Identification of cost-optimal and NZEB refurbishment levels for representative climates and building typologies across Europe

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Abstract The energy consumptions of the building stock are playing a central role in the energy policy of the European Union. While the Member States are applying the Directives in force, the European Commission is working to update the regulatory framework. Specifically, it is necessary to achieve the great unrealized potential for energy savings in existing buildings. With this aim, the nearly zero-energy building (NZEB) target was introduced, and a comparative methodology framework to calculate cost-optimal levels of minimum energy performance requirements was proposed. This study focuses on the issue of building renovation, and it presents the results obtained with the application of a cost-optimal calculation method for identifying proper retrofit measures to reach cost-optimal levels and NZEB levels. The assessment takes into account an exhaustive set of passive and active renovation options and it was extended to various building types of 60s–70s (residential and non-residential) in a wide range of representative European climatic conditions. A very relevant energy-saving potential was found for all cost-optimal benchmarks, and in many cases, the obtained NZEB refurbishments have resulted interesting also from an economic point of view.

Keywords EPBD recast · NZEB · Cost-optimal calculation · Retrofit measures

Introduction

Motivation

The European building stock consumes approximately 40% of primary energy, and it is responsible for 36% of the EU greenhouse gas emissions. A significant reduction of this energy demand is a requisite to meet Europe’s GHG emission reduction targets, and buildings are a strategic sector for the European energy policy. In fact, it is a pillar of the Energy Union as set by the 2015 Communication1 of the European Commission (EC). The Energy Performance of Buildings Directive (EPBD)—together with the Energy Efficiency Directive (EED) and the Renewable Energy Directive (RED)—defined a framework that creates the conditions for long-term improvements in the energy performance of Europe’s building stock. Without it, the indicative target at the EU level of at least 27% for improving energy efficiency in 20302 cannot be obtained.

In the frame of the implementation of the European Directive 2010/31/EU (EPBD recast by the European

1 COM/2015/080 final.
2 This will be reviewed by 2020, having in mind an EU level of 30%.
Parliament 2010), the EU Member States were asked to develop policies appropriate to their national situations and provide the necessary financing to foster the transition to nearly zero-energy building (NZEB). The EPBD recast requires that from 2019 onwards, all new buildings occupied and owned by public authorities are NZEBs and all new buildings by the end of 2020. However, acknowledging the variety in building culture and climate throughout Europe, the EPBD does not prescribe a uniform approach for implementing NZEB. Member States were required to draw up National Plans for increasing the number of NZEBs, with targets that may be differentiated for different building categories. According to paragraph 3 of Article 9, these plans shall include NZEB definitions reflecting national, regional, or local conditions, and a numerical indicator of primary energy use.

Moreover, the EPBD recast asked Member States to calculate cost-optimal levels of minimum energy performance requirements for new and existing buildings by using the comparative methodology framework established by the Commission with the Delegated Act No. 244/2012 (European Parliament 2012a, b) of 16 January 2012 (including explanatory guidelines).

This cost-optimal calculation framework involves the following steps: (i) definition of national reference buildings representing national building stock, (ii) identification of energy efficiency measures and packages to be evaluated, (iii) calculation of primary energy demand of the reference buildings with the identified energy efficiency measures, (iv) calculation of global costs related to each the energy efficiency measure and package considering long-term expenditures and savings during the calculations period, (v) sensitivity analysis for input data, and (vi) derivation of cost-optimal levels of energy performance requirements.

While the Member States are updating their plans, the cost-optimal approach may be very effective both to upgrade the energy performance requirements in force at the national level3 and to assess the effects of policy measures implemented or proposed by the Member States to achieve the NZEB target, particularly in the case of policy measures based on financial incentives for energy efficiency (EE) and renewable energy systems (RES) technologies and the transformation of these technologies national markets.

Literature review

In general application of optimization, methods for low-energy and sustainable building design (including also the cost-optimal objective) are well summarized in the review analyses by Evins (2013), Nguyen et al. (2014) and Machairas et al. (2014). Further review studies on these subjects more specifically focusing on NZEB developments are presented by Attia et al. (2013) and Lu et al. (2015). Several examples of application of this method also with the aim of determine the optimum in terms of energy performances and costs (life cycle or initial costs) are presented in numerous studies (Diakaki et al. 2008; Brown et al. 2010; Morrissey and Horne 2011; Asadi et al. 2012; Fesanghary et al. 2012; Kumbaroğlu and Madlener 2012; Rysanek and Choudhary 2013; Nguyen and Reiter 2014; Penna et al. 2015).

