential energy savings and associated costs, facilitating the prioritisation of investments in energy efficiency and decarbonisation based on the expected cost per unit of energy saving or emission reduction. Additionally, they allow for the inclusion of explicit technological details in the graphical representation, pinpointing the decarbonisation measures responsible for specific segments of the curve [16]. However, their implementation requires careful consideration. The accuracy of MAC curves depends significantly on the quality of underlying data and assumptions, which may vary across different regions or scenarios.

Within the energy-saving cost curves methodology, the literature review presented in Table 1 reveals a variety of approaches tailored to diverse building stocks and countries. All these articles contribute to understanding energy efficiency and building retrofit measures, yet they also have limitations in terms of geographical scope, openness of used data, and building simulation timestep compared to the approach proposed in this article, as detailed in the following paragraphs. The articles are reviewed in chronological order, from the oldest to the newest.

Jakob [17] (2006) analysed the Swiss residential sector, evaluating the marginal costs of energy efficiency investments and producing a marginal cost curve. The Building Stock (BS) is categorised into two groups, with 12 retrofit measures considered. The cost database is specific to Switzerland and does not utilize an open BS database. This study focuses solely on Switzerland and employs a static (annual timestep) building simulation model. Lund et al. [18] (2014) adopted a similar static annual timestep model, categorising the BS into 27 categories with 5 retrofit measures. The study is based on a cost database for Denmark and lacks an open BS database. It focuses exclusively on Denmark. Promjiraprawat [19] (2014) utilised a static annual timestep model, with a single BS category and 7 retrofit measures. The cost database is for Thailand, and the study does not employ an open BS database. It covers only Thailand.

Harmsen et al. [20] (2018) employed a static annual timestep model, dividing the BS into 10 categories with 12 retrofit measures. The labour cost index was used as cost database, and the study is based on the Heat Roadmap Europe's (HRE) open BS database. It

Table 1
Literature review on the topic of cost curves for heat savings in buildings.

Authors	Year of publication	Building simulation model: timestep, static vs. dynamic	Building types times construction periods subdividing the BS per country	Number of retrofit measures	Retrofit costs database	Open database of building stock	Number of countries covered
Jakob [17]	2006	Static (annual timestep)	2	12	For Switzerland	x	1 (Switzerland)
Lund et al. [18]	2014	Static (annual timestep)	27	5	For Denmark	x	1 (Denmark)
Promjiraprawat [19]	2014	Static (annual timestep)	1	7	For Thailand	x	1 (Thailand)
Harmsen et al. [20] (HRE)	2018	Static (annual timestep)	10	12	Labour cost index	✓ (Heat Roadmap Europe)	14 (EU countries)
Toleikyte [21]	2018	Monthly energy balance approach based on ISO 13790:2008	30	15	Costs database for Lithuania	x (Invert/EE-Lab)	1 (Lithuania)
Filippi Oberegger et al. [23]	2020	PHPP (monthly timestep)	16	19	Costs database for South Tyrol	x	1 (Italy, South Tyrol)
Hummel et al. [15]	2021	Quasi-steady-state energy balance approach with monthly timestep	Variable[a]	10	For Germany, extrapolated to other countries through the construction cost index	x (Invert/EE-Lab)	6 (AT, CZ, DK, DE, IT, RO)
Our approach	–	ISO 52016–1:2017 [26] with hourly timestep	21	10	For Italy, extrapolated to other countries through the construction cost index	✓ (Hotmaps)	EU-27, via clustering analysis

[a] Country-dependent, using as BS subdivisions building types, construction periods, historical renovations, and climate regions.

covers 14 EU countries. Toleikyte [21] (2018) used a monthly energy balance approach based on EN13790, with 30 BS categories and 15 retrofit measures. The study relies on a cost database for Lithuania and the Invert/EE-Lab BS database [22]. It covers only Lithuania. Filippi Oberegger et al. [23] (2020) employed the Passive House Planning Package (PHPP) model [24] with a monthly timestep, dividing the BS into 16 categories with 19 retrofit measures. The cost database is for the South Tyrol region of Italy and does not use an open BS database. The study covers only the South Tyrol region. They calculated that doubling current investments might result in energy savings of 60 %, while more than tripling current investments would be needed to reach maximum savings of 75 %. Hummel et al. [15] (2021) employed a quasi-steady-state monthly energy balance approach, with a country-dependent variable number of BS subdivisions and 10 retrofit measures. They used costs for Germany, transformed for other countries using the construction cost index, and the Invert/EE-Lab BS database. The study covers six countries: Austria, Czech Republic, Denmark, Germany, Italy, and Romania. They found that the costs for reaching savings of 40–60 % are remarkably lower than for reaching higher savings and that the highest and cheapest savings are achieved for buildings that are poorly insulated or have inefficient heating systems. Hummel et al.'s study concentrates on six European countries only and does not provide a harmonised subdivision of the national BS across all EU-27 countries.

This concludes our literature review. As highlighted, our approach stands out from the cited papers in mainly three aspects: openness of data sources, geographical scope while maintaining a high level of detail at national level, and temporal resolution in building simulation. Our study utilises the Hotmaps open BS database [13,14] offering a harmonised categorisation of the national BS and encompasses each of the EU-27 countries through clustering. We segment the BS into 21 categories (comprising three residential building sizes across seven construction periods) and apply 10 types of retrofit measures (various combinations of façade, roof, and floor insulation, as well as window replacement), of which nine turn out to be cost-effective. The costs for Italy are extrapolated for other countries using the 2019 construction cost index [25]. With respect to Hummel et al.'s study [15], we provide more detailed, harmonised charts of the energy-saving cost curves for each of the EU-27 countries, showing the retrofits implemented at each stage of the BS transition, along with the corresponding percentage of total energy savings achieved (Fig. 10), and for each building type (Fig. 11) and construction period (Fig. 12). We further employ a dynamic hourly timestep model, adhering to the Energy Performance of Buildings (EPB) standards, which play a crucial role in supporting the Energy Performance of Buildings Directive (EPBD) of the EU, and most notably, the ISO 52016–1:2017 standard [26].

In summary, the literature has explored various methodologies and approaches to create energy-saving cost curves, employing different timesteps, categorisations of the building stock, and retrofit measures. However, most studies are confined to a single country or region and lack a consistent open building stock database. Our proposed approach offers a more comprehensive, harmonised, and adaptable method, covering all EU-27 countries and leveraging the Hotmaps open BS database. The Hotmaps database and its derived datasets were used to populate the European Building Stock Observatory (BSO) [27], which is intended by the EU to serve as a one-stop shop for building stock statistics throughout Europe. Moreover, while existing studies employ a static approach for the building simulation model, ours is the first to be based on a dynamic building simulation model with hourly time-step intervals.

Therefore, the first novelty of our paper lies in proposing a framework to derive heat saving cost curves for a BS retrofitting utilising openly available online data sources that are accessible at no cost. We primarily draw upon data from the Hotmaps project [13,14], which offers harmonised data on building stock characteristics and retrofit costs for all EU-27 Member States at country level. Additionally, we incorporate other open data sources such as Eurostat to complement or validate our data inputs.

As a second novelty, we apply this methodology to calculate cost curves for every EU-27 Member State at country level. Previous studies have focused on a subset but not all EU-27 countries.

As a third novelty, we employ a high temporal resolution approach to building simulation through dynamic models with hourly timesteps. These models are openly available [28] and conform to the EU standardisation framework. This represents a significant advancement over existing methodologies in the field, which predominantly rely on undisclosed steady-state models based on energy balance evaluated with annual or monthly timesteps. The enhanced temporal resolution and dynamic approach enable modellers to explore more detailed and accurate representations of energy dynamics within buildings, capturing weather variations, equipment schedules, occupancy patterns, etc., that models with lower time resolution overlook.

Additionally, our approach is distinguished by its comprehensive BS categorisation and the retrofit measures it includes. This extensive categorisation and detailed reporting in charts significantly enhance the granularity and interpretability of the resulting energy savings cost curves. Such detailed analysis is crucial for accurately assessing the impact and cost-effectiveness of various energy efficiency interventions. Consequently, our methodology offers a more nuanced and precise tool for energy analysis, paving the way for more effective and targeted energy-saving strategies in building management and policy formulation.

Our paper addresses a gap in the literature by offering a simple yet comprehensive tool to generate heat saving cost curves for BS retrofit based on open data sources and providing a complete set of results for all EU-27 countries. This tool and these results can assist modellers of energy systems in integrating energy conservation measures into their process of developing scenarios, without the need for proprietary or confidential data or modelling tools.

The paper follows this structure: Section 1 gives an overview of existing literature concerning cost curves for heat savings in buildings; Section 2 outlines the methodology employed to derive cost curves from open data sources; Section 3 presents, validates, and discusses the results obtained for each EU-27 country; Section 4 concludes with policy implications and suggestions for future research.

2. Materials and methods

The purpose of this section is to outline the methodological steps taken to achieve the desired outcome, which is the creation of energy-saving cost curves for each of the EU-27 countries using open data. The steps can be summarised as follows.

1. The first phase entails preparing and analysing all pertinent open data necessary for the study. This data encompassed the heated area, the U-values, and the useful energy demand for space heating for each Member State, building type, and construction period. Additionally, we obtained Heating Degree Days (HDD) and a construction cost index for each country from open datasets.
2. Utilising the data from phase 1, we performed a clustering analysis to identify sets of buildings suitable for similar energy renovation. The objective of this phase is not only to identify and interpret the clusters but also to determine the optimal number of clusters according to the silhouette score method, as described below. This process involves grouping together similar building types, climates, and heating characteristics across various EU countries.
3. In the third phase, we conducted building simulations for the identified cluster centroids, adhering to the standard EN ISO 52016–1:2017 [26]. These simulations served to calibrate the simulation model to the baseline energy demand and to calculate the energy savings and costs associated with each retrofit step. To extend the simulation results to the entire cluster, we linearly scaled the results obtained for the centroid using the characteristics of the other reference buildings in the cluster as scaling factors. The purpose of these simulations was to assess the energy performance of all building stock segments before and after each energy retrofit, and to evaluate the retrofit costs.
4. In the fourth and final phase, the different retrofit measures are ranked, and the energy savings cost curves are created for all EU-27 countries. The ranking is based on the results obtained in step 3, which include the energy performance of the building stock before and after each energy retrofit and the associated retrofit costs.

Fig. 1 illustrates the comprehensive workflow utilised to derive the energy-saving cost curves for each of the EU-27 Member States. This methodology encompasses data collection, clustering analysis, building simulation, ranking of retrofit measures, and generation of the energy savings cost curves.

In essence, this methodology furnishes a valuable instrument to aid modellers of energy systems in integrating building energy conservation measures into the development of energy scenarios. Rooted in open data sources, the cost curves can further assist policymakers in formulating an energy strategy geared toward realising the European Green Deal's objective of climate neutrality by 2050.

2.1. Data preparation

The Hotmaps database provides a comprehensive overview of the BS for each of the EU-27 Member States including seven construction periods (before 1945, 1945–1969, 1970–1979, 1980–1989, 1990–1999, 2000–2010, and post 2010) and three residential building types (single-family/terraced houses, multifamily houses, and apartment blocks). This categorisation into building type and construction period is relevant because energy demand and retrofitting strategies may vary. From the Hotmaps database, the following indicators have been gathered: heated area [Mm^2], number of buildings [Mil.], average U-value of facades, roofs, floors, and windows [$W/(m^2 K)$], and space heating useful energy demand [$kWh/(m^2 a)$]. It is worth noting that the Hotmaps project's open database is

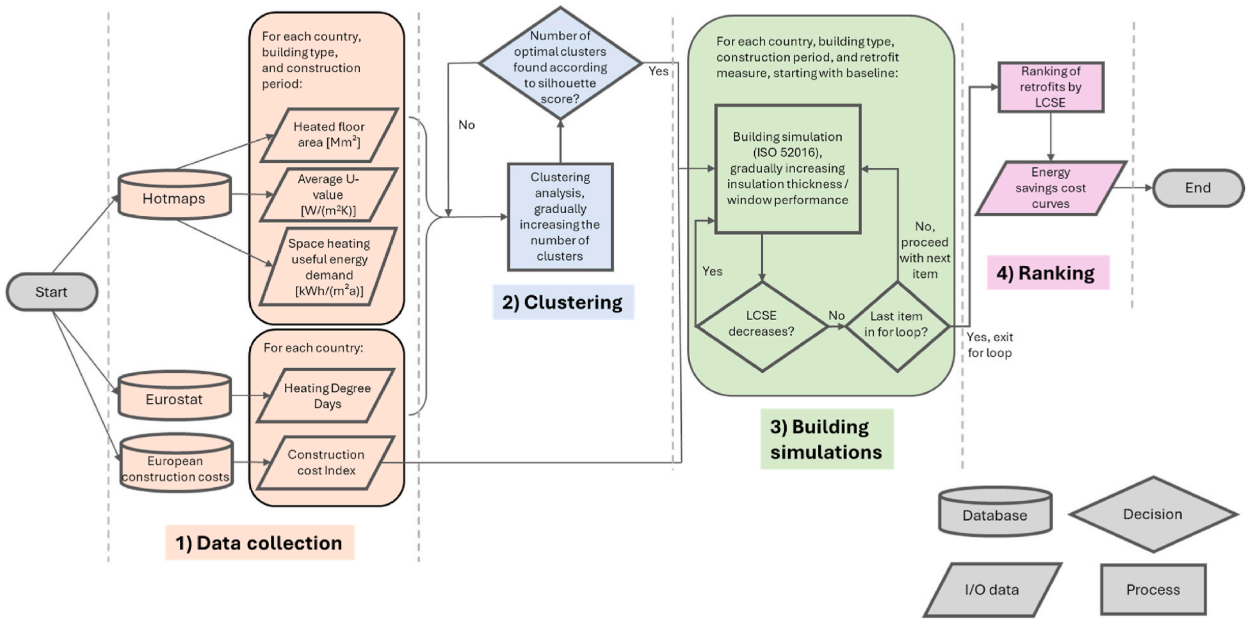

Fig. 1. Methodological workflow.

extensively utilised. It has recently contributed to the Moderate [29] and Ambience [30] project datasets and the EU Building Stock Observatory (BSO) [27].

