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Bottom-up building stock retrofit based on levelized cost of saved energy

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ABSTRACT

Policy makers need scientific support to set ambitious yet realistic environmental targets for the transition to energy efficient buildings and to develop cost-effective policies to meet these targets, but comprehensive, manageable procedures to this aim are still lacking. Our proposed method ranges from baseline creation to transition scenarios depending on annual retrofit budget and specifies the buildings to renovate according to location, size, and age, and the energy efficiency measures to apply based on cost and energy saving. We show how to extrapolate a baseline from few available data, determine retrofit costs, and create calibrated models to estimate energy savings. Retrofits are ranked by levelized cost of saved energy, which ensures that for any budget allocated to retrofit maximum energy savings are obtained at minimum cost to society. The results are summarized in an energy efficiency cost curve enabling policy makers to estimate potential costs and energy savings. We demonstrate the method on a housing stock in northern Italy and show that facade insulation of old buildings in colder climates can compete with gas heating. About 60% baseline energy consumption can be saved doubling current investments, while a maximum saving of 75% requires over three times the current investments.

1. Introduction

Building stock energy retrofit is an important opportunity for climate change mitigation [1] and provides other benefits, e.g. improved indoor environmental quality [2]. Since current renovation rates and depths in Europe are largely insufficient [3], policy makers and public authorities need to constantly work on developing, deploying, and evaluating climate plans and energy retrofit initiatives. Setting ambitious and realistic future environmental targets, assessing whether these targets are likely to be met, and making informed choices about the most suitable energy retrofit policy requires detailed scenarios that specify the buildings to be renovated and the Energy Efficiency Measures (EEM) to be applied within certain constraints, e.g. on total annual budget, renovation rate, emissions, or energy savings. This requires a knowledge of the costs and potential energy savings of each EEM depending on factors such as building type and location. Because of the constraints, not all the EEMs can be applied at once, making it necessary to define a criterion for ranking them in order to define new compliant policies. Furthermore it is important to keep the methods leading to a detailed building stock energy transition plan applicable even if only few data is known, and to provide quantitative and visual means for quick overall evaluation of the plan, such that it can be integrated into climate plans and broader studies of the transition of energy systems towards decarbonisation.

Despite the vast amount of literature on building energy retrofit there is still a need for complete and flexible but manageable procedures, from the definition of a reliable baseline to detailed energy transition scenarios for building stocks, that specify the buildings to be renovated and the EEMs to apply to these buildings based on a transparent ranking criterion. Several studies explored approaches and pathways towards low energy consumption and CO_2 emissions for housing stocks but without including the energy efficiency costs in the analysis. Aksoezen et al. [4] worked on building stock data for the city of Basel, Switzerland, and argued that thorough knowledge of morphological properties and measured energy performance is important for differentiated

Abbreviations: AB, Apartment block; BAU, Business As Usual; BM, Big multi-family house; DHW, Domestic Hot Water; EEM, Energy Efficiency Measure; EUI, Energy Use Intensity; GIS, Geographic Information System; HDD, Heating Degree Day; LCSE, Levelized Cost of Saved Energy; S/V, Envelope (Surface) area to Volume ratio; SM, Small multi-family house; ST, Single- to two-family house; UFA, Usable Floor Area.

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renovation of existing buildings. Dascalaki et al. [5] created a housing stock model for Greece based on typical buildings (two building sizes, three age groups, four climate zones) developed according to the framework of the EU projects TABULA [6] and EPISCOPE [7] and on census and statistical data. As EEMs they considered envelope thermal insulation, high-performance heating, and solar thermal panel integration. Several envelope, system, and combined transition scenarios were created under different refurbishment rates. Annual calculations were performed over the 2012–2030 period with a quasi-steady state monthly method to estimate heating consumption. Mastrucci et al. [8] presented a statistical methodology based on Geographic Information System (GIS) data to estimate the energy consumption and energy saving potential for heating for the city of Rotterdam in the Netherlands. The building stock was subdivided into four age groups and six dwelling types. EEMs considered were envelope insulation, window replacement, and a heating and ventilation system upgrade. A multiple linear regression model was developed to downscale measured gas and electricity consumption from post-code to address level using type of dwelling, year of construction, floor surface, and number of occupants at address level. Energy consumption for space heating was corrected based on Heating Degree Days (HDDs). The model was validated against national benchmarks. The energy saving potential was estimated in the wide range of 4–70% depending on dwelling type and age. Siller et al. [9] considered energy transition scenarios for the Swiss housing stock modelled as list of heated areas by construction year, building type, time and type of last renovation, energy standard, and heating system. Their model uses annual update rules for renovation, demolition, and new construction. Facade insulation, heating system upgrade, and window replacement were implemented in several scenarios differing in transition percentage and energy standard. Results showed a 40–55% final energy consumption reduction by 2050. They raised as important open question the impacts of additional costs incurred by more ambitious scenarios. Petersdorff et al. [10] examined the heating energy saving potential of the EU-15 building stock triggered by the Energy Performance of Buildings Directive [11]. They found a main potential in thermal insulation of existing buildings by extrapolating results from calculations according to EN 832 [12] for five building types, eight insulation standards according to building age and renovation status, and three climates.

Studies similar in purpose and scope that quantified economic impact considered several retrofit scenarios but did not rank the EEMs based on building type, cost, and other factors to derive a step-by-step retrofit plan and energy efficiency cost curve. Ballarini et al. [13] determined potential energy savings and cost-optimal refurbishments for 120 buildings (four sizes, six construction periods, five climates) typical for the Italian housing stock. Examined EEMs were envelope thermal insulation, window replacement, heat generator replacement, and installation of a solar thermal Domestic Hot Water (DHW) system. The non-renewable primary energy use for heating, cooling, ventilation, and DHW was calculated according to national technical standards using a monthly time step. The cost evaluation followed the European cost-optimality framework [14] based on global cost, i.e. the sum of the net present values of investment, running, replacement, and disposal costs. Actual costs were taken from national price lists and recent renovation projects. An extrapolation from the typical buildings to the whole Italian housing stock was not performed. Results showed that heat generator replacement had the lowest global cost for most building types. However, envelope measures could lead to higher energy savings of about 65% and were cost-effective for old, small buildings in cold climates. Mata et al. [15] presented a strategy for energy, carbon, and cost assessment for building stocks based on an energy balance engineering model for a single building with one thermal zone using an hourly time step in order to allow the investigation of demand-shifting measures like changes in facility management and occupant behaviour. The model was validated against other software and measured data for an office and a residential building. It was used to simulate 1400 buildings representative for the Swedish housing stock. Considered EEMs were envelope thermal insulation, window replacement, increased system efficiency, and lower indoor air temperature. Results at building level were extrapolated to the building stock by multiplication with the fraction of buildings in the stock belonging to the same category. Cost assessment consisted in post-processing model results using user inputs and suitable conversion factors. Uihlein and Eder [16] investigated policy options for the EU-27 housing stock. They divided the living areas per country according to six different building types and gave rules for stock development, construction, renovation, and demolition. EEMs included climate-dependent roof, wall, and window refurbishment at three energy efficiency levels. Costs were retrieved for Germany and derived for other countries through building cost indexes. By studying accelerated refurbishment scenarios, they argued that roof insulation and window replacement outside major renovation cycles would offer 30% energy savings in addition to current EU policies. Guler et al. [17] evaluated energy efficiency upgrades for the Canadian housing stock by simulating EEMs including envelope insulation, window replacement, and heating system replacement at building level. The prices of materials, equipment, and installation costs were determined from published cost data and data from professionals. Extrapolation to the building stock was performed using the number of houses each simulated building was represented in the stock. They used the simple payback period to assess economic feasibility.

Other studies on retrofit alternatives focused on single buildings [18–21], single building categories [22], or a sample of buildings [23] and did not extend the analysis to a regional or national building stock. Some papers dealt with the development of energy efficiency cost curves for building stock retrofit [24,25] but did not present a method to create a reliable baseline. Other papers [26–28] focused exclusively on building stock modelling and baseline creation, without investigating transition scenarios. Dall'O' et al. [29,30] presented a process from data gathering to retrofit scenarios for housing stocks but did not elaborate on a ranking of EEMs to create an energy efficiency cost curve for further use in broader studies.

Several economic indicators were proposed in these studies: global cost and discounted payback period [13], energy saving cost [15], cost compared to reference [16], energy savings per monetary unit invested and simple payback [17], simple payback, cost per energy saved per year, and annual cost savings per dwelling [18], life cycle cost, net present value, carbon and financial payback period [19], savings-to-investment ratio [20,21], saving in global cost [22], simple payback, total and specific cost [23], marginal and average cost of energy efficiency [24], levelized cost [25], total cost, money saving, and simple payback [29]. In the context of electric energy efficiency, Hoffman et al. [31] compared different U.S. utility customer-funded programs based on levelized cost of saved electricity.