In literature, while it is available also, an extensive literature on the cost optimization of specific building element calculation—e.g., the optimal insulation thickness for the various building elements and in various climatic conditions, as summarized by Fokaides and Papadopoulos (2014)—rarer is the published applications of cost optimization procedures on the whole building-plant system and only some of these refer explicitly to the framework of EPBD Recast Directive. Because the method described in this paper is proposed as a direct application of the European comparative approach, the following previous experiences were considered particularly relevant: Kurnitski et al. (2011), Hamdy et al. (2013, Corrado et al. (2014), Ganic and Zerrin Yilmaz (2014), Pikas et al. (2014), Ferrara et al. (2014), Brandão de Vasconcelos et al. (2016), Becchio et al. (2016), Ashrafiana et al. (2016), Ortiz et al. (2016a, b).

From a methodological point of view, the majority of previous studies have focused on a limited number of building variants, selected through a combination of technical measures/packages or applying (more or less sophisticated) multi-stage search-optimization techniques (Table 1). Often to quantify the energy needs for heating, cooling, and lighting, the calculations were made by dynamic simulations, while the computation of final energy uses could be obtained by more simplified calculations (e.g., semi-stationary methods). For

\footnote{It is provided that if the result of the comparative analysis carried out shows that the minimum requirements in force are considerably less efficient than those arising from the analysis of the cost-optimal levels (deviation greater than 15%), the MS must give justification for this difference or develop a plan outlining the appropriate measures to be introduced in order to reduce significantly the energy gap.}
example, this is the case of Hamdy’s (2013) analysis, which developed a multi-stage methodology based on a multi-objective genetic algorithm able to reduce the number of the building envelope simulations and, in a second time, applying appropriate efficiency factors to optimize the plant systems. In this way, he has increased the number of considered building variants compared to other studies. With this aim also, Ferrara et al. (2014) applied a simulation-based optimization process, combining the use of TRNSYS (Solar Energy Laboratory 2012) with GenOpt (Wetter 2008). Brandão de Vasconcelos et al. (2016), who considers only the envelope technologies, adopted a two-step approach which consists in (i) preliminarily discarding of measures with the same or worse thermal transmission coefficient and higher global costs comparatively with other measures and (ii) combination of all resulting measures with each other, creating 35,000 packages of measures. A good number of building variants (i.e., 2000) was considered also by Ortiz (Ortiz et al. 2016a, b), who conversely applied a “brute-force” approach to obtain a complete characterization of the problem.

As shown in Table 2, the most considered energy end-uses are space heating, cooling, and lighting. In line with the EPBD, the appliances (e.g., domestic equipment) are rarely taken into account. The energy calculations were made referring to similar indoor comfort conditions by the authors.

About the cost calculation (Table 3), all authors referred to a financial perspective (including taxes and not monetizing the environmental damage of emissions) and—except Kurnitski et al. (2011), who did not taken into account maintenance, replacement, and disposal costs—they considered all cost items indicated by the Commission Delegated Act No. 244/2012 (European Parliament 2012a, b). A real interest rate between 2 and 4% and a yearly increase of energy prices around 2% were used.

On the application side (Table 4), the majority of previous studies have focused on residential building