In addition, the clustering analysis (Section 2.2) and building simulations (Section 2.3) required the HDD as input, which we derived from hourly weather data, see Section 2.3. To quantify construction costs, we used a regional price list for construction in 2021 [31] and adjusted it by a correction factor for the different countries based on the 2019 construction cost index [25].

2.2. Clustering analysis

Conducting building simulations for each BS category would entail a significant effort due to the multitude of building stock segments and retrofit combinations to consider. Specifically, with 27 countries, 3 building categories, and 7 construction periods, there are 567 combinations. To simplify this task and facilitate future scalability to even more detailed BS descriptions, a clustering analysis was conducted to identify clusters of Member States and building categories, encompassing building type and construction period, which may represent all buildings in a cluster.

Clustering analysis is a technique used in the data mining field that subdivides a dataset into groups, or clusters, depending on their similarity. In this study, we employed the K-Means method [32], which partitions a dataset into K pre-defined clusters based on the average distance between the data points and the centroid of a cluster [33]. We deemed the K-Means method appropriate because the point cloud for the indicators used (see below and Fig. 8) revealed that clusters of close-to-spherical shape and comparable size and density could be formed.

To ascertain the optimal number of clusters, two heuristic metrics were used: the Elbow Method [34] and the Silhouette Score [35]. The Elbow Method indicates as the optimal number of clusters the value of K where the explained variance stops increasing. The explained variance is measured as sum of the squared distances between the data points and the respective centroid. Conversely, the Silhouette Score uses the notion of similarity between points and assesses how similar a point is to the points in its own cluster compared to other clusters. The score varies between −1 and 1. A score near 1 indicates that the point is well embedded in its own cluster and not in the other clusters.

The clustering analysis was conducted using three building stock features with equal weighting: average U-value, space heating useful energy demand, and HDD. The average U-value was selected to represent the construction and insulation characteristics of residential buildings in each country. It offers insight into the inherent energy efficiency of building structures, reflecting the thermal performance of facade, roof, floor, and windows. Space heating useful energy demand was included to provide insight into the actual energy demand for heating, influenced not only by building construction quality and external climate but also building operation. Lastly, HDD was utilised to furnish information about the external climate in which the buildings are situated. This aids in distinguishing buildings based on the intensity and duration of heating required, which can vary due to climate variations.

The U-values for façade, roof, floor, and windows were combined into a single U-value, calculated as weighted average with respect to the surface area of each building component.

Kragh et al. [36] outline a method to estimate the geometry and surface areas of the buildings under consideration. This method relies on a simplified geometrical model, assuming the building to be a cuboid where each storey has a floor area of A^{floor}, a width of 8 m, a height h ranging from 2.5 to 2.8 m according to the construction year, and a window area equal to 15 % of the floor area. Hence, $A^{window} = F^{w} \cdot A^{floor}$, where F^{w} is set to 15 %. The external wall area A^{wall} of each storey is subsequently determined using Eq. (1):

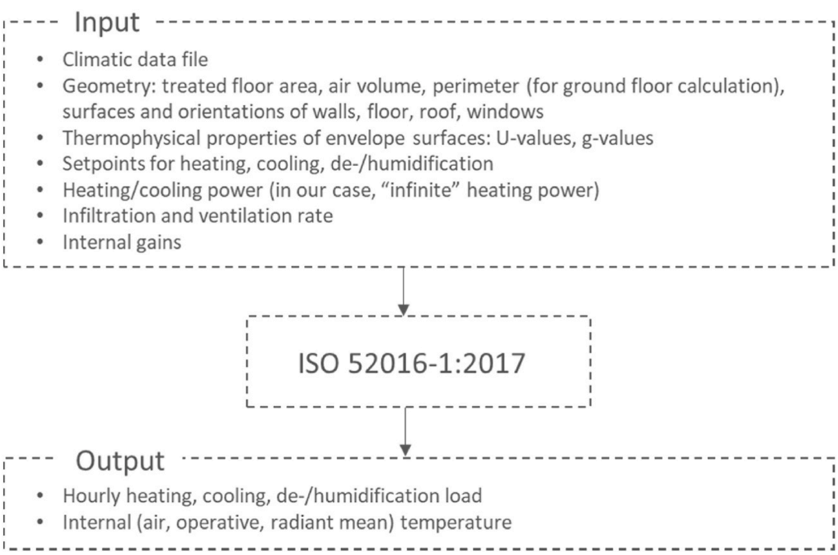

Fig. 2. Building simulation inputs and outputs.

$$A^{wall} = 2 \bullet h \bullet \left(8 + \frac{A^{floor}}{8}\right) - A^{window} \quad (1)$$

The Hotmaps project database provided the heated floor area. The façade, roof, floor, and window areas were then calculated utilising the simplified geometrical model of Kragh et al. [36]. With these areas, the mean U-values were calculated for each of the countries, building types, and construction periods according to Eq. (2):

$$U^{average}_{s,c,p} = \sum_i U^i_{s,c,p} \bullet A^i_{s,c,p} \quad (2)$$

where i is the index of the building element (façade, roof, floor, or window) and the sum is taken over all values of i. $U^i_{s,c,p}$ is the U-value of building element i for country s, building type c, and construction period p. $A^i_{s,c,p}$ is the area of building element i for country s, building type c, and construction period p. $U^{average}_{s,c,p}$ is the resulting average U-value for country s, building type c, and construction period p.

As an optional step in the clustering analysis, we conducted a Principal Component Analysis (PCA), a technique used to reduce the dimensionality of the clustering features, thereby allowing better visualisation and interpretation of the clusters. In our case, the three features are energy demand, average U-value, and HDD. PCA combines these variables into two principal components, allowing us to visually distinguish the clusters, their shape, and data variance in a 2D plot (see Fig. 8).

2.3. Building simulations as per standard ISO 52016–1:2017

After clustering, one single-building model was created per cluster, representing the cluster centroid, to compute its baseline and the expected energy savings for each retrofit package. Fig. 2 illustrates the input and output data of the simulation model.

We used a freely available Excel implementation [28] of the hourly calculation method outlined in the standard EN ISO 52016–1:2017. Firstly, we calibrated the simulation model for each cluster to match the characteristics of the respective centroid. For the weather data, we began by selecting the most populous city in the centroid country and obtained the weather file in TMY format for that city from the online tool PVGIS v5.2 [37]. This tool was selected because it provides hourly weather data for free. Subsequently, we calculated the HDD from the hourly outdoor air temperatures using Eqs. (3) and (4) as defined by Eurostat [38]:

$$HDD = \sum_d HD_d \quad (3)$$

$$HD_d = \begin{cases} 0 \;\; if \; T_d > 15 \\ 18 - T_d \quad else \end{cases} \quad (4)$$

where T_d represents the mean outdoor air temperature of day d in degrees Celsius. A tolerance of 3 % on the HDD was established to determine the suitability of the weather file. In cases where multiple TMY files for the same location were available on PVGIS, we selected the one with HDD closest to the centroid. If no suitable TMY file was found, we proceeded with the next city in descending order of population. Following this method, we could identify a suitable city for each of the four centroid countries.

A single, box-shaped thermal zone was simulated, with useful floor area and U-values for opaque and transparent building elements taken from the project Hotmaps. Surface areas and air volume were determined following Kragh et al. [36] as detailed in Section 2.2. A heating setpoint of 20 °C and heating schedule from 7:00 to 23:00 was assumed independently of the weekday. The hourly profiles for the internal gains produced by occupants, appliances, and lighting were taken from the informative Annex C of the standard EN 16798–1:2019 for the building type “residential, apartment (not retired).” The solar irradiances on roof, façade, and windows were calculated from the weather file solar irradiance data using a freely downloadable Excel calculation tool [39] implementing the standard ISO 52010–1:2017.

A set of parameters with high impact on the heating energy need are the convective/radiative external/internal heat transfer coefficients $h_{c,e}, h_{r,e}, h_{c,i}, h_{r,i}$. We chose the values recommended in Table 25 (p.127) of ISO 52016–1:2017, i.e., $h_{c,e} = 20, h_{r,e} = 4.14$, $h_{r,i} = 5.13$. As for $h_{c,i}$, the standard provides varying values from 0.7 to 5.0 depending on the direction of heat flow. However, the Excel implementation only accepts a constant input. We found that by using a constant value of $h_{c,i} = 1.5$ and adjusting the air change rate accordingly, we were able to align all building models with the centroid’s energy demand. See the details below for further clarification.

For simplicity, we maintained a constant air change rate for both ventilation and infiltration throughout the simulation. This parameter significantly affects the annual heating energy demand and must be chosen carefully to represent actual ventilation (controlled air exchange) and infiltration (uncontrolled air leakage) effects in alignment with the heating energy demand from the Hotmaps project. Infiltration is primarily related to building airtightness, which depends on factors such as construction quality, materials, and building age. Ventilation, on the other hand, is influenced by mechanical systems (if present), and occupant behaviour. Thus, we used air change rate as a proxy to model these effects, enabling the calibration of the building simulation model to match the centroid’s value. This was done iteratively with the secant method, which is a finite-difference approximation of Newton’s method (Eq. (5)). Starting with the initial air change rates $\varphi_0 = 0$ and $\varphi_1 = 1$, measured in cubic meters of outdoor air per hour and square meter of useful floor area [$m^3/(h\ m^2)$], as per the standard’s conventions, the iteration progresses as follows:

$$\varphi_n = \frac{\varphi_{n-2}Q(\varphi_{n-1}) - \varphi_{n-1}Q(\varphi_{n-2})}{Q(\varphi_{n-1}) - Q(\varphi_{n-2})}, n = 2, 3, \dots \quad (5)$$

where $Q(\varphi)$ represents the heating energy demand computed in accordance with the standard for a constant air change rate of φ, while n indicates the iteration step. For all centroids, either φ_2 or φ_3 provided a satisfactory match, meaning one or two applications of Eq. (5) were sufficient. In the case of centroids linked with Portugal, Ireland, and Sweden, see Table 3, the heating energy demand calibrated in this manner deviated by less than 1 % from the centroid. However, with Romania, we encountered the issue that the heating energy demand from the simulation model exceeded the centroid value for air change rates above 0.6. Consequently, we opted to set the air change rate at this value, as it aligns with typical passive house standards; going lower would have been unrealistic. With this value, the heating energy demand was 7 % higher than the centroid, a deviation we deemed acceptable given the uncertainties inherent in our simulation setup.

All parameters deemed secondary for the purposes of this paper were maintained at their default values in the Excel implementation. For a comprehensive reference to all the values set, the interested reader can download the published simulation models [40]. Once we calibrated to the centroid of heating energy demand, we proceeded with the energy retrofit simulation. We considered "staged" retrofitting, also known as "over-time" or "phased" retrofitting. In contrast to a one-off deep retrofit, a staged retrofit consists of several carefully planned retrofit steps executed over time [41]. This reduces the upfront investment cost at each step, which makes the retrofit more accessible. The considered retrofits are: 1) façade insulation, 2) roof insulation, and 3) floor insulation with varying thicknesses, and 4) windows replacement, considering three types of windows. In the initial stage of the staged retrofit process, only one of the four retrofit types – specifically, the one that minimizes the LCSE, see Section 2.4 – is implemented. In the second and third stage, one of the remaining retrofit types is selected based on its ability to minimise the LCSE. In the last and fourth stage, the remaining retrofit type is implemented.

2.4. Ranking of retrofits at each retrofit step

The Levelised Cost of Saved Energy (LCSE), henceforth also referred to as marginal cost, provides a straightforward means of comparing energy supply (such as those based on natural gas prices) and staged retrofit (energy efficiency measures) options:

$$LCSE = \frac{C}{S} \bullet CRF \quad (6)$$

$$CRF = \frac{r \bullet (1+r)^l}{(1+r)^l - 1} \quad (7)$$

Here, C denotes the total cost spread out in equal annual payments (with the investment cost treated as loan with annual repayment), S the total energy savings, CRF the capital recovery factor, r the discount rate set to 4 %, and l the retrofit lifetime set to 30 years, in line with assumptions made by Ballarini et al. [42] in their study on the energy refurbishment of the Italian residential building stock.