To our knowledge this study is the first to present and demonstrate a complete workflow to create detailed building stock energy transition scenarios according to the following steps.

1. Development of a validated energy consumption baseline for a building stock derived from a substantial sample of GIS-based building geometries and metered energy consumptions at building level. Using measured energy consumption data as opposed to calculated energy demand allows capturing real building behaviour including vacant spaces, intermittent heating, and variable occupancy;

2. Simulation of single and combined EEMs applied to the building stock subdivided by building size, age, and location;
3. Creation of a building stock retrofit plan specifying the order in which to apply EEMs to each building of the stock. The EEMs are ranked based on Levelized Cost of Saved Energy (LCSE). This allows a direct comparison with energy prices, energy supply, and energy efficiency programs and ensures maximum energy savings for a given investment budget;
4. Derivation of an energy efficiency cost curve and of retrofit scenarios from the retrofit plan, for use by policy makers and researchers to quantify the total investment required to achieve a certain total reduction of energy consumption.

These steps were developed with the intention to follow the best practices and overcome the limitations stated in the above literature review. We demonstrate the developed method on the housing stock of the region South Tyrol in northern Italy.

2. Materials and methods

Fig. 1 shows the workflow for our proposed "levelized cost method".

The left side of Fig. 1 reports the needed input data, namely, the features of the real buildings sample, aggregated data describing the building stock and context (i.e., floor areas and climate conditions), and the available budget for implementing the retrofits. The steps ultimately leading to the retrofit scenarios are shown on the right. The core idea of the method is to use the LCSE to prioritise different EEMs applicable to the building stock. Each step of the method is explained in detail in the next subsections using the case study as example.

2.1. Baseline creation

2.1.1. Case study

South Tyrol (530,000 inhabitants as of 2018 on 7400 km^2) is an Italian province in the Eastern Alps. Extreme average temperatures in Bolzano, the capital city of South Tyrol, typically range between −3 and 29 °C. Bolzano has 2791 HDDs and is the fifth mildest of the 116 South Tyrolean municipalities. Most others are considerably colder, with up to 5135 HDDs. Winters and early springs are dry [32,33]. Although summers in the valleys can be relatively warm, residential mechanical cooling is rare because occasional heat waves are short and shading systems and natural ventilation are widely used. We therefore focused on heating demand reduction through envelope thermal insulation and increased airtightness. We did not investigate climate change effects on the predicted energy saving potential. The methodology proposed in this paper was applied to the South Tyrolean housing stock as described in the next subsections.

2.1.2. Sample description and building stock characterisation

The main techniques to characterise a building stock are the definition of representative buildings [34], Bayesian approaches [35], or clustering techniques [36]. Representative buildings are suitable for homogeneous building stocks or if the input data is incomplete and requires integration with qualitative expert knowledge. The accuracy is increased by calibrating the representative buildings on measured data and statistics [37,38]. For heterogeneous building stocks or high accuracy, a Bayesian or clustering approach might give better results but requires more sophisticated methods or tools. Common characterisation factors subdividing the building stock into groups of similar buildings are building use,

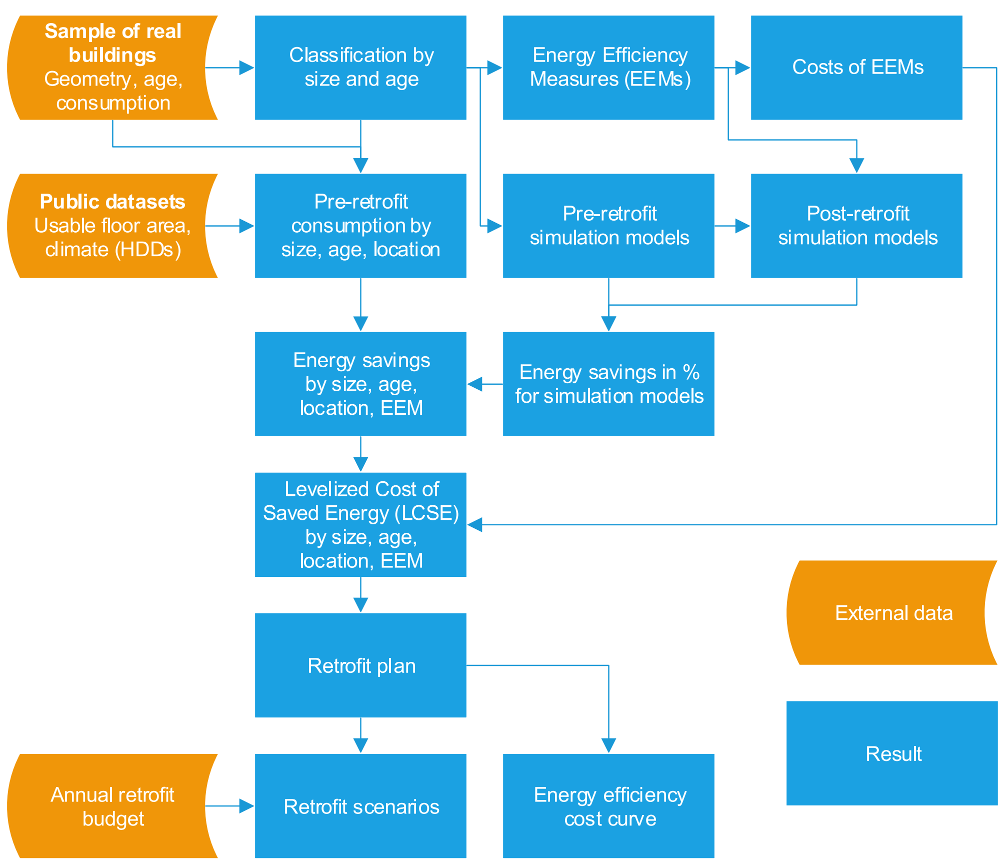

Fig. 1. Workflow of the "levelized cost method" to create retrofit scenarios for a building stock.

shape, age, equipment, and climate, as this data is easily available [39].

For the case study the starting point was a geo-referenced dataset for Bolzano [40,41], which included construction period, volume, footprint area, perimeter, height, gross floor area, and annual gas metering at building level of 1384 residential buildings for the years 2007–2011. The total Usable Floor Area (UFA) of the buildings in the dataset amounts to 1.9 million m^2 (52% and 10% of the residential UFA in Bolzano and South Tyrol in 2011, respectively).

We defined the following four housing types based on housing classifications for Bolzano [40], the Passiria valley in South Tyrol [42], and Italy [6,34,43].

- ST (single- to two-family): detached or semi-detached houses with 1–2 apartments and 1–2 floors;
- SM (small multi-family): buildings with 2–4 floors and not more than 10 apartments;
- BM (big multi-family): buildings with 2–5 floors and more than 10 apartments;
- AB (apartment block): high-rise buildings with more than 5 floors.

Manual inspection of the building shapes in the GIS for Bolzano followed to determine the housing type for those buildings where this base classification was inconclusive.

While the housing type reflects the building geometry, the age correlates with architectural and structural features affecting energy consumption. We created the four age groups “Before 1946”, “1946–1990”, “1991–2005”, and “After 2005” based on the following considerations.

- Before World War I, buildings in South Tyrol were mainly compact, small multi-family houses with high thermal mass. Between the world wars, mainly average-sized multi-family houses and the first high-rise buildings were erected in Bolzano.
- The main construction activity was after World War II, until the 1970s. Apartment blocks were predominant in the urban areas.
- In 1991, Italy passed the first law concerning the evaluation of building energy performance and made a first step towards energy performance certificates.
- From 2005 onward, the local law required new buildings in South Tyrol to have an annual thermal Energy Use Intensity (EUI) below 70 kWh/m^2a.

2.1.3. Sample data transformations

The UFA was approximated as gross floor area multiplied by 0.83 (appropriate for “average” constructions [44]). Annual final energy consumption (i.e., the energy entering the building) for heating was approximated as annual gas consumption in cubic meters multiplied by 9.45 kWh/m^3 [45]. The EUI was calculated as final energy consumption divided by UFA. It was impossible to disaggregate gas consumption into space heating and DHW preparation. We therefore estimated the consumption for the latter at 25 kWh/m^2a from a monitoring of a residential district in Bolzano [46].