| Reference | Calculation of energy needs | Calculation of final energy demand | Solving method | Number of building variants |
|-----------|-----------------------------|------------------------------------|----------------|-----------------------------|
| Kurnitski et al. 2011 | Dynamic simulation with IDA-ICE | Dynamic simulation with IDA-ICE | Combination of the considered measures/packages | < 50 |
| Hamdy et al. 2013 | Dynamic simulation with IDA-ICE | Simplified methods and auxiliary design calculations | Automatic multi-stage optimization method based on multi-objective genetic algorithm | 3400 |
| Corrado et al. 2014 | Semi-stationary method (EN 13790) | Semi-stationary method (EN 13790) | Sequential search-optimization technique | < 50 |
| Ganic and Zerrin Yılmaz 2014 | Dynamic simulation with EnergyPlus | Dynamic simulation with EnergyPlus | Combination of the considered measures/packages | < 50 |
| Pikas et al. 2014 | Dynamic simulation with IDA-ICE (1 floor) | Dynamic simulation with IDA-ICE (fixed HVAC) | Iterative three-step wise optimization | < 50 |
| Ferrara et al. 2014 | Dynamic simulation with TRNSYS | Dynamic simulation with TRNSYS | Simulation-based optimization process (GenOpt) | 6000 |
| Brandão de Vasconcelos et al. 2016 | Dynamic simulation with EnergyPlus | Dynamic simulation with EnergyPlus (fixed HVAC) | Combination of the considered measures (for envelope only) | 35,000 |
| Becchio et al. 2016 | Dynamic simulation with EnergyPlus | Dynamic simulation with EnergyPlus | Combination of the considered measures | < 50 |
| Ashrafiana et al. 2016 | Dynamic simulation with EnergyPlus | Dynamic simulation with EnergyPlus | Combination of the considered measures (for envelope only) | 55 |
| Ortiz et al. 2016a, b | Dynamic simulation with TRNSYS | Simplified methods and auxiliary design calculations | Combination of the considered measures | 2000 |
types, covering both the ambit of new design and building retrofit. Analyses on cost-optimal levels are mainly based on identification of energy efficiency measures/packages affecting energy performance of buildings, but, in general, the most investigated systems were the envelope solutions and the heating generators. In any study, the same calculation methodology was applied to more than two building types and more than three weather conditions.

Even though it is not trivial to compare the results obtained under different simplified assumptions and calculation methods, these previous experiences found cost-optimal primary energy levels in the range 90–150 kWh/m²/year. The authors, who did this type of comparison, found that the primary energy targets related to the cost-optimal levels are significant lower (20–50%) than those related to the standard requirements, in force at national level.

This same conclusion was derived from the analysis of the first cost-optimal calculations done by the Member States. Boermans et al. (2015) observes that about half of the EU countries reveal a significant gap (i.e., larger than 15%) between the cost-optimal levels and the energy requirements in force. The picture is very similar for the different building types and for both new and renovated buildings. From the methodological point of view, it is interesting to observe that about half of the national methodologies are in line with the CEN standards and refer to them (at least partly) for the calculation of primary energy and global cost. However, in most cases, the primary energy calculation is considered non fully reliable because the primary energy is not always used as energy performance indicator, the value of primary energy factors is low, and not all technical systems are addressed (Zirngibl and Bendzalova 2015).

### Table 2 Literature review: energy calculation

| Reference                        | Energy uses considered                                                                 | Electric primary energy factor | PV energy taken into account                          | Temperature set-points in winter and summer |
|---------------------------------|----------------------------------------------------------------------------------------|-------------------------------|------------------------------------------------------|---------------------------------------------|
| Kurnitski et al. 2011           | Heating, cooling, ventilation, pumps and fans, other technical service systems, DHW, lighting | 1.5                           | n.a                                                  | n.a—n.a                                    |
| Hamdy et al. 2013               | Heating, cooling, ventilation, pumps and fans, other technical service systems, DHW, lighting | 1.7 (for Finland)             | Self-consumed (by hourly load matching operation)    | n.a—25 °C                                  |
| Corrado et al. 2014             | Heating, cooling and DHW                                                              | 2.17 (for Italy)              | Self-consumed (by monthly load matching operation)   | 20 °C—26 °C                                |
| Ganic and Zerrin Yılmaz 2014    | Heating, cooling and lighting                                                          | 2.35 (for Turkey)             | Not considered (by hourly load matching operation)    | 21 °C—26 °C                                |
| Pikas et al. 2014               | Heating, cooling and lighting                                                          | n.a                           | Self-consumed (by hourly load matching operation) and exported to the grid | n.a—n.a                                    |
| Ferrara et al. 2014             | Heating, cooling                                                                      | 2.58                          | n.a                                                  | n.a—n.a                                    |
| Brandão de Vasconcelos et al. 2016 | Heating, cooling, ventilation, pumps and fans, other technical service systems, DHW | n.a                           | Not considered                                      | n.a—n.a                                    |
| Becchio et al. 2016             | Heating, cooling, DHW, lighting and appliances                                         | 2.18 (for Italy)              | n.a                                                  | 21 °C—26 °C                                |
| Ashrafiñana et al. 2016         | Heating, cooling, DHW, lighting                                                        | 2.36 (for Turkey)             | Not considered                                      | 20 °C—26 °C                                |
| Ortiz et al. 2016a, b           | Heating, cooling, DHW, lighting and appliances                                         | 2.464 (for Spain)             | n.a                                                  | 20 °C—24.5 °C                              |