In this phase of the overall methodology, the LCSE is calculated in EUR invested per kWh saved along the entire retrofit lifetime. The calculation of the LCSE is performed for each country, building type, construction period, and retrofit measure. Each next retrofit step is determined by ranking the retrofit measures according to LCSE and selecting the minimum. For each subsequent retrofit

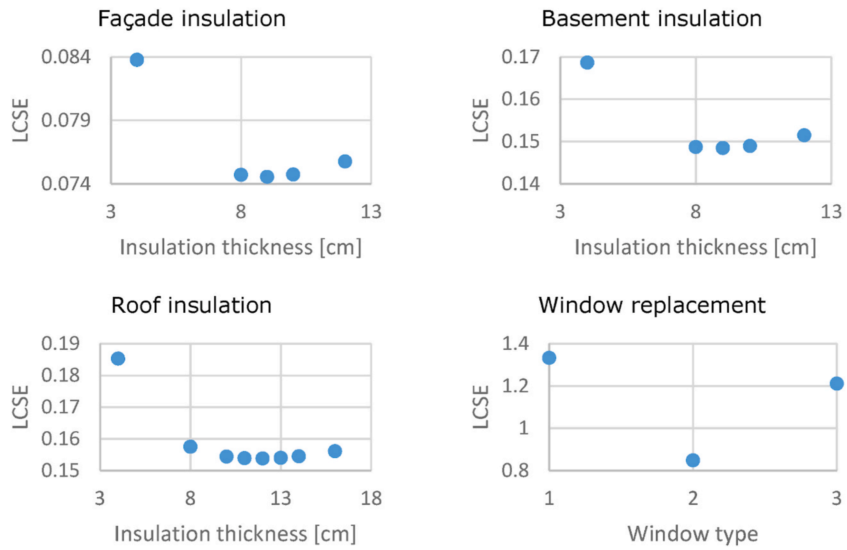

Fig. 3. LCSE [€ invested/kWh saved over lifetime] for different retrofit measures.

measure – façade insulation, roof insulation, floor insulation, or windows replacement – insulation thickness and window type are varied and eventually fixed at the minimal LCSE resulting from the additional useful energy demand saving compared to the prior state of the building, which may have already undergone up to three retrofit steps.

The costs of the retrofit measures were determined using a regional price list for construction in 2021 [31]. All figures mentioned henceforth are reported in €/m^2 of retrofitted surface area unless otherwise specified and encompass material and labour costs. For façade insulation, the fixed cost totalled 53 (comprising scaffolding: 11; priming: 3; plaster reinforcement: 13; plastering: 20; finishing: 6). Roof insulation incurred a fixed cost of 89 (including scaffolding: 11; removal of existing roof: 18; sealing: 25; rafters and battens: 11; tiling: 24). Floor insulation carried a fixed cost of 34 (covering priming: 3; plaster reinforcement: 10; plastering: 15; finishing: 6). To these fixed costs, the additional variable cost for insulation panels was added, set at 1.9 €/cm thickness of insulation, derived as the typical average cost of glass wool panels of varying thickness. Glass wool was selected as the representative insulation material due to its favourable €/R-value ratio, assuming an R-value per cm insulation of 0.29. For window replacement, three types of windows were considered: 1) a double-glazed window with an overall U-value of 1.7, a g-value of 0.7, and a cost of 459; 2) a more efficient double-glazed window with an overall U-value of 1.3, a g-value of 0.7, and a cost of 532; and 3) a triple-glazed window with an overall

Austria

[%]	SFH	MFH	AB
Before 1945	12.8	4.6	5.2
1945 - 1969	17.4	4.1	5
1970 - 1979	11.3	1.7	2.4
1980 - 1989	9.5	1.7	1.1
1990 - 1999	9.9	2.7	1.5
2000 - 2010	4.2	1.3	1.4
Post 2010	1.1	0.5	0.5

Belgium

[%]	SFH	MFH	AB
Before 1945	3.2	8.3	0.9
1945 - 1969	1	8.1	6
1970 - 1979	0.4	8.2	8.1
1980 - 1989	0.2	5.7	8
1990 - 1999	0.7	7.9	5.9
2000 - 2010	2.7	8	5.5
Post 2010	1.2	4.9	5.2

Bulgaria

[%]	SFH	MFH	AB
Before 1945	14.8	0.5	5.5
1945 - 1969	14.6	1.1	7
1970 - 1979	8.2	1.3	5.1
1980 - 1989	6.9	1.7	5.1
1990 - 1999	5.6	1.1	4
2000 - 2010	6	0.7	4.5
Post 2010	2.8	0.8	2.7

Croatia

[%]	SFH	MFH	AB
Before 1945	8.6	1.1	3.3
1945 - 1969	11.3	1.6	4.2
1970 - 1979	11.8	2.1	4.5
1980 - 1989	9.7	0.7	3.6
1990 - 1999	8.5	0.9	3.4
2000 - 2010	9.5	2.2	4
Post 2010	4.5	1.7	2.7

Cyprus

[%]	SFH	MFH	AB
Before 1945	6.2	1.4	0.2
1945 - 1969	25.1	2.2	5
1970 - 1979	12.9	1.7	2.7
1980 - 1989	5.5	1.1	0.6
1990 - 1999	4.5	1.5	0.1
2000 - 2010	15	1	3.4
Post 2010	8.1	0.1	1.5

Czech Republic

[%]	SFH	MFH	AB
Before 1945	12	0.7	4.8
1945 - 1969	12.4	0.8	6.9
1970 - 1979	12.8	0.8	6
1980 - 1989	7.5	2.5	3
1990 - 1999	3.9	4.3	1.1
2000 - 2010	6.4	3.1	2.4
Post 2010	3.4	4.4	0.8

Denmark

[%]	SFH	MFH	AB
Before 1945	12	6.5	2.1
1945 - 1969	9.5	7.3	1.5
1970 - 1979	11.3	7.3	1.5
1980 - 1989	1.3	8.3	0.5
1990 - 1999	1.3	8.3	0.5
2000 - 2010	1.9	8.2	0.6
Post 2010	1.7	7.9	0.6

Estonia

[%]	SFH	MFH	AB
Before 1945	27.2	2.2	3.8
1945 - 1969	15.2	0.9	5.1
1970 - 1979	2.5	3.9	2.2
1980 - 1989	1.6	4.3	1.7
1990 - 1999	1.4	8.5	1.9
2000 - 2010	1.1	8.3	2.1
Post 2010	2.9	2.7	0.7

Finland

[%]	SFH	MFH	AB
Before 1945	7.2	0.8	1.3
1945 - 1969	10.6	7.4	7.4
1970 - 1979	6.1	7.7	7.7
1980 - 1989	8.7	3.9	3.9
1990 - 1999	5.8	3.5	3.5
2000 - 2010	6.4	3.2	3.2
Post 2010	0.9	0.5	0.3

France

[%]	SFH	MFH	AB
Before 1945	11.5	6.1	0.7
1945 - 1969	4.1	7.8	2.2
1970 - 1979	5.6	8	2.1
1980 - 1989	4.9	8.3	1.8
1990 - 1999	0.4	8.6	0.9
2000 - 2010	4.7	8.3	1.7
Post 2010	2.4	9.5	0.5

Germany

[%]	SFH	MFH	AB
Before 1945	14.3	6.6	0.5
1945 - 1969	16.8	9.8	3.6
1970 - 1979	8.4	3.7	3.1
1980 - 1989	6.7	2.9	1.1
1990 - 1999	7	2.4	1.1
2000 - 2010	5.7	1.4	0.5
Post 2010	2.7	1.3	0.3

Greece

[%]	SFH	MFH	AB
Before 1945	4.6	2.5	1.1
1945 - 1969	13.4	3.2	6.1
1970 - 1979	10.9	3.4	4.8
1980 - 1989	12.5	3.2	6.6
1990 - 1999	9.8	1.8	4.6
2000 - 2010	2.7	3.4	0.2
Post 2010	1.7	3.4	0.1

Hungary

[%]	SFH	MFH	AB
Before 1945	12.1	2	3.9
1945 - 1969	11.6	2	4.1
1970 - 1979	7.7	3	2.4
1980 - 1989	10.8	3.1	4.5
1990 - 1999	4.5	3.3	3.2
2000 - 2010	5.6	3.2	3.9
Post 2010	3.4	2.5	3.3

Ireland

[%]	SFH	MFH	AB
Before 1945	7.5	0.1	8.7
1945 - 1969	7.2	0.2	9.1
1970 - 1979	7	0.6	4.8
1980 - 1989	6.1	0.4	9.6
1990 - 1999	9.4	0.5	0.3
2000 - 2010	18	1	2.5
Post 2010	5.6	0.1	1.5

Italy

[%]	SFH	MFH	AB
Before 1945	4.3	7.3	4.3
1945 - 1969	3.6	8.3	3.3
1970 - 1979	3.9	8.4	3.2
1980 - 1989	2.9	9.3	2.3
1990 - 1999	1.9	10.3	1.3
2000 - 2010	1.7	10.3	1.3
Post 2010	1.5	9.5	1.1

Latvia

[%]	SFH	MFH	AB
Before 1945	12.3	8	1.6
1945 - 1969	2.4	8.6	2.6
1970 - 1979	2.3	9.2	1.9
1980 - 1989	2.9	8.9	2.3
1990 - 1999	2.8	8.9	2.2
2000 - 2010	2.7	10	2.3
Post 2010	1.4	5.1	1.5

Lithuania

[%]	SFH	MFH	AB
Before 1945	13.3	0.8	3.4
1945 - 1969	13.3	1.3	6.3
1970 - 1979	8.2	1.4	5
1980 - 1989	9.3	0.3	5
1990 - 1999	6.5	2.4	2.4
2000 - 2010	7	2.5	2.4
Post 2010	5.5	2.3	1.4

Luxembourg

[%]	SFH	MFH	AB
Before 1945	20.6	1.9	2.8
1945 - 1969	13.5	2.1	2.7
1970 - 1979	9.2	3.9	0.8
1980 - 1989	6.9	4.4	0.3
1990 - 1999	3.6	5	0.3
2000 - 2010	8.9	2	1.3
Post 2010	7.7	1.5	0.7

Malta

[%]	SFH	MFH	AB
Before 1945	11.4	2.5	4.4
1945 - 1969	10.2	2.6	4.3
1970 - 1979	7.4	2.5	3.7
1980 - 1989	9	2.5	3.9
1990 - 1999	7.8	2.5	3.9
2000 - 2010	4.9	3.2	3.2
Post 2010	4	3.1	2.9

Netherlands

[%]	SFH	MFH	AB
Before 1945	20.6	1	1.1
1945 - 1969	19.3	1	1.1
1970 - 1979	11.3	1.7	0.4
1980 - 1989	11.9	1.6	0.5
1990 - 1999	10.7	1.7	0.4
2000 - 2010	7.7	1.9	0.2
Post 2010	3.8	2	0.1

Poland

[%]	SFH	MFH	AB
Before 1945	8.8	1.2	5.7
1945 - 1969	11.4	0.4	6.6
1970 - 1979	7.4	0.7	4.5
1980 - 1989	7.2	0.6	4.3
1990 - 1999	7.3	0.5	4.2
2000 - 2010	8.8	1.7	7.1
Post 2010	4.8	3.9	3

Portugal

[%]	SFH	MFH	AB
Before 1945	7.7	0.5	3.1
1945 - 1969	6.5	3.1	3.1
1970 - 1979	7.8	5.3	5.3
1980 - 1989	8	4.6	4.6
1990 - 1999	8.3	6.4	6.4
2000 - 2010	8.3	2.6	2.6
Post 2010	3.2	0.4	2.1

Romania

[%]	SFH	MFH	AB
Before 1945	9.2	0.5	2.8
1945 - 1969	20.4	2	8.6
1970 - 1979	5.6	0.8	6.3
1980 - 1989	4.8	0.6	5.3
1990 - 1999	6.8	0.6	2.8
2000 - 2010	6.7	1.2	3.8
Post 2010	6.4	1.2	3.6

Slovakia

[%]	SFH	MFH	AB
Before 1945	14.1	0.2	8.9
1945 - 1969	9.1	0.7	10.3
1970 - 1979	5.9	1.9	4.5
1980 - 1989	8.5	1.4	6
1990 - 1999	6.1	3.1	3.4
2000 - 2010	6.6	2.1	4.4
Post 2010	1.2	0.8	1.1

Slovenia

[%]	SFH	MFH	AB
Before 1945	5.9	3	3.5
1945 - 1969	20.8	3.2	5.1
1970 - 1979	6.2	3.3	3.2
1980 - 1989	4.4	3.6	2.8
1990 - 1999	4.1	3.7	2.8
2000 - 2010	7.4	3.1	3.3
Post 2010	4.8	2.9	3

Spain

[%]	SFH	MFH	AB
Before 1945	8	2	5.5
1945 - 1969	6.4	0.6	6.9
1970 - 1979	5.3	0.8	6.8
1980 - 1989	6.9	2	5.6
1990 - 1999	6.8	1.9	5.6
2000 - 2010	6.6	3.1	9.8
Post 2010	3.6	2.2	3.7

Sweden

[%]	SFH	MFH	AB
Before 1945	7.7	6.2	4.5
1945 - 1969	5.3	9.5	1.2
1970 - 1979	5.1	9.4	1.2
1980 - 1989	3.9	9.4	1.3
1990 - 1999	1.8	9.8	0.9
2000 - 2010	1.4	10.3	0.3
Post 2010	1.2	9.2	0.3

United Kingdom

[%]	SFH	MFH	AB
Before 1945	24.5	5.5	0.8
1945 - 1969	17.3	1.9	0.5
1970 - 1979	6.6	1.8	0.2
1980 - 1989	4.7	1.2	0.2
1990 - 1999	4.7	1.1	0.1
2000 - 2010	13.7	2.4	0.5
Post 2010	10.7	1.4	0.3

Fig. 4. Heated area as percentage of overall heated area by country, building category, and construction period.