2.1.4. Extrapolation to the building stock

We suggest using the UFA as scaling factor to extrapolate representative building or sample data to the whole building stock. For the case study the residential UFA at municipal level was available from the last national building census in 2011 [47]. The largest three municipalities in South Tyrol are Bolzano (3.60 million m^2 residential UFA in 2011), Merano (1.39 million m^2), and Bressanone (742,000 m^2). The total South Tyrolean residential UFA in 2011 amounted to 18.4 million m^2. To determine the UFA by housing type and age group, we first divided South Tyrol into an urban and a rural area according to the percentage of buildings of the housing type “apartment block”, which was about 15% in Bolzano, 5% in Merano, and 1% or less in the other municipalities. We considered Bolzano and Merano as urban areas and applied to them the UFA distribution of the sample. Specifically, for each housing type and age group we summed the UFAs of all buildings belonging to that housing type and age group and divided the sum by the total UFA of all buildings in the sample dataset. This calculation resulted in 16 percentages quantifying the UFA share of the total UFA in the dataset for each of the four housing types and age groups. These percentages were applied to the housing stock of the municipalities Bolzano and Merano. For all other municipalities we used the UFA shares by housing type and age group identified through an analogous calculation for the municipalities San Leonardo, San Martino, and Moso in the Passiria valley, a typical South Tyrolean rural area. Geometries, housing types, and age groups for this area had been determined from GIS data at building level, on-site inspection and photographic documentation of over 80% of the buildings in the three municipalities, a survey sent to 6% of all dwellings in the three municipalities, and regional statistics [42,48].

To adjust for climate variations we took Bolzano as reference location and corrected the EUI in other municipalities according to the HDDs at municipal level [33] as follows:

$$EUI_{SH} = EUI_{SH}^{Ref} \cdot \frac{HDD}{HDD^{Ref}}$$

where EUI_{SH} indicates the annual EUI for space heating, HDD the heating degree days, and superscript Ref the reference location. An analogous correction can be performed for the cooling period if needed.

We finally calculated the residential heating consumption baseline of South Tyrol by multiplying the average EUIs for every municipality, housing type, and housing age group by the corresponding UFAs.

2.1.5. Baseline validation

The baseline from a bottom-up approach in energy system transition studies is typically validated against aggregated data from official sources (see, e.g., [49]). However, in our case the final energy consumption of households in South Tyrol for heating was previously unknown. Therefore, we propose a comparative approach. For the municipality of Bolzano, residential final energy consumption for heating in 2010 from gas bills from the distribution network operator amounts to 0.68 TWh (63% of the total 1.08 TWh) [50]. South Tyrol’s heat demand (thermal energy transferred directly to the heated space, domestic water, etc.) in 2014 was estimated at 4676 GWh [49]. Our estimate of the final energy consumption of the South Tyrolean housing stock for heating (2.8 TWh in 2011; see Section 3.2) was derived from gas metering at building level and thus included the efficiency of the building’s heating systems. To convert to heat demand and correct for the different reference years we multiplied this estimate by an average gas boiler efficiency of 0.90 [49] and a total increase in final energy consumption for heating by 3% from 2011 to 2014 [51]. This resulted in a residential heat demand in 2014 estimated at 2.6 TWh (55% of the total 4676 GWh). We conclude that the residential shares of the total energy use for heating (63% vs. 55%) fairly agree. The first estimate is affected by incomplete gas consumption records and difficulties in assigning records to the correct end-use sector, while the second estimate is affected by a low EUI (94 kWh/m^2a on average) obtained from the sample dataset for Bolzano. As second comparison we collected EUIs from several studies (values in kWh/m^2a): 140 on average for the city of Bolzano [52]; 95–270 for not renovated buildings and 45–150 for renovated buildings in the municipality of Bolzano [50]; 220 on

Table 1
Characteristics of the standard and deep EEMs.

	Standard measure			Deep measure			Cost increase*
Insulation (EPS)	U-value [W/m²K]		Unit cost** [€/m²]	U-value [W/m²K]		Unit cost** [€/m²]	
Facade	0.34		103	0.18		119	16%
Roof	0.30		172	0.16		186	8%
Basement ceiling	0.33		67	0.20		77	15%
Replacement	U_f, U_g [W/m²K], g-value	Air changes per hour***	Unit cost** [€/m²]	U_f, U_g [W/m²K], g-value	Air changes per hour***	Unit cost** [€/m²]	
Window	1.6, 1.7, 0.7	1.5	510	1.0, 1.1, 0.56	0.60	660	29%

* *Cost increase of the deep measure with respect to the standard measure.*
** *Referred to the retrofitted facade, roof, basement ceiling, or window area.*
*** *At a building-to-outside pressure differential of 50 Pascal.*

average for old buildings in South Tyrol [53]; 99–188 for single- to two-family houses, 67–121 for small multi-family houses, and 60–103 for big multi-family and non-residential houses in Austria [54]. Our estimate for South Tyrol (150 on average; see Section 3.2) is based on measured consumption and thus includes real conditions such as vacant dwellings, unheated spaces, and variable setpoints. We therefore expect the other sources, in which the EUI was calculated with simplified quasi-steady state building energy modelling software considering a setpoint temperature of 20 °C, to report higher values.

2.2. Energy savings and cost of energy efficiency measures

2.2.1. Energy efficiency measures

For the case study we selected roof insulation, facade insulation, basement ceiling insulation, and window replacement, which are common in South Tyrol and amongst the better-monitored measures. We did not consider energy measures for active heating systems for the following reasons:

1. Compared to all other considered EEMs, replacing an old boiler with a more efficient one is assumed to be always advantageous for buildings with high EUI;
2. A study on the decarbonisation of South Tyrol [49] concluded that the local energy system should undergo massive electrification. Individual buildings would first be retrofitted by applying the EEMs considered in this paper and would then use heat pumps and low temperature heating distribution systems in combination with photovoltaics. A calculation of the energy savings and costs related to these technologies has not yet been conducted for South Tyrol.

With "facade insulation" we refer to the opaque part of the facade. The transparent part is retrofitted within the "window replacement" measure. We considered a "standard" (minimum legal and normative requirements) and "deep" (nearly zero-energy building) version for each type of measure. Table 1 summarises the characteristics of the considered measures. The thermal transmittances of window frame and glazing are denoted by U_f and U_g, respectively.

2.2.2. Estimation of energy saving percentages

We estimated energy saving percentages for the single and combined EEMs through simulation. We built four representative building models, one for each housing type, in PHPP version 7.1 [55]. PHPP is an MS Excel building energy calculation workbook adopting a quasi-steady state energy balance approach (see the Appendix for details). Since we focused on heating demand reduction through passive EEMs (cf. Section 2.2.1) we used the PHPP workbook to determine the annual space heating demand, which quantifies the thermal energy required to keep the indoor environment at the heating setpoint and is independent of the heat generation system. Concerning model geometry PHPP requires the areas and orientations of each building element. Model building heights and UFAs were taken as averages from the sample. The floor-to-floor height was set to 3.2 m, and a quadratic footprint was assumed.

Pre-retrofit features such as construction layers, thermo-physical properties, and glazed areas correspond to representative Italian housing built in 1946–1975 [6,43], see Table 2.

The pre-retrofit U-values and g-values reported in Table 2 correspond to the following building elements: 40 cm hollow brick masonry walls; pitched roof with timber structure, planking, and basic insulation (small buildings), or flat roof with reinforced brick-concrete slab and basic insulation (high-rise buildings); floor with reinforced brick-concrete slab; double-glazed window with 45 mm timber frame. The post-retrofit U-values reported in Table 1 are reached applying EPS with variable thickness and a thermal conductivity of 0.04 W/mK: 10 (20) cm to the walls, 15 (25) cm to the roof, and 10 (18) cm to the basement for the standard (deep) measure. The post-retrofit window performance is reached by a triple-glazed window with 68 mm timber frame for the standard measure and by a low-e argon-filled double-glazed window with 78 mm timber frame and warm edge spacer for the deep measure.

Other PHPP settings were (cf. the Appendix): internal heat gains q_I of 2.1 W/m²; internal air temperature T_a at 20 °C; ventilation air change rate of 0.3/h; variable infiltration rate depending on building airtightness (see Table 1 and Table 2); solar gain reduction factor f_r of 0.35 (north, west, and east windows) or 0.38 (south windows); and heating period length d_H of 179 days. Fig. 2 shows the climate data used in the simulations.

For each housing type we performed one pre-retrofit simulation, 15 simulations for standard retrofits (four single EEMs, six combinations of two EEMs, four combinations of three EEMs, and one application of all four EEMs) and another 15 for deep retrofits, for a total of $4 \times 31 = 124$ simulations. The energy saving percentage was calculated as difference between pre-retrofit and post-retrofit space heating demand divided by pre-retrofit space heating demand. To automate this process, we developed a parametric MS Excel tool executing a PHPP workbook multiple times with varying inputs and retrieving the desired outputs.

The simulations served the purpose of providing us with reasonable energy saving percentages, from which the absolute energy savings and costs were determined based on the EUIs and UFAs of the baseline (see Section 2.3).