*n.a* not available

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Generalizing the issue, it is interesting to remember that some critical points on the cost-optimal method itself were discussed. For instance, Tadeu et al. (2016) consider that the global cost indicator is not enough for describing the point of view of an investor and it must be complemented with additional information. Becchio et al. (2015) stressed the need to include in the global cost formula other benefits related to energy-design of buildings (as indoor comfort conditions, reduction of CO₂ emissions, embodied energy, real estate market value).

Objectives and overview

Against the regulatory background, the main objective of this study is to identify primary energy levels and benchmarks for building renovation which may represent the cost-optimal and NZEB⁴ targets across Europe.

The paper covers the main aspects discussed above and it proposes an additional calculation method consistent with the European framework (European Parliament 2012a, b). Compared to previous methods and applications, (i) it is single stage rather than multi-

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**Table 3** Literature review: global cost calculation

| Reference                  | Considered costs                                                                 | Economic perspective | Building’s lifetime (year) | Real interest rate (%) | Annual increase of energy prices |
|----------------------------|----------------------------------------------------------------------------------|----------------------|----------------------------|------------------------|----------------------------------|
| Kurnitski et al. 2011      | Energy, labor, materials, overheads and taxes                                    | Financial            | 30                         | 3                      | 2%                               |
| Hamdy et al. 2013          | Energy, labor, materials, maintenance, replacement, disposal and taxes           | Financial            | 30                         | 3                      | 2%                               |
| Corrado et al. 2014        | Energy, labor, materials, maintenance, replacement, disposal and taxes           | Financial            | 30                         | 4                      | Electric 2% Gas 2.8%             |
| Ganic and Zerrin Yılmaz 2014 | Energy, labor, materials, maintenance, replacement, disposal and taxes       | Financial            | 20                         | 4.12                   | n.a                              |
| Pikas et al. 2014          | Energy, labor, materials, maintenance, replacement, disposal and taxes           | Financial            | 20                         | 4                      | n.a                              |
| Ferrara et al. 2014        | Energy, labor, materials, maintenance, replacement, disposal and taxes           | Financial            | 30                         | 4                      | 2%                               |
| Brandão de Vasconcelos et al. 2016 | Energy, labor, materials, maintenance, replacement, disposal and taxes | Financial            | 30                         | 3                      | n.a⁵                             |
| Becchio et al. 2016        | Energy, labor, materials, maintenance, replacement, disposal and taxes           | Financial            | 30                         | 2.3                    | n.a                              |
| Ashrafiana et al. 2016     | Energy, labor, materials, maintenance, replacement, disposal and taxes           | Financial            | 30                         | 2.4⁶                    | n.a                              |
| Ortiz et al. 2016a, b      | Energy, labor, materials, maintenance, replacement, disposal and taxes           | Financial            | 30                         | 2.5⁷                    | Electric 2.5% Gas 2%             |

n.a not available

⁴ Referring to the analysis of Marszal et al. 2011, this study is based on the “ZEB limited” definition: a low-energy building, fulfilling any national/local energy efficiency requirements, which offsets the yearly balance between its weighted energy demand for heating, DHW, cooling, ventilation, auxiliaries and built-in lighting, and the weighted energy supplied by on-site generation systems driven by on- or off-site sources and connected to the energy infrastructure. Static (or quasi-static) and symmetric primary energy factors are used as weights in the balance.