U-value of 0.8, a g-value of 0.5, and a cost of 555. The above costs were adjusted by a correction factor based on the 2019 construction cost index [25] in different countries.

The above process is illustrated for the centroid identified for Romania (refer to Table 3). Computing the LCSE for each initial retrofit measure by varying insulation thicknesses in increments of 1 cm until an inflection point is reached, and testing window types from 1 to 3, produces the graphs depicted in Fig. 3.

According to Fig. 3, the first retrofit measure with the lowest LCSE is identified as 9 cm façade insulation. For the second retrofit measure, simulations need to be conducted for the following retrofit combinations: 1) façade plus floor insulation, 2) façade plus roof insulation, and 3) façade insulation plus window replacement. This is because the energy savings from individual retrofit measures cannot simply be added. For instance, in the case of the Romania centroid, the energy saving from façade (floor) insulation alone is 50 % (5 %), but together they result in a 57 % energy saving. The lowest LCSE is achieved with 9 cm of floor insulation. Among all potential retrofit measures for the third step, the lowest LCSE is achieved with 12 cm of roof insulation. Lastly, window type 2 minimizes the LCSE for window replacement.

Austria

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	173.3	103.6	107.9
1945 - 1969	175.8	120.9	111.8
1970 - 1979	163.2	111.9	103.7
1980 - 1989	131.4	93.4	85.8
1990 - 1999	118.6	81.6	77.1
2000 - 2010	107.9	79.1	70.9
Post 2010	92.4	66.7	61.6

Belgium

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	410.9	195.4	195.4
1945 - 1969	410.9	195.4	195.4
1970 - 1979	333.1	182.1	182.1
1980 - 1989	255.2	168.7	168.7
1990 - 1999	112.9	102.4	102.4
2000 - 2010	195.6	91.5	91.5
Post 2010	96.2	80.7	80.7

Bulgaria

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	76	55.3	55.3
1945 - 1969	78.8	54.3	54.3
1970 - 1979	74.8	49.6	49.6
1980 - 1989	41.9	45.8	45.8
1990 - 1999	66.2	40.7	40.7
2000 - 2010	50.9	31.1	31.1
Post 2010	45.5	29.6	29.6

Croatia

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	190.8	162.7	162.7
1945 - 1969	204.2	136.8	136.8
1970 - 1979	163.8	90.5	90.5
1980 - 1989	161	107.9	107.9
1990 - 1999	55.5	76.3	76.3
2000 - 2010	77.1	49.3	49.3
Post 2010	36.4	42.2	42.2

Cyprus

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	56.6	45.6	45.6
1945 - 1969	57.1	42.6	42.6
1970 - 1979	57.3	39.6	39.6
1980 - 1989	57.6	40.5	40.5
1990 - 1999	56.4	39.2	39.2
2000 - 2010	56.4	37.3	37.3
Post 2010	56.4	34.1	34.1

Czech Republic

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	190.3	123.8	123.8
1945 - 1969	186.3	121	121
1970 - 1979	171.7	118.1	118.1
1980 - 1989	141.8	90.2	90.2
1990 - 1999	177.8	90.2	90.2
2000 - 2010	115.5	90.1	90.1
Post 2010	110.5	77.8	77.8

Denmark

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	226.4	153.2	153.2
1945 - 1969	202.6	145.8	145.8
1970 - 1979	168.4	89.6	89.6
1980 - 1989	149.2	75.5	75.5
1990 - 1999	109.4	67.2	67.2
2000 - 2010	69.6	59	59
Post 2010	54.8	39.7	39.7

Estonia

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	291.8	202.3	202.3
1945 - 1969	236.4	137	137
1970 - 1979	245.6	129.3	129.3
1980 - 1989	190.4	99.8	99.8
1990 - 1999	173.8	70	70
2000 - 2010	227.3	105.3	105.3
Post 2010	192.3	77.1	77.1

Finland

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	254.1	147.9	147.9
1945 - 1969	233.1	124.9	124.9
1970 - 1979	240.2	129.1	129.1
1980 - 1989	224.2	130.6	130.6
1990 - 1999	202.4	126.5	126.5
2000 - 2010	194.5	82.4	82.4
Post 2010	188.5	30	30

France

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	243.9	166	166
1945 - 1969	197.9	130.5	130.5
1970 - 1979	225.3	135.3	135.3
1980 - 1989	194.5	89	89
1990 - 1999	153.4	81.6	81.6
2000 - 2010	106.9	64.5	64.5
Post 2010	66.9	51.3	51.3

Germany

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	261.9	209.2	155.2
1945 - 1969	232.4	198.6	141.3
1970 - 1979	210.9	144.8	104.7
1980 - 1989	163.6	131.9	101
1990 - 1999	109.9	84.5	76.9
2000 - 2010	101.9	81.5	59.3
Post 2010	68.2	50.6	46

Greece

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	105.8	72.3	72.3
1945 - 1969	109.2	75.1	75.1
1970 - 1979	111.7	75.4	75.4
1980 - 1989	91.6	75.7	75.7
1990 - 1999	102	90.6	90.6
2000 - 2010	171.6	21.3	21.3
Post 2010	149.4	19.1	19.1

Hungary

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	243.1	84.9	84.9
1945 - 1969	204.1	120.2	120.2
1970 - 1979	178.1	86.5	86.5
1980 - 1989	153.7	52.9	52.9
1990 - 1999	141.1	44.2	44.2
2000 - 2010	131.1	30	30
Post 2010	121	15.7	15.7

Ireland

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	131.1	155	155
1945 - 1969	118.4	160.2	160.2
1970 - 1979	116.5	139.9	139.5
1980 - 1989	99.8	64.4	64.4
1990 - 1999	83.2	65.9	65.9
2000 - 2010	75.6	39.9	39.9
Post 2010	67.5	10.8	10.8

Italy

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	147.3	123.2	123.2
1945 - 1969	206	126.1	126.1
1970 - 1979	185.8	121.3	121.3
1980 - 1989	165.9	118.8	118.8
1990 - 1999	129.4	93.7	93.7
2000 - 2010	118.7	78.7	78.7
Post 2010	108	75.3	75.3

Latvia

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	308.7	185.1	185.1
1945 - 1969	289.8	165.3	165.3
1970 - 1979	296.1	164.5	164.5
1980 - 1989	273	142.4	142.4
1990 - 1999	198.8	121	121
2000 - 2010	151.4	107.4	107.4
Post 2010	102	98	98

Lithuania

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	299	233.3	233.3
1945 - 1969	264.9	180.3	180.3
1970 - 1979	181.1	103.9	103.9
1980 - 1989	144	91	91
1990 - 1999	106.9	78	78
2000 - 2010	86.3	63.5	63.5
Post 2010	65.6	49	49

Luxembourg

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	344.4	195	195
1945 - 1969	337.4	202.8	202.8
1970 - 1979	202.5	123	123
1980 - 1989	183.5	102.9	102.9
1990 - 1999	122.2	71.4	71.4
2000 - 2010	101.2	35.9	35.9
Post 2010	44.1	5.2	5.2

Malta

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	34.6	14.1	14.1
1945 - 1969	34.3	15.3	15.3
1970 - 1979	29	11.7	11.7
1980 - 1989	27.7	11.1	11.1
1990 - 1999	25.6	10.5	10.5
2000 - 2010	18.4	9.9	9.9
Post 2010	17.6	8.6	8.6

Netherlands

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	152.2	212.8	212.8
1945 - 1969	155.7	215.2	215.2
1970 - 1979	139.4	194.6	194.6
1980 - 1989	96.8	112.6	112.6
1990 - 1999	59.8	70.9	70.9
2000 - 2010	34.9	57.5	57.5
Post 2010	12	13.9	13.9

Poland

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	312.4	171.1	171.1
1945 - 1969	253.8	99.4	99.4
1970 - 1979	194	73.3	73.3
1980 - 1989	176	70.6	70.6
1990 - 1999	158	67.8	67.8
2000 - 2010	121.9	62.3	62.3
Post 2010	121.9	57.6	57.6

Portugal

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	136.2	101.4	101.4
1945 - 1969	116.8	78.8	78.8
1970 - 1979	116.1	78.1	78.1
1980 - 1989	107.5	72.7	72.7
1990 - 1999	90.4	84.8	84.8
2000 - 2010	73.3	50.7	50.7
Post 2010	78.7	33.7	33.7

Romania

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	181.4	111.9	111.9
1945 - 1969	172.5	79.8	79.8
1970 - 1979	175	78.2	78.2
1980 - 1989	140.6	66.4	66.4
1990 - 1999	172.2	104.7	104.7
2000 - 2010	91.5	40	40
Post 2010	64.5	37.4	37.4

Slovakia

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	140.9	111.6	111.6
1945 - 1969	182.7	111.7	111.7
1970 - 1979	168.1	99.7	99.7
1980 - 1989	153.4	87.7	87.7
1990 - 1999	152.3	93.1	93.1
2000 - 2010	142.9	74.1	74.1
Post 2010	133.5	70.6	70.6

Slovenia

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	201	127.8	127.8
1945 - 1969	198	113.6	113.6
1970 - 1979	170.8	83.1	83.1
1980 - 1989	162.6	63.9	63.9
1990 - 1999	130.4	56.7	56.7
2000 - 2010	99	49.5	49.5
Post 2010	83	36.1	36.1

Spain

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	75.9	59.3	59.3
1945 - 1969	80.3	55.8	55.8
1970 - 1979	76.4	51.2	51.2
1980 - 1989	46.9	38.1	38.1
1990 - 1999	47.3	36.4	36.4
2000 - 2010	43.4	29.2	29.2
Post 2010	31.7	24.1	24.1

Sweden

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	263.5	182.6	182.6
1945 - 1969	216.6	134.1	134.1
1970 - 1979	160.9	87.1	87.1
1980 - 1989	140.3	70.6	70.6
1990 - 1999	166.4	77.4	77.4
2000 - 2010	156.3	67.6	67.6
Post 2010	146.2	57.8	57.8

United Kingdom

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	210.5	111.2	111.2
1945 - 1969	189.6	89.1	89.1
1970 - 1979	128.2	49.3	49.3
1980 - 1989	120	44.9	44.9
1990 - 1999	112.4	40.5	40.5
2000 - 2010	97.1	31.7	31.7
Post 2010	45	23.7	23.7

Fig. 5. Space heating useful energy demand [kWh/(m^2a)] by country, building category, and construction period.

3. Results and discussion

3.1. Presentation of findings

In this section, we present and discuss the outcomes of our methodology applied to derive heat savings cost curves for each of the EU-27 countries. Detailed analyses of input data, such as the proportion of heated area in various building types across different countries, space heating energy demand values for each country's building categories, and a linear correlation study between HDD and space heating energy demand across different building types and construction periods, are included. Subsequently, the results from the clustering analysis are presented, along with the resulting energy savings cost curves for each of the EU-27 countries. Finally, a comparative analysis of potential energy savings and retrofit costs is provided.

Fig. 4 illustrates the heated area as a percentage of the overall heated area for each country, building category, and construction period. Analysing this data reveals significant variations and potential groupings based on shared characteristics.