2.2.3. Validation of building energy models

The PHPP software has been validated against dynamic building energy simulation software and empirical data in several studies [56–58] demonstrating that heat demand is well predicted for passive houses and low-energy buildings but also buildings with poorer energy standards. To assess the accuracy of the PHPP calculations performed in this paper, we created an additional model of the pre-retrofit apartment block using an MS Excel workbook

Table 2
Pre-retrofit simulation model parameters used for estimating EEM costs and energy savings.

Parameters depending on housing type	ST	SM	BM	AB
Usable floor area (UFA) [m^2]	154	540	1,534	2,205
S/V	0.72	0.51	0.39	0.34
Space heating demand [kWh/m^{2}a]	224	159	123	117
Facade area [m^2] and ratio*	229 (149%)	584 (108%)	1,187 (77%)	1,817 (82%)
Roof/basement ceiling area** [m^2] and ratio*	89 (58%)	190 (35%)	485 (32%)	430 (20%)
Window area [m^2] and ratio*	23 (15%)	92 (17%)	166 (11%)	219 (10%)
Window-to-wall ratio (WWR)***	10%	16%	14%	12%

Parameters independent of housing type

Facade U-value [W/m^{2}K]	Roof	Basement ceiling	Window glazing	Window frame	Window g-value	Infiltration Air changes per hour†
1.10	1.35	1.37	2.80	2.50	0.77	2.0

* *The ratio given in brackets is calculated dividing the facade, roof, basement ceiling, or window area by the UFA.*
** *Roof and basement ceiling areas are assumed equal.*
*** *The WWR is calculated dividing the window area by the facade area.*
† *At a building-to-outside pressure differential of 50 Pascal.*

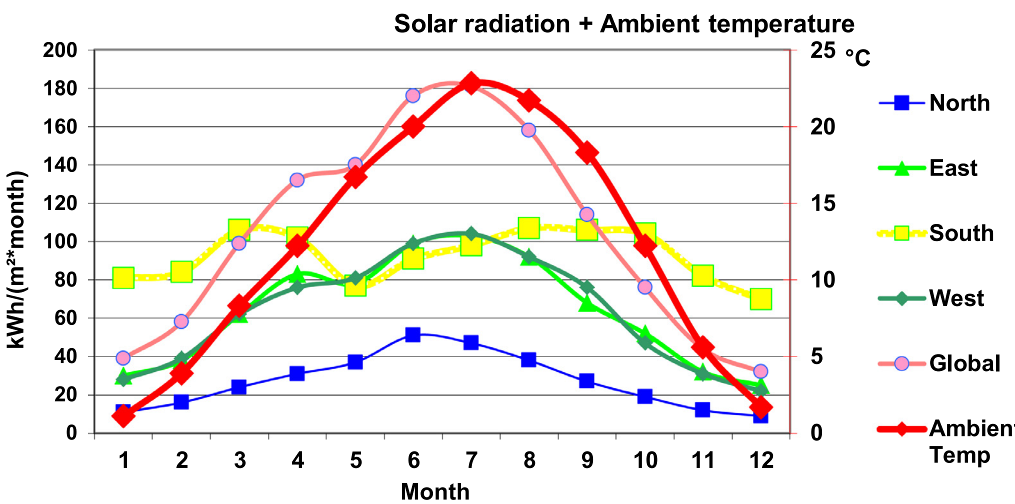

Fig. 2. Monthly climate data for Bolzano used in the PHPP simulations.

[59] implementing the hourly dynamic calculation according to standard BS EN ISO 52016-1:2017 [60] and with the same inputs and parameters as in the PHPP model. We found less than 5% difference in annual space heating demand between the two models. Then we tested an intermittent heating (heating system off from 23:00 to 05:00 every day) and occupancy pattern ("residential, apartment" as per standard EN 16798-1:2019 [61]), which was modelled verbatim in the dynamic model. In PHPP we modified the reduction factor for night saving from the default of 1 to 0.75 (as the heating system is inactive for 6 of 24 h). With these settings the results' difference was 15%, which we considered acceptable. However, if heating and occupancy profiles can be estimated for the analysed building stock, or if EEMs heavily acting on these profiles are investigated, we advise the reader to consider using a more detailed dynamic model with at least hourly time steps.

2.2.4. Cost of energy efficiency measures

The unit costs (costs per square metre of retrofitted facade, roof, basement ceiling, or window area in 2019 Euros) for the considered EEMs were taken from the regional informative price list [62] including labour, construction material, scaffolding, installation, plastering, and painting costs. The standard measure cost breakdown for thermal insulation is (values in €/m^2): scaffolding (9), insulation (52), priming (3), plaster reinforcement (13), plastering (20), and finishing (6) for the facade; scaffolding (9), removal of existing roof (18), insulation (85), sealing (25), rafters and battens (11), and tiling (24) for the roof; application of insulation panels from below (67) for the basement ceiling. The deep measure's extra cost is due to the extra amount of insulation. The standard measure cost breakdown for window replacement is removal of existing window (25), glazing (105), timber frame (305), and extra charge for double casement (75). The deep measure's extra cost is 51 for the glazing, 79 for the timber frame, and 20 for the double casement. Operation and maintenance costs and salvage value were neglected.

2.3. Prioritizing energy efficiency measures: the retrofit plan

This step is the core of the "levelized cost method". As underlying criterion for prioritizing EEMs we propose to use the Levelized Cost of Saved Energy (LCSE) [25,31]:

$$\mathrm{LCSE} = \frac{C}{S} \cdot \mathrm{CRF}$$

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1}$$

where C is the total cost of the energy saved, spread in equal payments over the economic lifetime n of the EEM, S denotes the annual energy savings, i is the discount rate, and CRF denotes the capital recovery factor. Contrary to other indicators mentioned in Section 1, such as global cost and payback period, this indicator allows a direct comparison of energy supply and energy efficiency programs [31].

The retrofit plan consists of a series of steps specifying the buildings to be retrofitted, the EEMs to be applied, the costs, and the potential energy savings. The EEMs are listed in ascending order by LCSE. In each step an EEM is applied to all buildings within the same group as specified for instance through a housing type, age range, and climate zone. Each building undergoes a series of EEMs in succession, from the lowest to the highest LCSE. The number of steps of the retrofit plan is determined as in a full factorial design, i.e., as the number of all possible combinations of values across all characterisation factors of the building stock. The UFAs, energy savings, costs, and LCSE are calculated according to the following algorithm (taking as example the characterisation factors used for the case study, for which the algorithm was programmed in Python [63] using NumPy [64]).

1. For each combination of housing type and EEM: calculation of *specific cost* (cost per UFA) from *unit cost* (cost per retrofitted area) by multiplying the unit cost with the respective retrofitted area to UFA ratio in Table 2;
2. For each combination of housing type, age group, municipality, and EEMs:
   a Calculation of post-retrofit EUI for space heating from pre-retrofit EUI and energy saving percentage p_{sav} in percent: $EUI_{post} = EUI_{pre} \cdot (1 - p_{sav}/100)$;
   b Calculation of annual energy savings by multiplying the difference between pre-retrofit and post-retrofit EUI with the UFA;
   c Calculation of EEM cost by multiplying the specific cost with the UFA;
3. First EEM applied to each building: for each combination of housing type, age group, and municipality, calculation of the LCSE for all single EEMs;
4. Creation of a list of rows specifying UFA, energy saving, cost, and LCSE for each combination of housing type, age group, municipality, and EEM, and sorting of the list in ascending order of LCSE;
5. For the second EEM applied to each building and for each combination of housing type, age group, and municipality:
   a Calculation of the LCSE for the remaining EEMs from the savings and costs *additional* to those of the already applied EEMs;
   b Iteration over the list starting from the position where the previous EEM has been applied to the respective combination of housing type, age group, and municipality. Insertion of a new row specifying UFA, energy saving, cost, and LCSE for the EEM with the lowest LCSE amongst the possible ones, directly before the row with the next higher LCSE.
6. Repeat Step 5 for the third and fourth EEM applied to each building.

To calculate the LCSE for the case study we had to estimate the economic lifetimes for the EEMs and a discount rate. Literary sources report a lifespan of thermal insulation and wooden windows of at least 30 years [65,66]. We therefore assigned a lifespan of 30 years to the EEMs and considered the transition period 2020–2049. As real discount rate we chose 4% [13]. Table 5 shows the retrofit plan for the case study.