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⁵ The authors refer to the EU’s forecasts for energy costs trends (European Commission 2014)

⁶ Calculated as difference between the market interest rate (11.25%) and the inflation rate (8.85%)

⁷ Calculated as difference between the market interest rate (4.5%) and the inflation rate (2%)
| Reference                  | Application area (reference period) | Measures/packages considered (number of variation steps in addition to the base case)                                                                 | Building types (area) | Climatic conditions      |
|----------------------------|-------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|-----------------------|--------------------------|
| Kurnitski et al. 2011      | New building design                 | Insulation levels of building envelope (4), air leakages rate (4), windows (4), heating systems (7), solar systems (thermal (2), PV (2)) | Single house (171 m²) | Cold Estonian climate    |
| Hamdy et al. 2013          | New building design                 | Insulation levels of building envelope (8–16), air tightness levels (3), window types (3), shading systems (4), efficiency of heat recovery (3), cooling (2) and heating (4) plants, solar systems (2) | Two-storey house (143 m²) | Vantaa (Finland)         |
| Corrado et al. 2014        | Refurbishment (1946–1960)           | Insulation levels of building envelope (5–7); window type (5); solar shading devices (2); solar systems (thermal (3), PV: 4); generators for heating, cooling and DHW (11) | Apartment block (1550 m²) | Milan (Italy)            |
| Ganic and Zerrin Yılmaz 2014 | Refurbishment (before regulation standards) | Insulation levels of building envelope (2), window systems (2), lighting system (2), and chiller EER (2)                                                                                   | Office (4500 m²) | Anjara, Antalya (Turkey) |
| Pikas et al. 2014          | New building design                 | Insulation of external walls (5), window area and glazing type (6), external shading, PV panel size                                                                                       | Office (n.a.) | Cold Estonian climate    |
| Ferrara et al. 2014        | New building design                 | Envelope systems (3), insulation levels of building envelope (20), window type (4), windows width (38), heating and cooling systems (4), ventilation strategy (2) | Single house (155 m²) | Rhone-Alpes region (France) |
| Brandão de Vasconcelos et al. 2016 | Refurbishment (1960–1990)       | Insulation levels of building envelope (49), window types (9)                                                                                                                                  | Apartment block (1500 m²) | Lisbon (Portugal)        |
| Becchio et al. 2016        | Refurbishment (1900)                | Insulation levels of building envelope (3), window types (3), heating and cooling systems (2), ventilation (2), solar systems (thermal (1), PV (8)).                                               | Ex-industrial (3600 m²) | Turin (Italy)            |
| Ashrafiana et al. 2016     | Refurbishment (1985–1999)           | Insulation levels of building envelope (9), window types (6)                                                                                                                                     | Apartment block (2729 m²) | Turkey (Istanbul, Antalya, and Erzurum) |
| Ortiz et al. 2016a, b      | Refurbishment (1991–2007)           | Insulation levels of building envelope (32), windows type (2), solar protection (1), heating and cooling systems (2), ventilation strategy (2), user behavior (1), solar systems (2) | Apartment block (400 m²) | Barcelona (Spain)        |

n.a. not available
stage (it considers in one single step all the technologies and their combinations, rather than optimizing step by step); (ii) it describes the entire Energy-Cost plane rather than being limited to the Pareto frontier; (iii) it computes a large number of variants, thus avoiding to rely on a pre-judgment from the analyst of the suitable combinations which might miss some relevant variant; and iv) it includes a base refurbishment level as a useful reference for the entire energy and cost calculation.

To populate a large database of comparable results across Europe, the calculation is applied to four building types (two residential and two non-residential), representative of the EU stock built in years ‘60–‘70, in ten European climatic contexts.

The rest of this paper is structured as follows: “Methodology” section describes the calculation methodology and the main input data used. “Results and discussion” section presents and discusses the main results obtained. Finally, the most relevant conclusions are outlined in “Conclusions” section.

**Methodology**

To identify cost-optimal benchmarks for building renovations across Europe, a comprehensive methodology was developed. It consists of seven steps, starting from the selection of reference climates in EU28 and ending
with the development of a sensitivity analysis. In general, the methodology of the study is as follows:

- Step 1: selection of representative climate conditions within the European Union.
- Step 2: definition of reference building types (including its thermos-physical, passive and active components) and determination of base levels of retrofit measures.
- Step 3: selection of renovation measures and packages applicable to the building types.
- Step 4: execution of energy calculations for each combination of retrofit measures, with the determination of the (net) primary energy demand.
- Step 5: execution of economic calculations for each combination of retrofit measures, determining the investments costs and the global costs over the calculation period.
Step 6: identification of energy levels representing the cost-optimal and the NZEB targets and optimum packages of retrofit measures (i.e., technological benchmarks).