A grouping by building type is feasible: i) high share of Single-Family Houses (SFH) in countries like Austria, the Netherlands, the

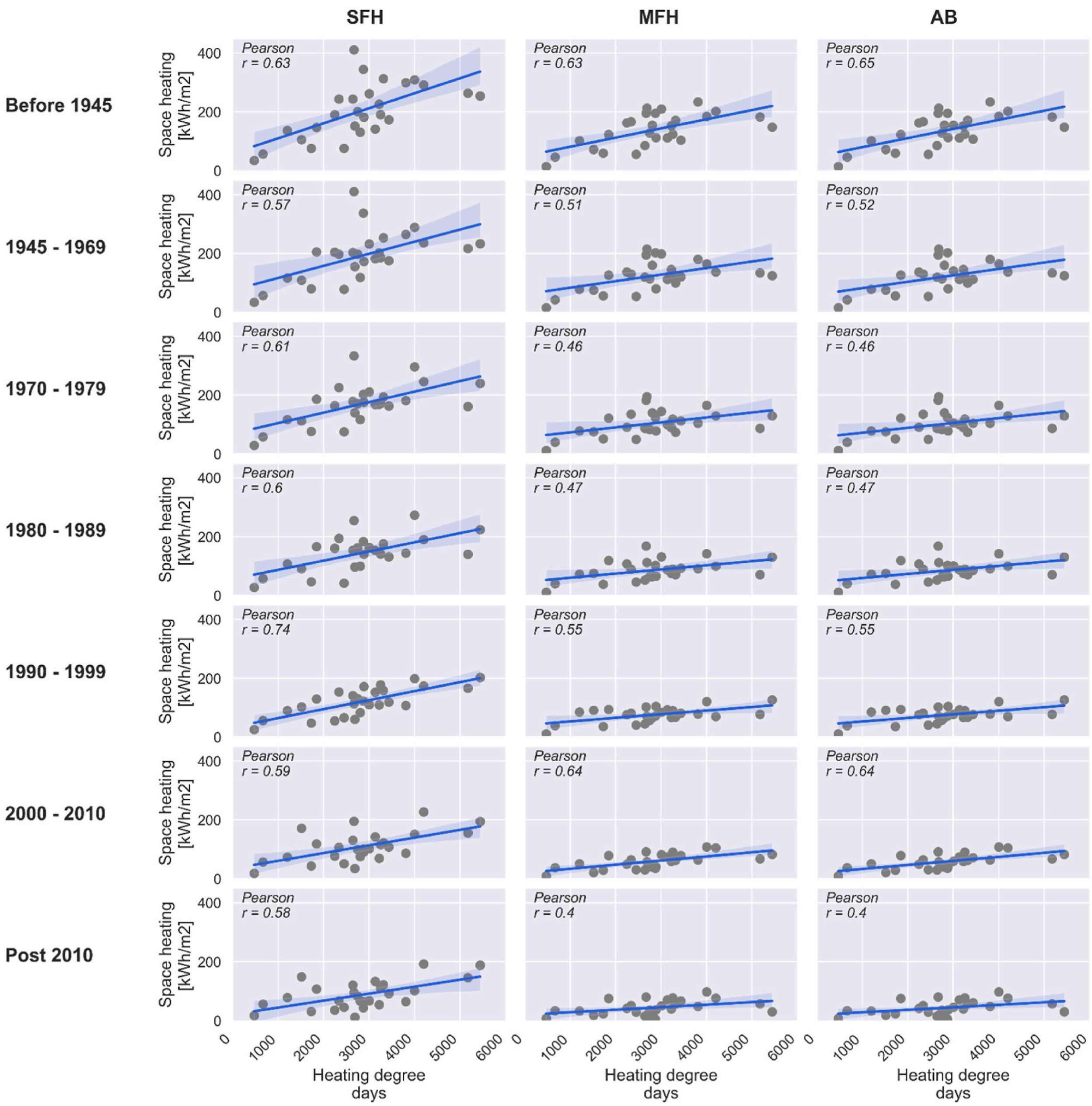

Fig. 6. Correlation between heating degree days and space heating energy demand for each building category and construction period.

United Kingdom, Estonia, and Germany exhibit a higher proportion of heated area in SFH, indicating a prevalence of such housing types. This could reflect lifestyle preferences, suburban development patterns, or land availability. ii) Prevalence of Multi-Family Houses (MFH): countries such as Belgium, Italy, France, and Sweden show a high heated area share of MFH, suggesting urbanised settings with higher population densities. iii) Predominance of Apartment Blocks (AB): while there are few countries with most of the heated area in the AB category, some, like Belgium, Ireland, Slovakia, and Spain, have a significant share in this category. This suggests urban planning favouring high-density housing, possibly influenced by historical and socioeconomic factors.

A grouping by building stock age is also feasible: i) countries with a newer building stock, like Ireland, the United Kingdom, and Cyprus, where the heated areas in buildings constructed post-1990 are relatively higher, indicate a more recent expansion in their building stock. This could be attributed to recent economic development or a surge in construction activities in these countries. ii) Countries with an older building stock, like Austria, Bulgaria, Estonia, Germany, Luxemburg, the Netherlands, Romania, and Slovakia, with substantial heated areas in buildings dating before 1945, reflect an older building stock. These countries may encounter unique challenges in retrofitting and improving energy efficiency due to historical preservation concerns and the technical difficulties of modernizing older buildings. However, they also have significant opportunities, as retrofitting their older building stock can lead to significantly higher energy savings and reductions in CO_2 emissions, serving as a substantial leverage point in achieving climate goals.

Fig. 5 illustrates the space heating useful energy demand values in kWh/(m^2 a) for each of the EU-27 countries, building category, and construction period. The data shows that in most countries the oldest single-family/terraced houses feature higher space heating requirements. In a few exceptions however, space heating energy consumption is higher in newer buildings than in older ones. In Italy, for example, SFH in 1945–1969 perform worse in this regard than SFH in the period before 1945. Other examples for this are Croatia, Estonia, and France. In some countries with warmer climates, such as Cyprus, Malta, and Spain, space heating energy demand is generally lower.

Fig. 6 illustrates the linear correlation between HDD and space heating for each building category and construction period. The graphs show that as we transition from SFH to MFH and AB, the linear correlation between space heating and HDD becomes less pronounced. This indicates that colder climates have a greater impact on space heating in SFH compared to MFH and AB. This is reasonable because the ratio of building heat loss surface area to floor area is typically larger for SFH than for MFH and AB. Regarding the construction period, the linear correlation becomes less pronounced from older to newer buildings. This suggests that the climate has a reduced influence on space heating in newer buildings compared to older ones, which is expected due to the increased insulation found in modern buildings.

Following the extensive data collection phase, our attention turns to the results of the clustering analysis. Fig. 7 illustrates a correlation matrix, revealing the interrelationships among the features used for clustering: energy demand, average U-value, and HDD.

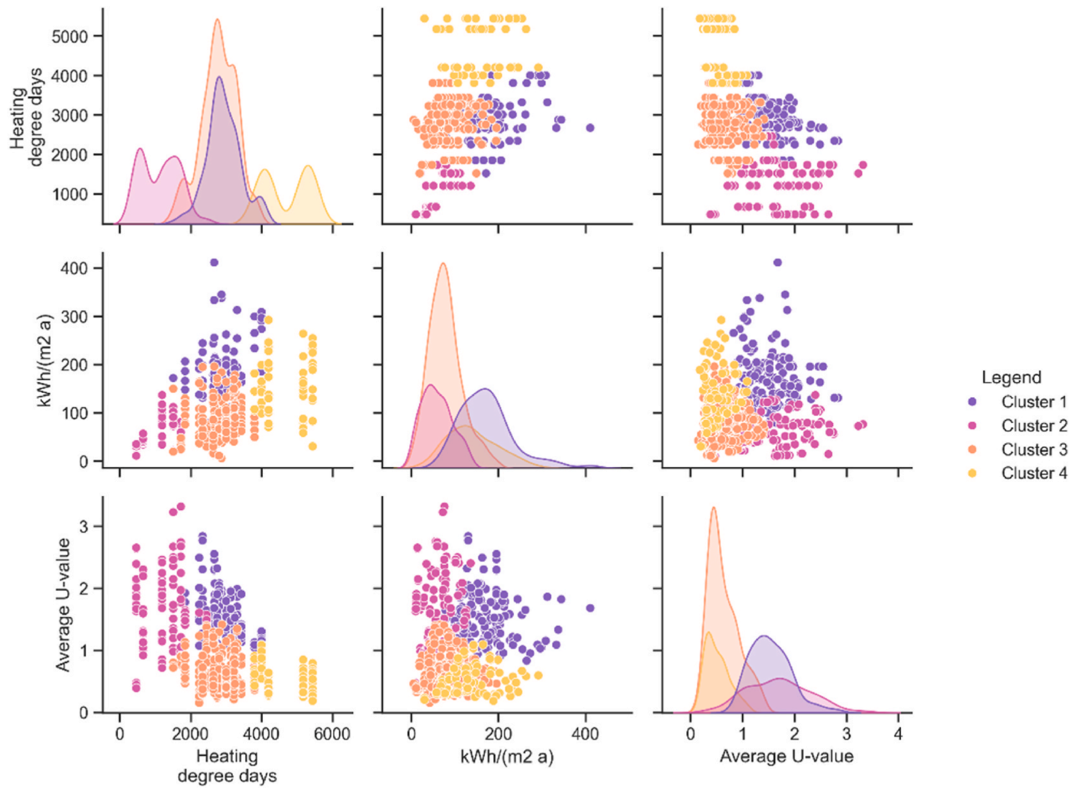

Fig. 7. Graphical representation of the clustering analysis with 4 clusters.

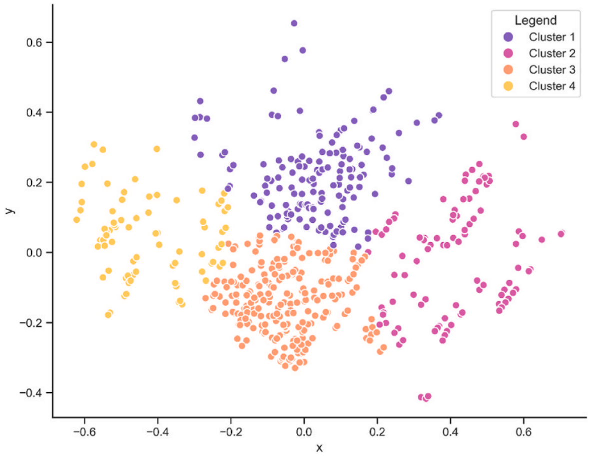

Fig. 8. Results of the application of PCA allowing 2-d visualisation.

The analysis identifies four distinct clusters.

1. Cluster 1 displays medium HDD, high energy demand, and high average U-values, indicating regions with moderate climates but inefficient energy usage and building insulation.
2. Cluster 2, characterised by low HDD, low energy demand, and high U-values, represents areas with mild climates but inefficient insulation.
3. Cluster 3 combines medium HDD with low energy consumption and efficient insulation, reflecting regions with balanced climate conditions and better energy efficiency.
4. Cluster 4 is characterised by high HDD, medium energy consumption, and efficient insulation, indicative of colder regions with moderate energy use and good insulation standards.

These clusters highlight significant variations in energy efficiency and climate conditions across the EU, underscoring the necessity of tailored approaches for decarbonising the building stock in different regions.

Fig. 8 shows the scatter plot resulting from PCA. The two principal components, labelled "x" and "y", are plotted on the x and y axes, respectively, allowing us to visualise the four clusters in a 2-d space.

Each point on the plot represents a segment of the building stock characterised by the three features energy demand, average U-value, and HDD.

To better understand the meaning of the principal components, we calculated the correlation between the clustering analysis features and the principal components. The correlation matrix is shown in Table 2.

Referring to Table 2, or upon close inspection of Figs. 7 and 8, it becomes evident that the x-value of the PCA correlates strongly and negatively with HDD, moderately and positively with U-value, and weakly and negatively with energy demand. Thus, a higher x-value primarily indicates a warmer climate, moderately suggests reduced insulation, and weakly implies a tendency towards lower energy demand. It could therefore roughly be described as "climate warmth indicator." The y-value correlates strongly and positively with energy demand, moderately and positively with U-value, and weakly and positively with HDD. Hence, a higher y-value primarily indicates higher energy demand, moderately suggests reduced insulation, and weakly implies a tendency towards a colder climate. A suitable label for it could thus be "energy intensity indicator."

Fig. 9 presents a visualisation of our clustering analysis results, emphasizing the space heating energy demand of the building stock segments across the different countries. Each table within the figure corresponds to a specific country, with rows representing construction periods and columns representing building types. The energy demand values in kWh/(m^2a) for each building type and construction period are displayed in the cells, colour-coded according to the cluster they belong to from our four-cluster analysis. This colour coding illustrates how different segments of a country's building stock are categorised into clusters based on their energy demand profiles, aiding in a more intuitive understanding of the data.

Table 3 shows the centroids of each cluster used to calibrate the building energy performance simulation models. These models are used to calculate the energy savings obtained with each retrofit step.

Table 2
Correlation matrix for the PCA.