2.4. Retrofit scenarios and energy efficiency cost curve

The retrofit plan described in Section 2.3 lacks the time dimension, i.e. it does not inform about the pace of the energy transition. Furthermore, policy makers may consider implementing only part of the plan. To obtain a transition path within a predefined timeframe, e.g. from the present to 2050, we suggest connecting the retrofit plan to an annual retrofit budget and possible additional constraints like technical feasibility. By varying this annual budget, retrofit scenarios with different levels of ambition can be created realising a smaller or larger part of the retrofit plan. We recommend at least three scenarios: Business As Usual (BAU) implements the retrofit plan until the cumulative cost exceeds the current annual retrofit budget multiplied by the transition timeframe (e.g., 30 years); a maximum energy saving scenario, implementing the whole retrofit plan; and a balanced scenario determined from the energy efficiency cost curve. This curve visualises the functional relationship between LCSE and total annual energy saving (see Fig. 8). The balanced scenario is not rigidly defined but stops before the “knee” of the curve, i.e., when EEMs start to become costly with respect to their energy saving potential. Alternatively, retrofit scenarios can be explored by fixing an energy saving target and evaluating the annual budget necessary to meet the target. The retrofit scenarios for the case study are presented in Section 3.6.

2.5. Analysis and evaluation of results

We propose the following procedure to analyse and evaluate the results shown in Fig. 1.

1. Descriptive sample statistics (cf. Section 3.1): an overview of the ranges and averages of the primary building features after subdividing the sample into groups gives insight about the building stock and the groups’ distinctness. EUI box plots show how effective past policies have been to drive an increase in building energy performance from older to newer buildings, and for which building types they have been most effective.
2. Descriptive baseline statistics (cf. Section 3.2): an overview of the floor areas and energy consumptions illustrates the assumptions made during the extrapolation from the sample to the whole building stock and highlights the groups to be targeted by energy policies.
3. Reporting the energy saving potential, cost, and LCSE for the different kinds of retrofits at representative building level before dealing with the whole building stock enables reviewing the retrofits (cf. Section 3.3). If building energy models are used, inspecting this data offers an additional check that the pre-retrofit models and EEMs were implemented correctly.
4. With the retrofits reviewed in Step 3, an overview of the retrofittable areas together with knowledge about the EEM unit costs offers rough information about the potential of the local retrofit market (cf. Section 3.4).
5. Retrofit plan analysis (cf. Section 3.5): standard inspection techniques for tabular data such as filtering, grouping, adding, and averaging can be used. By comparing the LCSE of an EEM in the retrofit plan with energy prices it can be assessed whether a final customer will be willing to invest in the EEM without incentives. For public authorities it is advised to compare the LCSE of the EEM with the LCSE of alternative energy supply and energy efficiency programs. For the case study we averaged the LCSE across all municipalities to identify the most promising EEMs depending on housing type and age group. These EEMs should be addressed by policies.
6. The energy efficiency cost curve is generated directly from the retrofit plan. With this curve, decision makers can decide on an appropriate balanced retrofit scenario and total energy saving target by reading the corresponding total investment and LCSE off the graph (cf. Section 3.6). This functional relationship between cost and energy saving can be implemented in broader energy transition studies, e.g. for multi-objective optimization

Table 3
Size feature ranges of the housing types used in the building stock analysis, with averages in brackets.

	Single- to two-family house (ST)	Small multi-family house (SM)	Big multi-family house (BM)	Apartment block (AB)
Number of floors	1–3 (2.2)	1–5 (3.4)	1–5 (4.2)	5–11 (6.0)
Volume [m^3]	271–859 (632)	535–3,426 (2,115)	3,435–42,020 (6,986)	1,928–64,441 (9,343)
S/V	0.64–1.0 (0.76)	0.40–1.1 (0.52)	0.22–0.62 (0.40)	0.20–0.52 (0.35)
Usable floor area (UFA) [m^2]	63–223 (157)	139–885 (528)	793–10,899 (1,728)	500–16,714 (2,394)

of a regional energy system as demonstrated by Prina et al. [49] for the case study in this paper.

3. Results

3.1. Descriptive sample statistics

We applied the evaluation procedure proposed in Section 2.5 to the case study. Table 3 shows the housing type's size features of the sample for Bolzano.

The number of floors was calculated as building height divided by a floor-to-floor height of 3.6 m for buildings built before 1946 and 3.2 m otherwise, and then rounded to the nearest integer. We calculated the envelope area required for the S/V by multiplying the building perimeter by the building height and adding twice the footprint area (for ground floor and roof).

All size feature averages are clearly distinct. The pre-retrofit model parameters in Table 2 were chosen in line with the averages in Table 3. Fig. 3 shows the heating EUI distribution resulting from the sample dataset for Bolzano and the housing classification in Section 2.1.2.

Most distributions are non-normal and show a large variability. Focusing on the medians, each housing type has a different trend concerning EUI throughout the years. While there is a clear downward trend for single- to two-family houses, big multi-family houses built after 2005 seem to perform worse than big multi-family houses built in 1991–2005. Apartment blocks seem to show an improvement in terms of EUI only after 2005. However, this improvement is small when compared with the energy performance of apartment blocks built before 1946. The median EUI of small multi-family houses has slightly worsened since 1991. Focusing on the means, trends are in line with those of the medians, except for apartment blocks built after 2005 where the mean is much higher than the median because of two blocks with EUIs above 300 kWh/m^2a.

3.2. Descriptive baseline statistics

Fig. 4 shows the floor area distributions calculated according to Section 2.1.4.

Each of the three stacked bar series “Urban”, “Rural”, and “South Tyrol” sums up to 100%. By definition there are no apartment blocks in rural areas. Expectedly, most single- to two-family houses are in rural areas. The cities of Bolzano and Merano cover 27% of the total residential floor area in South Tyrol. This explains the drop in the single- to two-family houses share from 52% to 38% from “Rural” to “South Tyrol” and the drop in the apartment blocks share from 48% to 13% from “Urban” to “South Tyrol”. Unsurprisingly, the UFA of small multi-family houses is larger in rural than in urban areas. We observe the opposite for big multi-family houses.

Fig. 5 shows the residential heating consumption baseline.

The total annual baseline heating consumption is 2.8 TWh (average EUI: 150 kWh/m^2a), with single- and two-family houses accounting for 53% (1.5 TWh) and buildings constructed in 1946–1990 accounting for 58% (1.6 TWh). With an estimated energy use of 0.46 TWh/a for DHW (25 kWh/m^2a times the residential UFA for South Tyrol), the baseline space heating consumption is 2.3 TWh/a.

3.3. Energy saving percentages and retrofit cost

Table 4 shows the energy saving percentage, specific cost, and LCSE by housing type and retrofit for the PHPP simulations.

The “standard” retrofits of facade (SF), roof (SR), basement ceiling (SB), and windows (SW) have a higher LCSE than their “deep” counterparts, DF through DW. The rest of the table thus focuses on deep retrofits. However, if a strategic objective is to limit in-

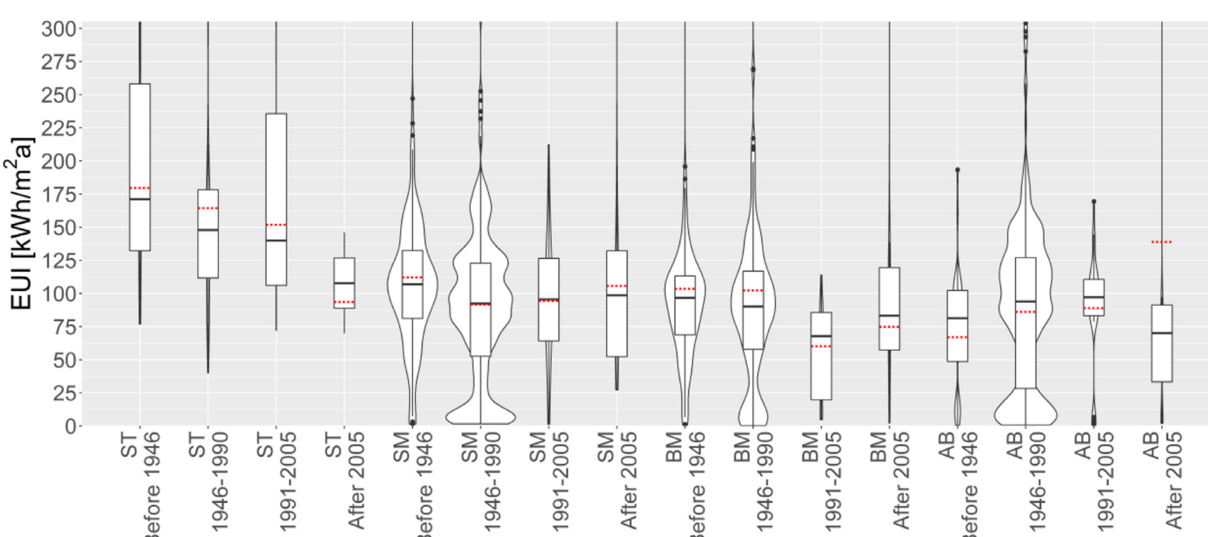

Fig. 3. Heating EUI box and kernel density plots by housing type and age group for Bolzano from gas metering in 2011. The black solid segments and dotted red segments indicate the median and arithmetic average EUI, respectively. ST=single- to two-family houses, SM=small multi-family houses, BM=big multi-family houses, AB=apartment blocks.