Step 7: development of a sensitivity analysis focused on some key calculation parameters.

To provide a comparison with the bibliography discussed in the introduction, a summary of the methodology applied in this study is shown in Table 5. The following subchapters provide more details about the main steps of the calculation approach.

Selecting the EU reference climates

The climate of Europe is temperate-continental, with the influence of the ocean on the western coasts and a Mediterranean climate in the South. The climate is strongly influenced by the Gulf Stream, which keeps mild air over the high-latitude north-western region over the winter months. While Western Europe has an oceanic climate, Eastern Europe has a drier, continental climate. Parts of the Central European plains have a hybrid oceanic/continental climate. Four seasons occur in Eastern Europe, while Southern Europe experiences distinct wet season and dry seasons, with prevailing hot and dry conditions during the summer months.

To assess the energy and comfort performances of buildings, climatic conditions are usually represented as sets of data that describe the climate at a certain location at different degrees of detail. Since several weather variables affect the building behavior, it is not straightforward to establish a definition of typical weather. Different definitions and hence different types of data sets are available based on different weighting of the parameters and other choices. In this case, the analysis was based on the datasets developed by the International Weather for Energy Calculations (IWEC), which consist in hourly data of the main climatic variables arranged in typical weather years. This same data was subsequently used to carry out the energy simulations.

To take into account the climatic variety of the EU28 area, nine target European countries were chosen. Within them, the climatic conditions of 24 cities were chosen for their representativeness. To further filter the selection, three indicators were used as reference: the Winter Severity Index and the Summer Severity Index proposed by F. Sanchez de la Florthe (2006) and the Climatic Cooling Potential developed by Artmann et al. (2007). These indexes were calculated for all cities (Fig. 1), and ten of them were finally chosen also depending on their relevance in terms of urban population. Finally, the following climate conditions were selected: Seville (ES), Madrid (ES), Rome (IT), Milan (IT), Bucharest (RO), Vienna (AT), Paris (FR), Prague (CZ), Berlin (DE), and Helsinki (FI).

Defining the reference building types

According to the Building Stock Observatory of the European Commission, in 2013, the EU residential stock (which accounts for about 65% of consumption) is composed by almost 250 million of dwellings (single-family houses represent 65% of residential floor space, against 35% for apartments), of which almost 43% built in the period 1945–1979. Out of the total floor area of the service sector, 29% is used for offices (public and private), 27.5% for wholesale and trade, 16% for educational activities, 14.5% for hotels and restaurants and 6.5% for health and medical activities, and the remaining 6.5% for other activities.

In this context and in line with the principles of the EPBD Directive, four typologies of buildings (two residential and two examples of the non-residential sector) were selected. The attention was focused on the relevant and strategic subcategory of buildings built in the 60s–70s, before the appearance of significant energy performance requirements in the European and national regulations. To establish models representative of the national building stocks and, at the same time, to allow a direct cross comparison between countries, it was decided to fix the envelope geometries and the internal gains. Taking into account the data collected by previous studies (Tabula: Ballarini et al. 2014; Corgnati et al. 2013; Odyssee-Mure: Lapillonne et al. 2012) and asking the advice of national experts participating to the research project ENTRANZE, these reference cases were obtained:

- a single (detached) house, composed by two floors over the ground level and an underground level, with a net conditioned area of about 140 m² and a

\[5\] The IWEC weather files are the result of the ASHRAE Research Project 1015 by Numerical Logics and Bodycote Materials Testing Canada for ASHRAE Technical Committee 4.2 Weather Information. They were derived from up to 18 years of DATSAV3 hourly weather data.

\[6\] http://ec.europa.eu/energy/en/eu-buildings-database
ratio of envelope area and conditioned net volume ($S/V$ ratio) of 0.7,

- a four-floor block of 12 apartments with a conditioned area of 1000 m$^2$ and a $S/V$ ratio of 0.33,
- a medium-size and highly glazed office building, with five floors (of 3-m height each), $S/V$ ratio of 0.33 and a net heated area of 2400 m$^2$ (prospects shown in Fig. 2), and
- a two-floor school of medium size with $S/V$ ratio of 0.46 and a net heated area of 3500 m$^2$ (Fig. 2).