	Heating degree days	kWh/(m^2 a)	Average U-value
x	−0.95	−0.35	0.72
y	0.21	0.82	0.63

Austria

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	173.3	103.6	107.9
1945 - 1969	175.8	120.9	111.8
1970 - 1979	163.2	111.9	103.7
1980 - 1989	131.4	93.4	85.8
1990 - 1999	118.6	81.6	77.1
2000 - 2010	107.9	79.1	70.9
Post 2010	92.4	66.7	61.6

Belgium

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	410.9	195.4	195.4
1945 - 1969	410.9	195.4	195.4
1970 - 1979	333.1	182.1	182.1
1980 - 1989	255.2	168.7	168.7
1990 - 1999	112.9	102.4	102.4
2000 - 2010	195.6	91.5	91.5
Post 2010	96.2	80.7	80.7

Bulgaria

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	76	55.3	55.3
1945 - 1969	78.8	54.3	54.3
1970 - 1979	74.8	49.6	49.6
1980 - 1989	41.9	45.8	45.8
1990 - 1999	66.2	40.7	40.7
2000 - 2010	50.9	31.1	31.1
Post 2010	45.5	29.6	29.6

Croatia

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	190.8	162.7	162.7
1945 - 1969	204.2	136.8	136.8
1970 - 1979	163.8	90.5	90.5
1980 - 1989	161	107.9	107.9
1990 - 1999	55.5	76.3	76.3
2000 - 2010	77.1	49.3	49.3
Post 2010	36.4	42.2	42.2

Cyprus

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	56.6	45.6	45.6
1945 - 1969	57.1	42.6	42.6
1970 - 1979	57.3	39.6	39.6
1980 - 1989	57.6	40.5	40.5
1990 - 1999	56.4	39.2	39.2
2000 - 2010	56.4	37.3	37.3
Post 2010	56.4	34.1	34.1

Czech Republic

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	190.3	123.8	123.8
1945 - 1969	186.3	121	121
1970 - 1979	171.7	118.1	118.1
1980 - 1989	141.8	90.2	90.2
1990 - 1999	177.8	90.2	90.2
2000 - 2010	115.5	90.1	90.1
Post 2010	110.5	77.8	77.8

Denmark

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	226.4	153.2	153.2
1945 - 1969	202.6	145.8	145.8
1970 - 1979	168.4	89.6	89.6
1980 - 1989	149.2	75.5	75.5
1990 - 1999	109.4	67.2	67.2
2000 - 2010	69.6	59	59
Post 2010	54.8	39.7	39.7

Estonia

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	291.8	202.3	202.3
1945 - 1969	236.4	137	137
1970 - 1979	245.6	129.3	129.3
1980 - 1989	190.4	99.8	99.8
1990 - 1999	173.8	70	70
2000 - 2010	227.3	105.3	105.3
Post 2010	192.3	77.1	77.1

Finland

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	254.1	147.9	147.9
1945 - 1969	233.1	124.9	124.9
1970 - 1979	240.2	129.1	129.1
1980 - 1989	224.2	130.6	130.6
1990 - 1999	202.4	126.5	126.5
2000 - 2010	194.5	82.4	82.4
Post 2010	188.5	30	30

France

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	243.9	166	166
1945 - 1969	197.9	130.5	130.5
1970 - 1979	225.3	135.3	135.3
1980 - 1989	194.5	89	89
1990 - 1999	153.4	81.6	81.6
2000 - 2010	106.9	64.5	64.5
Post 2010	66.9	51.3	51.3

Germany

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	261.9	209.2	155.2
1945 - 1969	232.4	198.6	141.3
1970 - 1979	210.9	144.8	104.7
1980 - 1989	163.6	131.9	101
1990 - 1999	109.9	84.5	76.9
2000 - 2010	101.9	81.5	59.3
Post 2010	68.2	50.6	46

Greece

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	105.8	72.3	72.3
1945 - 1969	109.2	75.1	75.1
1970 - 1979	111.7	75.4	75.4
1980 - 1989	91.6	75.7	75.7
1990 - 1999	102	90.6	90.6
2000 - 2010	171.6	21.3	21.3
Post 2010	149.4	19.1	19.1

Hungary

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	243.1	84.9	84.9
1945 - 1969	204.1	120.2	120.2
1970 - 1979	178.1	86.5	86.5
1980 - 1989	153.7	52.9	52.9
1990 - 1999	141.1	44.2	44.2
2000 - 2010	131.1	30	30
Post 2010	121	15.7	15.7

Ireland

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	131.1	155	155
1945 - 1969	118.4	160.2	160.2
1970 - 1979	116.5	139.9	139.5
1980 - 1989	99.8	64.4	64.4
1990 - 1999	83.2	65.9	65.9
2000 - 2010	75.6	39.9	39.9
Post 2010	67.5	10.8	10.8

Italy

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	147.3	123.2	123.2
1945 - 1969	206	126.1	126.1
1970 - 1979	185.8	121.3	121.3
1980 - 1989	165.9	118.8	118.8
1990 - 1999	129.4	93.7	93.7
2000 - 2010	118.7	78.7	78.7
Post 2010	108	75.3	75.3

Latvia

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	308.7	185.1	185.1
1945 - 1969	289.8	165.3	165.3
1970 - 1979	296.1	164.5	164.5
1980 - 1989	273	142.4	142.4
1990 - 1999	198.8	121	121
2000 - 2010	151.4	107.4	107.4
Post 2010	102	98	98

Lithuania

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	299	233.3	233.3
1945 - 1969	264.9	180.3	180.3
1970 - 1979	181.1	103.9	103.9
1980 - 1989	144	91	91
1990 - 1999	106.9	78	78
2000 - 2010	86.3	63.5	63.5
Post 2010	65.6	49	49

Luxembourg

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	344.4	195	195
1945 - 1969	337.4	202.8	202.8
1970 - 1979	202.5	123	123
1980 - 1989	183.5	102.9	102.9
1990 - 1999	122.2	71.4	71.4
2000 - 2010	101.2	35.9	35.9
Post 2010	44.1	5.2	5.2

Malta

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	34.6	14.1	14.1
1945 - 1969	34.3	15.3	15.3
1970 - 1979	29	11.7	11.7
1980 - 1989	27.7	11.1	11.1
1990 - 1999	25.6	10.5	10.5
2000 - 2010	18.4	9.9	9.9
Post 2010	17.6	8.6	8.6

Netherlands

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	152.2	212.8	212.8
1945 - 1969	155.7	215.2	215.2
1970 - 1979	139.4	194.6	194.6
1980 - 1989	96.8	112.6	112.6
1990 - 1999	59.8	70.9	70.9
2000 - 2010	34.9	57.5	57.5
Post 2010	12	13.9	13.9

Poland

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	312.4	171.1	171.1
1945 - 1969	253.8	99.4	99.4
1970 - 1979	194	73.3	73.3
1980 - 1989	176	70.6	70.6
1990 - 1999	158	67.8	67.8
2000 - 2010	121.9	62.3	62.3
Post 2010	121.9	57.6	57.6

Portugal

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	136.2	101.4	101.4
1945 - 1969	116.8	78.8	78.8
1970 - 1979	116.1	78.1	78.1
1980 - 1989	107.5	72.7	72.7
1990 - 1999	90.4	84.8	84.8
2000 - 2010	73.3	50.7	50.7
Post 2010	78.7	33.7	33.7

Romania

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	181.4	111.9	111.9
1945 - 1969	172.5	79.8	79.8
1970 - 1979	175	78.2	78.2
1980 - 1989	140.6	66.4	66.4
1990 - 1999	172.2	104.7	104.7
2000 - 2010	91.5	40	40
Post 2010	64.5	37.4	37.4

Slovakia

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	140.9	111.6	111.6
1945 - 1969	182.7	111.7	111.7
1970 - 1979	168.1	99.7	99.7
1980 - 1989	153.4	87.7	87.7
1990 - 1999	152.3	93.1	93.1
2000 - 2010	142.9	74.1	74.1
Post 2010	133.5	70.6	70.6

Slovenia

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	201	127.8	127.8
1945 - 1969	198	113.6	113.6
1970 - 1979	170.8	83.1	83.1
1980 - 1989	162.6	63.9	63.9
1990 - 1999	130.4	56.7	56.7
2000 - 2010	99	49.5	49.5
Post 2010	83	36.1	36.1

Spain

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	75.9	59.3	59.3
1945 - 1969	80.3	55.8	55.8
1970 - 1979	76.4	51.2	51.2
1980 - 1989	46.9	38.1	38.1
1990 - 1999	47.3	36.4	36.4
2000 - 2010	43.4	29.2	29.2
Post 2010	31.7	24.1	24.1

Sweden

[kWh/(m²a)]	SFH	MFH	AB
Before 1945	263.5	182.6	182.6
1945 - 1969	216.6	134.1	134.1
1970 - 1979	160.9	87.1	87.1
1980 - 1989	140.3	70.6	70.6
1990 - 1999	166.4	77.4	77.4
2000 - 2010	156.3	67.6	67.6
Post 2010	146.2	57.8	57.8

- Cluster 1
- Cluster 2
- Cluster 3
- Cluster 4

Fig. 9. Results of the clustering analysis in terms of energy demand.

Figs. 10–12 present energy-saving cost curves for each of the EU-27 countries, illustrating the relationship between cumulative energy savings in percent and marginal cost in EUR/kWh saved of the retrofit measures applied to residential building categories. Each subplot represents a different EU country, providing a detailed analysis of how various retrofit measures contribute to energy savings and their associated costs (Fig. 10) and how these retrofit measures are applied across different building types (Fig. 11) and construction periods (Fig. 12).

The curves demonstrate a wide range of marginal costs for energy savings across different countries, building types, and construction periods. Notably, certain interventions such as façade or roof insulation offer significant energy savings at relatively low costs. In the following quantitative analysis, all marginal costs are expressed in Eurocents invested per kWh saved over the retrofit lifetime. The lowest 50 marginal costs, ranging from 2.5 to 4.3 Eurocents, appear in the countries Belgium, Croatia, Estonia, Greece, Hungary, Latvia, Lithuania, Luxembourg, Poland, Portugal, Romania, and Slovakia. Of the 20 % retrofit measures with lowest marginal costs, 53 % target SFH. In terms of construction period, within these low-cost retrofit measures, 31 % concern pre-1945 buildings, 26 % those built in 1945–1969, and 19 % those built in 1970–1979, with decreasing shares for newer buildings. As first retrofit measure, façade insulation is chosen in 82 % of cases, while roof insulation is selected in the remaining 18 %. In contrast, floor

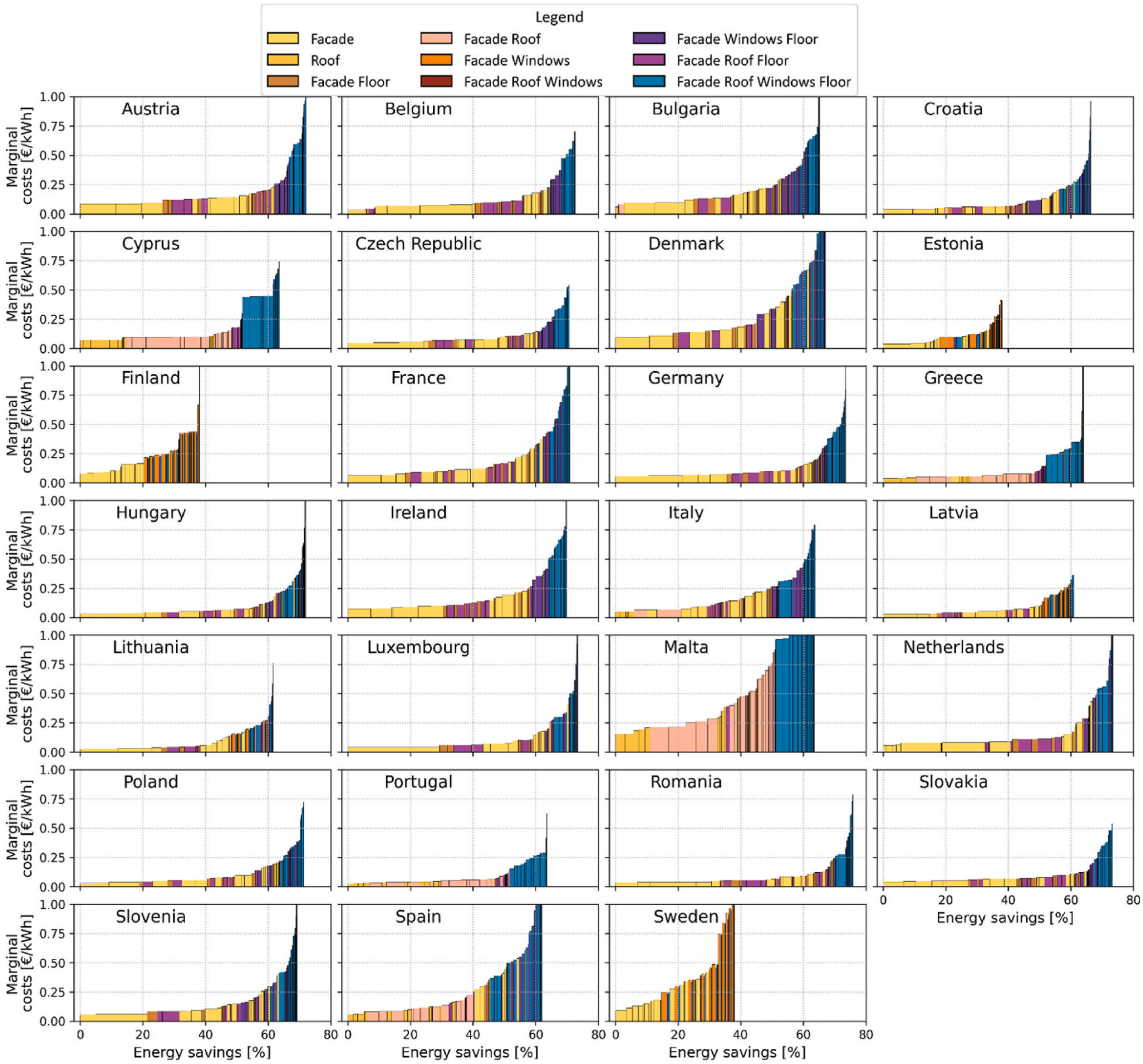

Fig. 10. Energy saving cost curves for each of the EU-27 countries showing the retrofit measures composing the curves.

insulation and window replacement are never selected as the first measures due to their higher marginal costs. The marginal cost of façade insulation starts at 2.8 Eurocents for pre-1945 SFH in Latvia, where baseline energy consumption is high (Fig. 5). Roof insulation starts at a marginal cost of 2.5 Eurocents for pre-1945 SFH in Portugal, followed closely by SFH built between 1945-1969 and 1970–1979, with a marginal cost of 2.9 Eurocents. For pre-1945 MFH and AB, the minimum marginal cost is 3.4 Eurocents for roof insulation in Portugal.