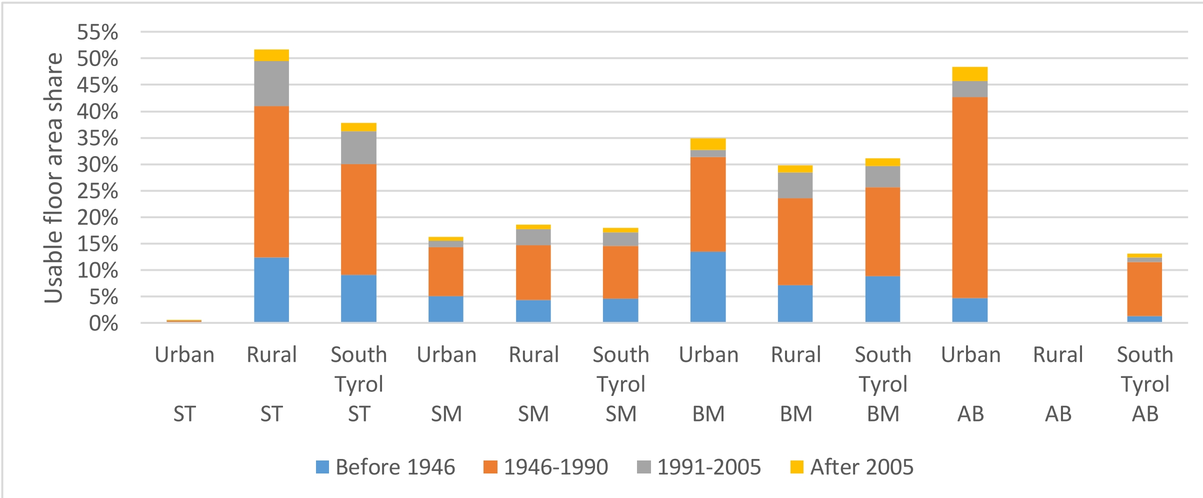

Fig. 4. Estimated floor area distributions in South Tyrol by housing type, age, and urbanisation.

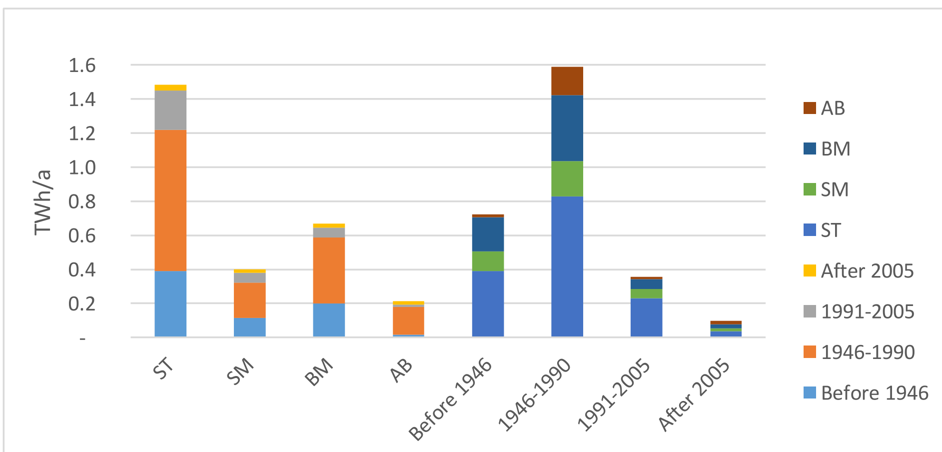

Fig. 5. Estimated annual residential heating consumption in South Tyrol by housing type and age group.

Table 4
Space heating energy savings in percent and specific cost by housing type and retrofit. *S*=standard retrofit, *D*=deep retrofit, *F*=facade insulation, *R*=roof insulation, *B*=basement ceiling insulation, *W*=window replacement.

	Single- to two-family house (ST)			Small multi-family house (SM)			Big multi-family house (BM)			Apartment block (AB)		
Retrofit	Energy saved in %	Spec. cost [€/m^2]	LCSE [€/kWh]	Energy saved in %	Spec. cost [€/m^2]	LCSE [€/kWh]	Energy saved in %	Spec. cost [€/m^2]	LCSE [€/kWh]	Energy saved in %	Spec. cost [€/m^2]	LCSE [€/kWh]
SF	37	153	0.1062	38	112	0.1068	35	80	0.1061	39	85	0.1069
SR	18	99	0.1428	11	60	0.1914	13	54	0.1921	9	34	0.1918
SB	4	39	0.2543	3	24	0.3133	2	21	0.3987	2	13	0.3778
SW	5	75	0.4068	7	87	0.4236	7	55	0.3634	7	51	0.3545
DF	44	177	0.1033	45	129	0.1043	42	92	0.1036	46	98	0.1047
DR	21	107	0.1332	13	65	0.1784	15	59	0.1791	10	36	0.1788
DB	5	44	0.2351	3	27	0.2820	3	24	0.3449	2	15	0.3297
DW	8	97	0.3105	12	112	0.3265	13	71	0.2581	13	66	0.2480
DFR	65	284	0.1136	58	194	0.1219	57	151	0.1248	56	134	0.1185
DFB	48	221	0.1194	47	156	0.1197	44	116	0.1243	48	113	0.1168
DFW	52	274	0.1351	57	241	0.1527	55	163	0.1405	59	164	0.1365
DRB	26	151	0.1519	17	92	0.1992	19	83	0.2075	12	51	0.2059
DRW	29	204	0.1828	26	177	0.2500	28	130	0.2152	23	102	0.2180
DBW	13	141	0.2830	16	139	0.3172	16	95	0.2761	15	81	0.2602
DFRB	68	328	0.1240	60	221	0.1331	59	175	0.1392	58	149	0.1281
DFRW	73	381	0.1355	70	306	0.1584	70	222	0.1499	69	200	0.1433
DFBW	56	319	0.1470	60	268	0.1628	57	188	0.1549	61	179	0.1451
DRBW	34	248	0.1898	29	204	0.2534	32	154	0.2282	25	117	0.2276
DFRBW	77	426	0.1437	73	333	0.1664	72	246	0.1608	71	215	0.1505

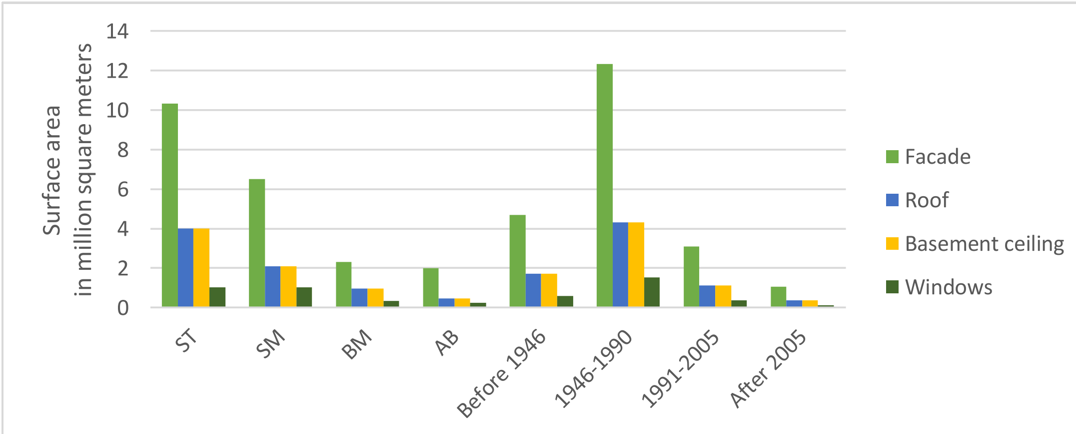

Fig. 6. Estimated retrofittable surface areas.

vestment, standard retrofits can still be a sensible option. As first EEM applied to a non-retrofitted building, facade insulation (DF) is preferable (has a lower LCSE) over the other EEMs for all housing types, followed by roof insulation (DR) as second-best choice. Expectedly, DR is more interesting for single- to two-family (ST) houses than for the other housing types because the roof to floor area ratio is higher (see Table 2). Insulating the basement ceiling (DB) would be the third choice for single- to two-family and small multi-family (SM) houses. Although DB can only provide small energy savings, it does not require a big upfront investment. Clearly, replacing windows (DW) requires a bigger upfront investment than DB but can provide interesting energy savings, making this a better choice in terms of LCSE than DB for big multi-family houses (BM) and apartment blocks (AB).