Additional details about these types are provided in Table 6. Under the ground floors of all the reference buildings, there is an unconditioned basement. The residential models, as well as the school, have an unconditioned space between the last slab and the slope roof. Only for the apartment block, different window areas were selected in different climates: 15% of the total façade surface for the Spanish, Italian, and French cases; and 30% in the other countries.

To simulate the internal gains, typical design levels and schedules were applied (Fig. 3). They were defined mediating the slightly different indications provided by the national experts, who referred to national standards or previous studies. A more precise method was used for the lighting loads in the non-residential buildings, where the switching on the lights was simulated dynamically to

![Fig. 3 Prospects of the non-residential building models](image-url)

**Table 6** Fixed building characteristics of the selected reference buildings

| Building characteristic | Single-family house (SFH) | Apartment block (AB) | Office | School |
|-------------------------|--------------------------|----------------------|--------|--------|
| No. of heated floor     | 2                        | 4                    | 5      | 2      |
| $S/V$ ratio (m$^2$/m$^3$) | 0.7                      | 0.33                 | 0.33   | 0.46   |
| Main orientation        | S/N                      | S/N                  | S/N    | S/N    |
| Net dimensions of heated volume       | $8.5 \times 8.5 \times 6$ m | $24.6 \times 11.2 \times 12.8$ m | $30 \times 16 \times 15$ m | $45 \times 60 \times 7$ m (U shape) |
| Net floor area of heated zones (m$^2$) | 140                      | 990                  | 2400   | 3500   |
| Area of S and N façade (m$^2$)  | 51                       | 315                  | 450    | 752.5  |
| Area of E and W façade (m$^2$)  | 51                       | 143                  | 240    | 315    |
| Area of the roof/basement (m$^2$) | 72.25                    | 54                   | 480    | 1750   |
| Window area on S façade (%)    | 25                       | 15–30                | 56     | 32     |
| Window area on E façade (%)    | 7                        | 0                    | 32     | 22     |
| Window area on N façade (%)    | 25                       | 15–30                | 50     | 29     |
| Window area on W façade (%)    | 7                        | 0                    | 35     | 40     |
| Occupancy design level (m$^2$/person) | 50                      | 25                   | 18     | 5.6    |
| Lighting design level (W/m$^2$) | 3.5                      | 3.5                  | 18     | 18     |
| Appliances design level (W/m$^2$) | 4                        | 4                    | 9      | 1.75   |
Table 7 Variable characteristics of selected base refurbishment levels. The $U$ values were calculated applying the standard ISO 6946 (ISO 2007) for the building components selected as typical by the national experts.