In contrast, more comprehensive measures entail higher costs but are necessary for achieving the highest energy savings in specific building types or construction periods. Even so, combined roof and façade insulation can maintain low marginal costs, starting at 3.4 Eurocents for pre-1945 SFH in Portugal. Façade and floor insulation starts at a marginal cost of 3.9 Eurocents for pre-1945 SFH in Latvia. The most affordable three-measure combination – façade, roof, and floor insulation – starts at 4.0 Eurocents for pre-1945 SFH in Latvia. Including window replacement raises the lowest marginal cost to 9.3 Eurocents in combination with façade and floor insulation for pre-1945 SFH in Estonia. The lowest marginal cost implementing all four retrofit measures is 9.7 Eurocents for pre-1945 SFH in Estonia. Some countries with low HDD, like Malta, exhibit high marginal costs for retrofit measures. This is primarily due to the relatively low space heating energy demand, resulting in minimal energy savings and CO_2 emission reductions from any of the considered retrofits. For instance, achieving a 60 % energy savings in Malta requires measures with marginal costs up to 180 Eurocents, with the lowest at 16 Eurocents for roof insulation in pre-1945 SFH. Consequently, in these countries, the energy saving cost curves are pushed upwards, indicating that higher percentages of energy savings come at a high cost.

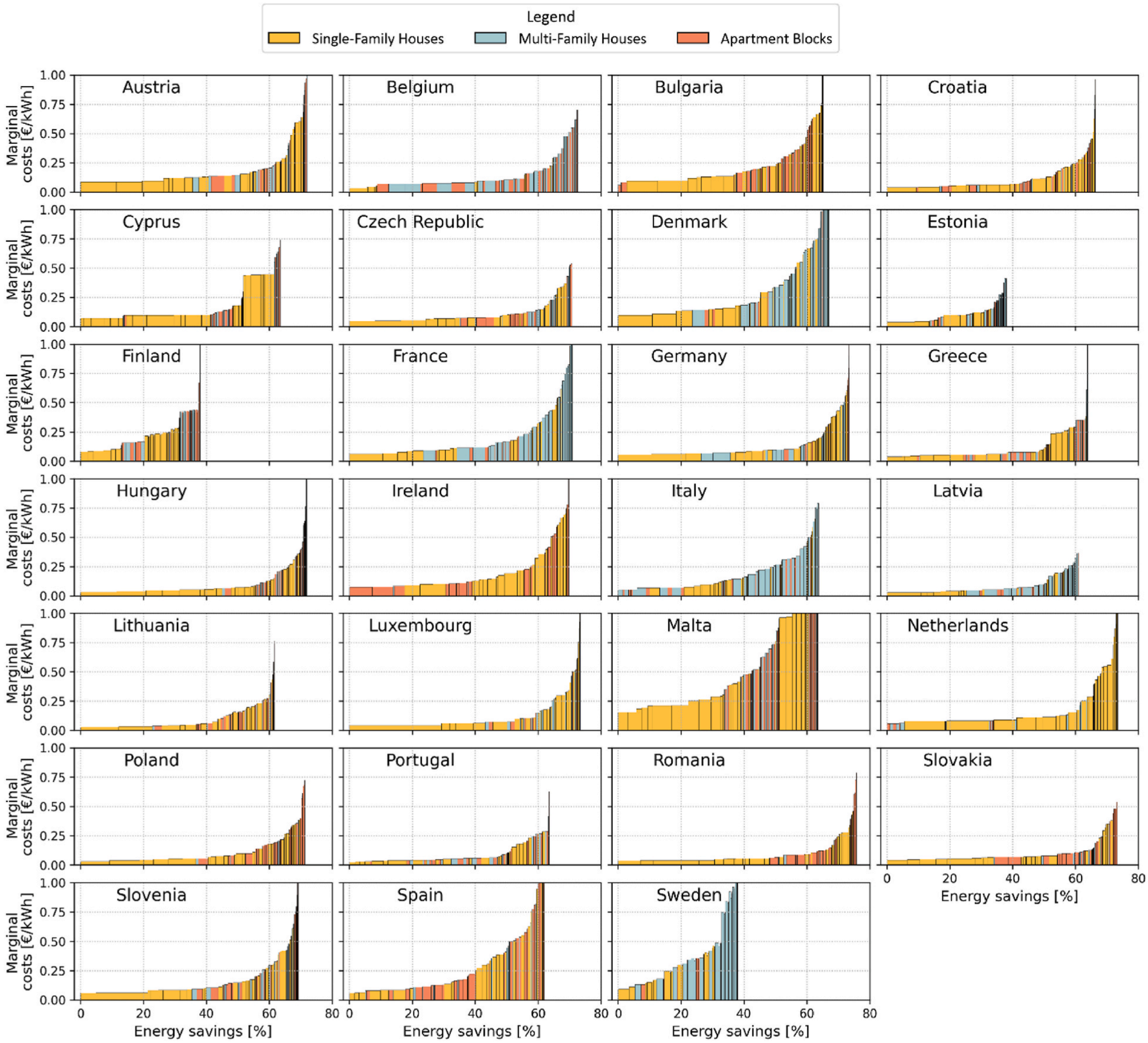

Fig. 11. Energy saving cost curves for each of the EU-27 countries showing the building types the retrofits are applied to.

Countries with higher HDD, such as Hungary, Lithuania, Poland, Slovakia, and Belgium, additionally have numerous poorly insulated buildings with higher U-values in their building stock. This further contributes to their higher space heating requirements and makes retrofits more cost-effective.

Thus, the cost-effectiveness of retrofits targeting space heating and cooling is influenced by both climatic conditions (HDD) as well as the insulation quality (the U-values) of the existing building stock. Countries with colder climates and poorly insulated older buildings offer greater potential for cost-effective energy savings through such retrofits. On the other hand, countries with warmer climates and better insulation have more limited energy saving potential regarding space heating.

For instance, countries with the highest HDD – Finland, Sweden, Estonia, Latvia, and Lithuania – show diverse outcomes. Finland and Sweden do not achieve low marginal costs due to relatively low baseline energy consumption and better-insulated facades, with U-values of 0.60 and 0.59, respectively, for pre-1945 residential buildings. In contrast, Latvia and Lithuania have higher baseline energy consumption and façade U-values of 1.0 for the same type of buildings, making retrofits more effective. Retrofits are also effective in Estonia, where the respective façade U-value is 0.50, but the baseline energy consumption is higher, likely due to the cold climate.

Roof insulation in countries with low to medium HDD – Portugal, Greece, Croatia, Italy, Spain, Bulgaria, and Cyprus – exhibits low marginal costs due to the higher U-values ranging from 1.4 to 3.4 for pre-1945 buildings.

To make retrofitting economically viable and beneficial for higher thermal comfort in low-HDD regions, there is a need for retrofit technologies tailored to such climates. For instance, cool roof technologies, passive solar design, and climate-appropriate insulation materials could be impactful. Additionally, these regions may benefit more from other decarbonisation strategies like onsite

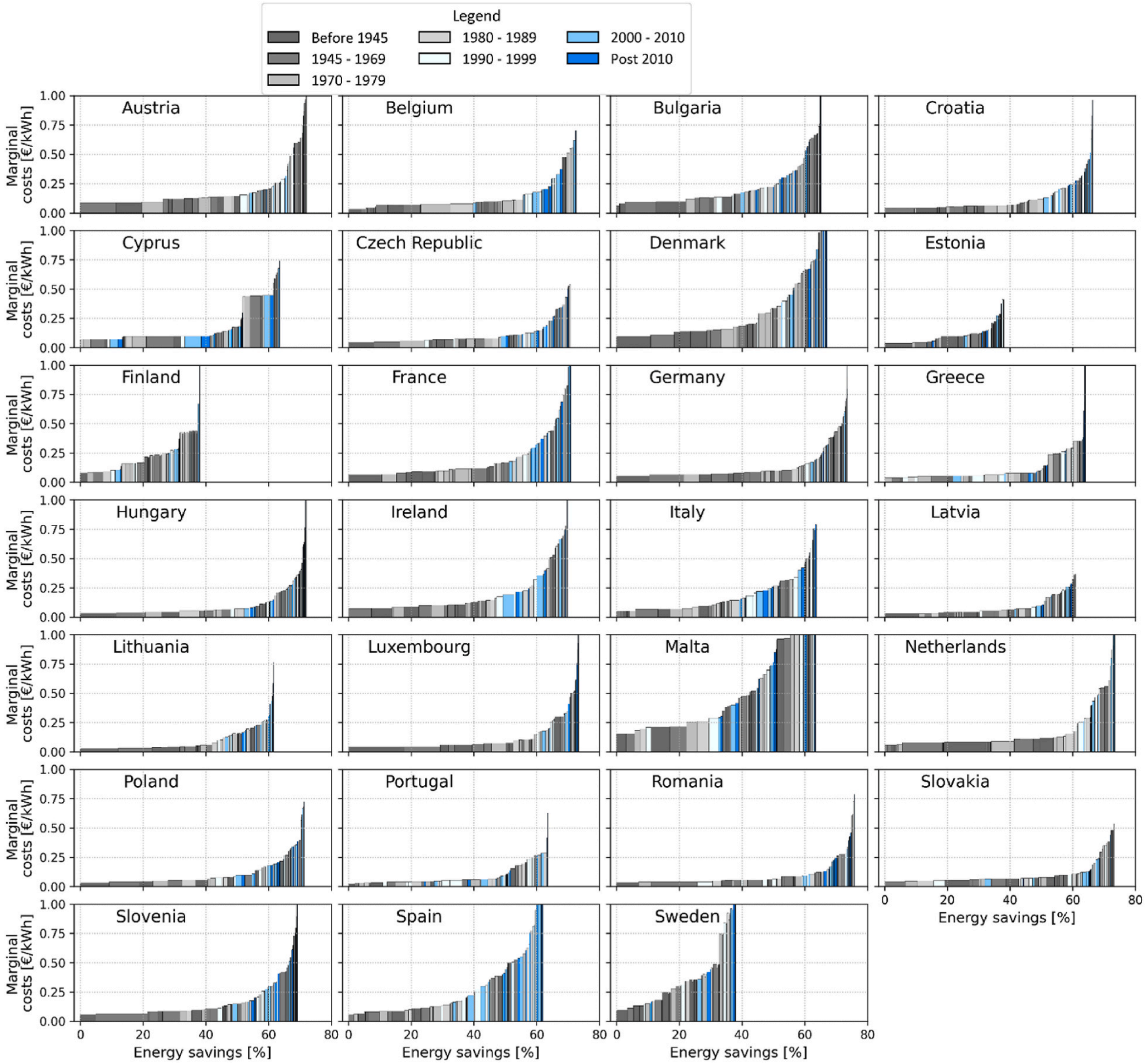

Fig. 12. Energy saving cost curves for each of the EU-27 countries showing the building construction periods the retrofits are applied to.

Table 3
Centroids used to calibrate the building energy performance simulation models.

Country	Construction Period	Building Type	HDD	kWh/(m^{2}a)	Mean U-value	Cluster
Romania	1970–1979	Single family-Terraced houses	2886	175	1.47	Cluster 1
Portugal	1990–1999	Apartment blocks	1199	84.8	1.72	Cluster 2
Ireland	1990–1999	Single family-Terraced houses	2804	83.2	0.69	Cluster 3
Sweden	1945–1969	Multifamily houses	5175	134	0.59	Cluster 4

renewables rather than solely relying on building retrofits. In essence, the relationship between energy savings potential, costs, and cost-effectiveness of retrofits depends greatly on climatic demands, building stock construction quality, and insulation standards. A nuanced understanding of these factors is essential.