When looking at two combined EEMs, facade and roof insulation (DFR) has the lowest LCSE for ST, whereas facade and basement ceiling insulation (DFB) is somewhat preferable over facade and roof insulation (DFR) for the other housing types because of the lower costs and still quite high energy saving percentages. Amongst all retrofits with three combined EEMs, insulating the building envelope (DFRB) has the lowest LCSE for all housing types. The other combinations include window replacements, which are costly compared to the energy savings they can provide. For the retrofits DF, DFR, DFRB, DFRW, and DFRBW, single- to two-family houses have the lowest LCSE amongst all housing types. This is due to the high pre-retrofit space heating demand and S/V.

3.4. Retrofittable areas

Fig. 6 summarizes the retrofittable surface area potential for the South Tyrolean housing stock.

For each type of retrofittable surface (facade, roof, basement ceiling, and window), the area is highest for single- to two-family houses, followed by houses increasing in size. Big multi-family houses provide more floor surface than small multi-family houses, but small multi-family houses have higher facade, roof, basement ceiling, and window surface to floor surface ratios than big multi-family houses. The latter factor outweighs the former in this case, which is why there are more retrofittable surfaces in small multi-family houses than in big multi-family houses.

3.5. Retrofit plan

Table 5 shows the retrofit plan for the case study.

The column “Status after EEM” in Table 5 shows all EEMs already applied to the indicated buildings. The 5600 steps in Table 5 are due to South Tyrol having 116 municipalities and considering two municipalities of urban type (Bolzano and Merano) and the other 114 of rural type, i.e., without apartment blocks. This resulted in 5472 steps for the rural areas (114 municipalities of rural type × 3 housing types × 4 age groups × 4 EEMs) and 128 steps for the urban areas (2 municipalities of urban type × 4 housing types × 4 age groups × 4 EEMs).

Fig. 7 shows the LCSE averaged over all municipalities by housing type, age group, and EEM.

The EEMs with the lowest and second-lowest average LCSE are facade and roof insulation, respectively, independently of the housing type, while the EEM with the third-lowest average LCSE depends on the housing type. For single- to two-family houses, basement ceiling insulation has a slightly lower average LCSE than window replacement, whereas for the other housing types it is the opposite. Consequently, the fourth and last EEM is window replacement for single- to two-family houses and basement ceiling insulation for the other housing types. Fixing the EEM, the variation of the average LCSE across housing types and age groups follows the variation of the mean pre-retrofit EUI, see Fig. 3.

A closer look at the retrofit plan shows that the LCSE tends to be lower in municipalities with cold climates, such as Corvara in Badia (5135 HDDs) and Selva di Val Gardena (5072 HDDs), and for buildings with high EUI, such as single- to two-family houses built before 1946. The lowest LCSE is about 0.08 €/kWh. This shows that the first measures in the retrofit plan are competitive with energy prices [67] and other kinds of energy efficiency programs [31]. Larger buildings have a lower retrofitted surface to floor surface ratio than smaller buildings. This reduces the specific cost, which lowers the LCSE. This is the reason why big multi-family houses built before 1946 are retrofitted in the third step of the retrofit plan, although their pre-retrofit EUI is lower than that of, e.g., small multi-family houses built before 1946. Note that the order in which EEMs are applied can vary – see the distinction between “DFRBW” and “DFRWB” in column “Status after EEM” to highlight this fact. With 2721 HDDs, the municipality “Cortina sulla Strada del Vino” appearing in the last step of the plan has the mildest climate in South Tyrol.

3.6. Retrofit scenarios

In the BAU scenario, €60 million per year, estimated from the 2011 tax relief report by the National Agency for Energy Efficiency [68] and from communication with the local Environment Agency [69], are invested in retrofit projects dealing with envelope insulation, window replacement, or both in 2020–2049, with cumulative annual savings of 0.86 TWh (37% of the baseline consumption) at an LCSE ranging between 0.076 and 0.16 €/kWh. In the Balanced scenario €120 million per year are invested achieving cumulative annual savings of 1.38 TWh (60% of the baseline consumption) at

Table 5
Retrofit plan for the housing stock in South Tyrol built before 2012 (excerpt).

Retrofit no.	EEM	Housing type	Age group	Municipality	Status after EEM	UFA [m²]	Energy savings [kWh/a]	Cost [€]	LCSE [€/kWh]
1	DF	ST	Before 1946	Corvara in Badia	DF	5,991	811,112	1,061,444	0.07568
2	DF	ST	Before 1946	Selva di Val Gardena	DF	11,032	1,473,770	1,954,561	0.07670
3	DF	BM	Before 1946	Corvara in Badia	DF	2,121	146,361	195,319	0.07717
...		...	...	...	...	...	...	...	...
943	DF	ST	Before 1946	Bolzano	DF	4,256	291,682	754,129	0.1495
...		...	...	...	...	...	...	...	...
1587	DR	ST	Before 1946	Bolzano	DFR	4,256	133,571	455,501	0.1972
...		...	...	...	...	...	...	...	...
2800	DW	ST	Before 1946	Brunico	DFRBW	70,527	1,272,988	6,844,728	0.3110
2801	DW	ST	1946–1990	Renon	DFRBW	78,336	1,413,925	7,602,568	0.3110
2802	DB	ST	1991–2005	Tubre	DFRB	3,474	28,608	153,895	0.3111
...		...	...	...	...	...	...	...	...
4200	DW	BM	1991–2005	Rasun Anterselva	DFRW	3,321	28,591	236,079	0.4775
4201	DW	BM	After 2005	Laces	DFRW	1,638	14,091	116,430	0.4778
4202	DB	SM	1946–1990	Sesto	DFRWB	12,222	39,965	330,342	0.4780
...		...	...	...	...	...	...	...	...
5598	DB	BM	1991–2005	Magrè sulla Strada del Vino	DFRWB	1,574	1,292	38,301	1.715
5599	DB	BM	1991–2005	Salorno	DFRWB	4,127	3,323	100,428	1.747
5600	DB	BM	1991–2005	Cortina sulla Strada del Vino	DFRWB	808	643	19,656	1.769

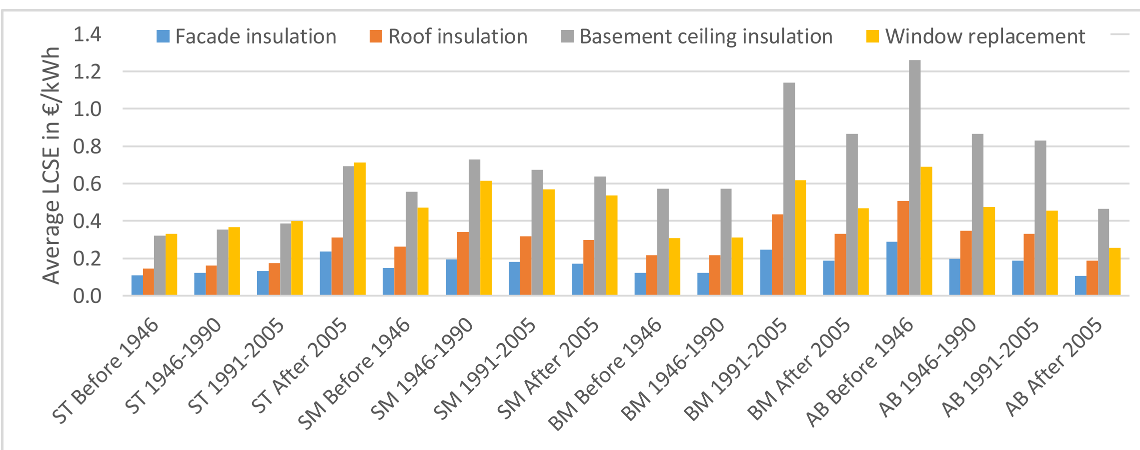

Fig. 7. Average LCSE by housing type, age group, and EEM.

an LCSE between 0.16 and 0.28 €/kWh. Finally, in the Max scenario €207 million per year are invested for cumulative annual savings of 1.72 TWh at an LCSE of up to 1.8 €/kWh. Fig. 8 summarizes the findings.

4. Discussion and conclusions

We presented a comprehensive but manageable procedure for developing detailed retrofit scenarios for building stocks depending on the annual available budget for building retrofit. The scenarios are based on a retrofit plan consisting of a series of steps specifying the buildings to be retrofitted, the Energy Efficiency Measures (EEMs) to be applied, the costs, and the potential energy savings. We prioritised each EEM according to Levelized Cost of Saved Energy (LCSE), thus maximizing the total potential energy saving given a fixed total cost. The LCSE is advantageous with respect to other economic indicators commonly used in literature since it allows for a direct comparison with energy supply and energy efficiency programs. An energy efficiency cost curve was derived from the retrofit plan, enabling public authorities and decision makers to determine a viable energy saving target and the respective cost for the energy transition.

The basis of any energy transition plan for a building stock is a reliable description of the building stock's characteristics and baseline energy consumption. We showed how to establish a baseline calibrated on a sample of real buildings with metered energy consumption. We demonstrated the proposed procedure on the case study region South Tyrol in northern Italy.

For the case study we lacked reliable monitored post-retrofit data and had to resort to calculation models to estimate energy saving percentages. This may have led to overestimated energy savings, as rebound effects, installation issues, and other constraints could not be accounted for. We used a simplified calculation tool based on quasi-steady state energy balance because more detailed, dynamic models require additional inputs, such as hourly internal gains, heating setpoints, and ventilation rates, which were unknown for the analysed building stock. Since we lacked data on the actual U-values of the building stock's envelopes, we used representative U-values for the peak construction period in the models. Before collecting additional model input

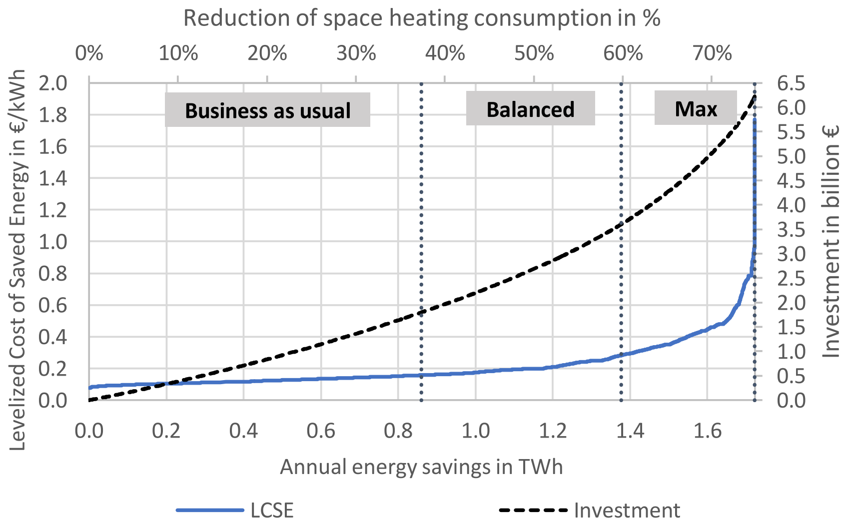

Fig. 8. LCSE (solid curve, scale on the left vertical axis) and cost (dashed curve, scale on the right vertical axis) against annual energy savings. The vertical dotted lines refer to different retrofit scenarios.

data, the effort involved and the risk of introducing error with approximate data must be carefully balanced against the expected increase in accuracy.

The developed method for defining building stock energy transition scenarios in terms of retrofit plans enables public authorities and policy makers to identify the most cost-effective actions for a city or region according to the fixed target and can support the decision process of policy measures to drive the main relevant EEMs.

Prioritizing retrofit steps based on LCSE might lead to a retrofit plan that is different from current retrofit trends. For instance, the plan for South Tyrol prioritizes envelope insulation over window replacement since the former can provide more massive non-renewable energy savings and be more cost-competitive in the long term. However, window replacement has been very popular in South Tyrol in the last years, more than envelope insulation [65]. Similarly, in Germany the top four individual measures supported by the German Energy Agency in 2014 were, in decreasing order of number of implementations, heating technologies, upgrade of windows, insulation for roofs, and facade insulation [70]. The reason why window replacements are so popular in South Tyrol is that they require relatively low initial investment and likely provide co-benefits, such as increased indoor environmental quality and market value of the property. Furthermore, installation is relatively straightforward, non-invasive, and easier to manage in the context of a multi-family house or apartment block than envelope insulation. The above-mentioned co-benefits should be monetised and introduced in the business model, but there is no consensus on the matter yet. Further research and pilot applications would still be needed to properly include this aspect in the building renovation evaluation. Summarizing, the low LCSE for facade and roof insulation in South Tyrol is an indication that future policies and research efforts should focus on business models to increase the popularity and competitiveness of these measures.

In the approach followed in this paper each building is retrofitted step-by-step undergoing multiple EEMs spread in time. Compared to fixing annual retrofit rates beforehand this has the advantage that owners can spread their investments over a period compatible with their financing capabilities without compromising on energy performance and building quality.

We suggest using the proposed method to support the creation, evaluation, and revision of climate plans, to review retrofitting policies and strategies, and to include the impact of retrofitting in studies of the transition of energy systems.

Declaration of Competing Interest

none

CRediT authorship contribution statement

Ulrich Filippi Oberegger: Conceptualization, Methodology, Software, Validation, Writing - original draft, Visualization, Project administration, Funding acquisition. **Roberta Pernetti:** Conceptualization, Methodology, Software, Investigation, Writing - review & editing. **Roberto Lollini:** Conceptualization, Writing - review & editing, Supervision.

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Appendix

We report the relevant steps of PHPP's monthly based calculation of annual space heating demand Q_H [kWh/a]. The building is modelled as one thermal zone.

$$Q_H = Q_T + Q_V - Q_G$$

where Q_T and Q_V are the heat losses by transmission and ventilation, respectively, and Q_G are the heat gains. Assuming n building surfaces:

$$Q_T = \sum_{i=1}^{n} Q_{T_i}$$

$$Q_{T_i} = A_i \cdot U_i \cdot G_t$$

where A_i [m^2] and U_i [W/m^{2}K] are the area and U-value of building surface i, respectively, and G_t [kKh/a] is a scaling factor considering the losses to the external environment (ground) according to external air (ground) temperature. These losses are determined on a monthly basis:

$$G_t = \sum_{\substack{j=1 \\ G_j > 0}}^{12} G_j$$

$$G_j = \frac{h_j\left(T_{a,j} - T_{e,j}\right)}{1000}$$

where h_j is the number of hours in month j, $T_{a,j}$ is the monthly mean indoor air temperature (20 °C by default), and $T_{e,j}$ is the monthly mean external air (ground) temperature for month j. The condition $G_j > 0$ makes sure that only heat losses are considered and not heat gains, which typically occur in the hot season.

Heat losses by ventilation are given as:

$$Q_V = V_a \cdot c_a \cdot n_a \cdot G_t$$

where V_a [m^3] is the indoor air volume, c_a [Wh/m^{3}K] is the specific heat capacity of air (0.33 by default), and n_a [1/h] is the air change rate including ventilation and infiltration.

The heat gains contributing to a reduction in space heating demand are calculated as:

$$Q_G = \eta_G \cdot Q_F$$

where Q_F denotes the free heat gains and η_G is a dimensionless utilisation factor that depends on the heat capacity of the building. For the models in this paper η_G is between 0.92 and 0.94 and increases Q_H by less than 2%. Therefore, we omit the calculation description for η_G.

$$Q_F = Q_S^{tot} + Q_I$$

where Q_S^{tot} and Q_I denote the (total) solar and internal heat gains, respectively. Solar heat gains are calculated separately for the orientations north, east, south, west, and horizontal, and then added up. For each orientation the following calculation is performed (to simplify the notation we omit the index specifying the orientation):

$$Q_S = f_r \cdot g \cdot A \cdot G$$

where g is the g-value, A [m^2] is the rough opening window area, G [kWh/m^{2}a] is the global radiation on the inclined surface (user input), and f_r is a dimensionless reduction factor.

$$f_r = f_s \cdot f_d \cdot f_{npir} \cdot f_g$$

where f_d is a dirt reduction factor (0.95 by default), f_{npir} is a non-perpendicular incident radiation reduction factor (0.85 by default), f_g is the glazing fraction (glazing area divided by window area), and f_s is the total shading reduction factor given as solar gains including shading divided by solar gains without shading.

$$f_s = r_H \cdot r_R \cdot r_O \cdot r_{oth}$$

where r_H is the horizontal shading reduction factor due to objects in front of the window, such as neighbouring buildings, r_R is the reveal shading reduction factor, r_O is the overhang shading reduction factor, and r_{oth} is an additional shading reduction factor due to balcony railings, trees, or similar (user input). The factors r_R and r_O (calculation description omitted) are calculated based on reveal and overhang dimensions, window orientation, and location.

Internal heat gains are calculated as:

$$Q_I = f_c \cdot d_H \cdot q_I \cdot A_{TFA}$$

where d_H [d/a] is the length of the heating period, q_I [W/m^2] are the specific internal heat gains (user input), A_{TFA} is the treated floor area, and $f_c = 0.024$ [kh/d] is a unit conversion factor.

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