In summary, for countries with higher HDD, higher U-values, or elevated baseline energy consumption – potentially due to additional factors like leakiness, mechanical ventilation, or window opening – the initial part of the energy saving cost curves shows an almost flat and gradual incline, indicating lower marginal costs for achieving significant energy savings. This is likely due to the substantial impact that basic retrofit measures (like insulation) can have in reducing the high baseline energy demand for heating. In those countries, policies encouraging the retrofit of older buildings could be highly beneficial in terms of energy savings and CO_2 emission reductions. This is less apparent in countries with low HDD, U-values, or baseline energy consumption, where the energy savings from similar measures are comparatively minor or come at a higher marginal cost. Such countries might need to focus on other energy efficiency strategies or renewable energy sources, as the cost-effectiveness of building retrofits is lower. There might be a need for innovative retrofit technologies or materials that are more effective in climates with low HDD to make retrofitting a viable option in these regions in terms of both economics and thermal comfort. Finally, there are countries in the middle of these extreme situations. These are the countries that neither have exceptionally low nor high HDD, U-values, and baseline energy consumption. Their energy saving cost curves might display a more moderate slope, indicating a balanced relationship between the cost of the retrofit measures and the achieved energy savings. In these countries, the choice of retrofit measures may vary significantly depending on the specific features of the building stock and regional energy policies.

3.2. Validation

We first validated the clustering approach and then critically compared our study's results with Hummel et al.'s findings [15] in 2021, with a particular focus on the energy savings cost curves derived in both studies.

To quantify the error from clustering, for each cluster we applied min-max normalisation to each feature to give them equal weight, calculated the Euclidean distance between each point in the cluster and the centroid, and chose the point with the largest distance. The point with the largest distance across all clusters is Belgium, 1945–1969, Single family-Terraced houses with 2667 HDD, a space heating useful energy demand of 411 kWh/(m^2 a), and an average U-value of 1.69 W/(m^2 K), located in cluster 1, see Table 4. This point is close to the centroid with respect to HDD and U-value but has a 135 % higher energy demand that is highest among all points in cluster 1, see Fig. 7. Furthermore, the two building stocks represented by the centroid and the farthest point from the centroid are different in size, heated area, and overall energy demand. We set up the ISO 52016-1 simulation model for the point and calibrated it to the baseline by varying the air change rate as explained in Section 2.3. Since the energy demand was very high with respect to the HDD and average U-value, we had to set the air change rate to a high value of 9 m^3/(h m^2). This allowed us to reach an energy demand of 402 kWh/(m^2 a) less than 2 % different from the target value. We then determined the first retrofit step with the lowest possible LCSE, which was 8 cm wall insulation with an LCSE of 0.062. For this retrofit step, we calculated the specific energy saving and cost.

In Table 4, we can observe that the annual energy savings and total cost per m^2 of heated area obtained for the farthest point from the centroid are 22 % and 1 % higher than the values obtained for the centroid, respectively. This deviation must be evaluated against the input and calculation errors. An unpublished comparison of number of dwellings and floor area among different data sources (official censuses, EU-SILC [43], ENTRANZE [44], and Hotmaps [13,14]) revealed a wide range of percentage deviations, with about 5–10 % deviation in the best and most-aggregated cases (e.g., total floor area at country level) and 30 % or more deviation in some granular cases (e.g., Single-Family Houses in single countries). To this deviation must be added the deviation caused by the ISO 52016–1:2017 calculation, which was reported to be in the 10–40 % range [45,46]. The found deviation due to clustering is in a comparable uncertainty range and aims to strike a balance between accuracy and implementation effort suitable for the purposes of this study. Therefore, while increasing the number of clusters would reduce clustering-related uncertainty, addressing the combined effect of input data and calculation errors is essential to improving the overall accuracy and reliability of the study's findings.

Regarding Hummel et al.'s study [15], our analysis reveals notable similarities and divergences between these curves, which are crucial for understanding the implications of our methodology and its potential advancements in energy system modelling and building decarbonisation.

As a typical example, Fig. 13 compares the energy savings cost curves for Germany. Both studies show a remarkable congruence in the initial sections of their respective energy savings cost curves, up to the point of around 60 % energy savings. Beyond this point, the two curves diverge significantly. Hummel et al.'s curve shows an exponential rise with a vertical asymptote at 64 %, while our curve extends further before increasing exponentially, reaching a vertical asymptote at 74 %. This divergence can be attributed to work performed in the Hotmaps project to improve the national BS databases.

Furthermore, different assumptions on costs contribute to the divergence. While Hummel et al. used a 4 % interest rate and a 40-year lifetime for calculating the annuity factor, our study considers a 4 % interest rate and a 30-year lifetime. Moreover, the price list used in this paper has 2021 as reference year, while it was 2016 in Hummel et al.'s paper. These variations in cost assumptions significantly impact the results, lowering Hummel et al.'s marginal costs with respect to ours because of inflation from 2016 to 2021 and since they consider a longer lifetime for the retrofit measures. These factors underscore the sensitivity of energy savings cost curves to financial parameters.

3.3. Study limitations and outlook

The specific retrofits and their ranking in this study depend on several uncertain variables, including energy prices and climate change. For instance, the optimal amount of insulation, in terms of investment cost per energy saved, depends on future fluctuations in energy prices. If energy prices increase, insulation becomes more cost-effective. For buildings in hot climates or those increasingly affected by heat waves due to climate change, Calama-González et al. [47] investigated whether insulating dwellings raises the risk of overheating. They found that well-insulated Mediterranean dwellings that used air-conditioning and nighttime natural ventilation required fewer hours of air-conditioning and provided better comfort during heat waves than poorly insulated dwellings. Fosas et al. [48] showed that although increased insulation can contribute to overheating in poorly designed or managed buildings—up to 5 % of the overall overheating response in super-insulated buildings—it reduces overheating in well-designed, well-managed buildings. The

Table 4
Comparison of centroid with farthest point from centroid for cluster 1.

Baseline	Country	Age	Type	HDD	SH UED [kWh/(m2 a)]	Average U-value	Number of buildings	Heated area [Mm2]	Average heated area per building [m2]	SH UED [TWh/a]
Centroid	Romania	1970–1979	Single family-Terraced houses	2886	175	1.47	510000	18.2	35.7	3.18
Farthest point	Belgium	1945–1969	Single family-Terraced houses	2667	411	1.69	50000	4.04	80.7	1.66
			Percent difference	**−8%**	**+135 %**	**+15 %**				

Retrofit #1	Measure	LCSE	Energy saving [TWh/a]	Energy saving [kWh/(m2 a)]	Cost [€/m2]
Centroid	9 cm wall insulation	0.075	1.58	87.1	112
Farthest point	8 cm wall insulation	0.062	0.43	106	113
			Percent difference	**+22 %**	**+1 %**

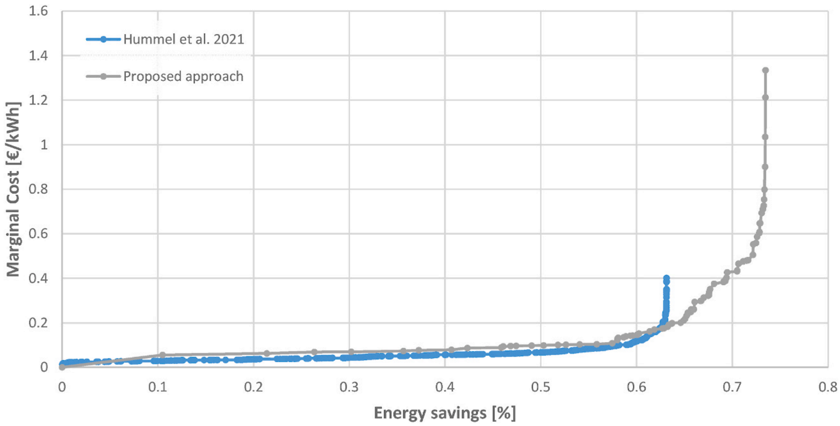

Fig. 13. Comparison between the energy savings cost curve obtained by Hummel et al. [15] (2021) and the one obtained through the proposed approach, for the case of Germany.

authors cite large unshaded windows or the absence of purge ventilation as examples of poor design or management. Farrokhirad et al. [49] conducted a systematic review on the risk of overheating in passive houses and highlighted several knowledge gaps. In conclusion, thermal insulation appears to be beneficial even during heat waves if combined with appropriate passive strategies, but further research is recommended.

Introducing a stochastic framework can help model such variables and provide cost and energy saving ranges with high confidence. While identifying the most critical random variables and defining appropriate ranges and probability distributions, especially for complex phenomena like climate change and energy economics, is not straightforward, and despite the computational demands involved, such an approach would enhance the robustness of the results.

The simplified geometric characterisation of buildings provided in Eq. (1) was identified for a specific residential building stock and might need calibration at the EU scale depending on the context.

In this investigation, we focused on basic retrofit types to reduce space heating energy demand. Hence, we did not fully exploit the potential offered by a standardised hourly building energy performance simulation model. Our building simulation model also allows for an analysis of summer conditions, in terms of both energy demand for space cooling and thermal comfort.

4. Conclusions

This research addresses the challenge of quantifying heat-saving costs in residential buildings across Europe. Using open data from the Hotmaps project and Eurostat, we applied a dynamic building simulation model with hourly resolution, offering greater accuracy than traditional annual or monthly models. This detailed approach captures energy dynamics and thermal comfort variations overlooked by lower-resolution models.

With our clustering analysis, energy system modellers can balance accuracy and implementation effort. The clustering analysis also demonstrates how to quantify and control the extrapolation error.

Additionally, the comprehensive categorisation of all EU-27 building stocks and associated retrofit measures allows for detailed energy savings cost curves, essential for assessing energy efficiency interventions.

The results in Section 3.1 show that basic retrofits, such as facade and roof insulation, offer significant savings at low marginal costs, comparable to energy supply options. For example, insulating only the façade can yield national energy savings of up to 47 %, with Romania achieving the highest ones, at marginal costs between 3.9 and 23 Eurocents per kWh saved over the retrofit lifetime. Continuing to consider only façade insulation, energy savings of at least 20 % (or 40 %) can be achieved in 22 (or 13) countries. In the Czech Republic and Slovakia, savings of 40 % are attainable at marginal costs below 20 Eurocents, while in Estonia and Latvia, 20 % savings can be achieved at similar costs. If the marginal cost threshold is raised to 30 Eurocents, additional countries – Belgium, Croatia, Italy, Lithuania, Poland, and Romania – can also achieve savings of at least 20 %. At a marginal cost threshold of 40 Eurocents, Austria, Bulgaria, France, and Germany can further reach these savings. Insulating only the roof can provide national energy savings of up to 16 %, with Portugal leading the way at marginal costs between 2.5 and 10 Eurocents. With this single measure, energy savings of at least 10 % can be achieved in five countries. In addition to Portugal, this level of savings is achieved at marginal costs below 20 Eurocents in Cyprus and Spain. By raising the marginal cost threshold to 30 Eurocents, Greece also reaches this level of savings.

Combining façade and roof insulation, while excluding other measures, allows for energy savings of up to 48 %. Section 3.1 further shows that climate and existing insulation levels in each country are key for cost-effective upgrades, with colder regions and buildings with high heat loss showing greater potential. In countries with high HDD and relatively high U-values or baseline energy consumption, national energy savings of 37 % (Estonia), 60 % (Latvia and Lithuania), and 66 % (Poland) are achievable at marginal costs below 30 Eurocents. Older, smaller buildings across countries have a high energy and emissions reduction potential, with energy savings ranging from 8.6 % in Belgium to 45 % in Luxembourg, achievable at marginal costs below 30 Eurocents when retrofit measures are applied exclusively to SFH built before 1970.

Our comparative analysis with Hummel et al. [15] (2021) shows strong initial convergence in energy savings cost curves up to 62 % savings. with divergence beyond this point due to differences in building stock categorisations, financial assumptions, such as the lower 30-year lifetime of the retrofits, and reference years for retrofit costs. Despite confirming our methodology's performance, the comparative analysis highlights sensitivities to input data and assumptions.

Looking ahead, we aim to integrate our methodology into energy system models to simulate decarbonisation pathways, which commonly exclude energy efficiency measures and their energy savings and costs. By providing granular heat savings potentials and associated costs, our approach enables system modelers to optimise decarbonisation strategies, considering retrofits alongside renewables expansion and technology shifts for more realistic and cost-effective outcomes.

CRediT authorship contribution statement

Ulrich Filippi Oberegger: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Matteo Giacomo Prina:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marcus Hummel:** Writing – review & editing, Validation. **Lukas Kranzl:** Writing – review & editing, Supervision. **Simon Pezzutto:** Writing – review & editing, Funding acquisition, Data curation. **Roberto Lollini:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Wolfram Sparber:** Writing – review & editing, Resources.

5. Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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