| Country | Type of building | Wall $U$ value [W/m² °K] | Roof $U$ value [W/m² °K] | Basement $U$ value [W/m² °K] | Window $U$ value [W/m² °K] | Heating generator system (emission system) | Cooling generator system (emission system) |
|---------|------------------|--------------------------|--------------------------|-----------------------------|---------------------------|------------------------------------------|-------------------------------------------|
| Seville | Residential       | 1.43                     | 1.90                     | 1.32                        | 5.84                      | Gas boiler                               | Chiller                                   |
|         | Non-residential   | 1.37                     | 1.29–2.19                | 1.54–2.57                  | 5.86                      | (radiator)                               | (fancoil/split)                           |
| Madrid  | Residential       | 1.43                     | 1.90                     | 1.32                        | 5.84                      | Gas boiler                               | Chiller                                   |
|         | Non-residential   | 1.37                     | 1.29–2.19                | 1.54–2.57                  | 5.86                      | (radiator)                               | (fancoil/split)                           |
| Rome    | Residential       | 1.22                     | 1.67                     | 1.69                        | 3.01                      | Gas boiler                               | Chiller                                   |
|         | Non-residential   | 1.17                     | 1.28–1.57                | 1.74                        | 5.78                      | (radiator)                               | (fancoil/split)                           |
| Milan   | Residential       | 1.22                     | 1.67                     | 1.69                        | 3.01                      | Gas boiler                               | Chiller                                   |
|         | Non-residential   | 1.17                     | 1.28–1.57                | 1.74                        | 3.47                      | (radiator)                               | (fancoil/split)                           |
| Bucharest | Residential     | 1.46                     | 1.6–1.25                 | 1.28                        | 2.67                      | District heating or gas boiler(radiator) | Chiller                                   |
|         | Non-residential   | 1.34                     | 1.01–4.14                | 1.10                        | 2.72                      | (air diffuser/fancoil)                   |                                           |
| Vienna  | Residential       | 1.25                     | 1.38                     | 1.80                        | 2.62                      | Gas boiler                               | Chiller                                   |
|         | Non-residential   | 1.19–2.59                | 1.11–1.50                | 1.24                        | 2.72                      | (radiator)                               | (fancoil/split)                           |
| Paris   | Residential       | 1.54–2.87                | 1.21–2.56                | 1.98                        | 3.47                      | Gas boiler                               | Absent or chiller                         |
|         | Non-residential   | 1.06–1.17                | 1.65–2.83                | 3.47                        | 5.78                      | (radiator)                               | (fancoil/split)                           |
| Prague  | Residential       | 1.34–0.63                | 1.33–0.65                | 1.24                        | 2.66                      | District heating or biomass boiler(radiator) | Absent or chiller                         |
|         | Non-residential   | 1.07–1.41                | 0.50–0.63                | 3.97                        | 3.50                      | (fancoil/split)                           |
| Berlin  | Residential       | 0.93–1.43                | 1.11–1.18                | 1.02–1.65                  | 2.67                      | Gas boiler                               | Absent or chiller                         |
|         | Non-residential   | 1.42                     | 0.68                     | 1.15                        | 2.72                      | (radiator)                               | (fancoil/split)                           |
| Helsinki| Residential       | 0.48–0.60                | 0.30–0.39                | 0.48                        | 2.50                      | District heating                         | Absent                                   |
|         | Non-residential   | 0.46–0.62                | 0.39–0.84                | 0.53–0.7                   | 2.95                      | (radiator)                               |                                           |
achieve a specified illuminance set-point on the visual task (i.e., 750 lx).

In order to obtain homogeneous building variants in terms of functionality, esthetic aspect, and liveability (conditions normally not evaluated by a cost-optimal analysis), the concept of “base refurbishment level” (BRL) was introduced. It represents the lower level of renovation to which compare the more efficient ones. In other words, it is not contemplated the possibility of not intervening in any way on a building older than 40 years. Avoiding to consider the renovation of building elements without an influence on the thermal energy needs, the BRL includes the rehabilitation of the building façade and roof (finishing material), the substitution of the old window systems and of the old heating/cooling systems with similar (in terms of technology) components, and the installation of an active cooling system (to guarantee similar thermal comfort conditions, if necessary). This methodological refinement (the Commission’s Guidelines do not require explicitly to define this refurbishment level) allows to clearly recognize also which costs could be omitted and to fix the end-life of the original building components (older than 40 years).

Unlike geometries and thermal gains, the physical property of the envelope components (wall, roof, basement, windows) and the configurations of the thermal systems of the base cases (i.e., the base refurbishment levels) were diversified by country. They are shown in Table 7.

Table 8 Ranges of envelope variants selected for the residential type in the considered contexts

| Packages              | Building parameter | Base renovation level Value range | Variation step 1 Value range | Variation step 2 Value range | Variation step 3 Value range |
|-----------------------|--------------------|-----------------------------------|-----------------------------|-------------------------------|-----------------------------|
| Opaque envelope elements | $U$ value of external walls [W/m² °K] | 0.48–2.87 0.22–0.52 0.17–0.31 0.15–0.23 |
|                       | $U$-value of Roof [W/m² °K] | 0.3–2.56 0.14–0.56 0.12–0.33 0.09–0.23 |
|                       | $U$ value of basement [W/m² °K] | 0.48–1.98 0.45–0.57 0.29–0.48 0.21–0.48 |
| Window systems        | $U$ value of windows [W/m² °K] | 2.5–5.84 1.03–2.6 0.7–1.71 – |
|                       | Infiltration air change rate per houra [1/h] | 0.27–0.77 0.11–0.61 0.08–0.58 – |
| Passive cooling strategies | Solar shading device and control External blinds manual | External blinds automated – – |
|                       | Night ach ventilation rate [1/h] | 0 4 – – |
|                       | Lighting load [W/m²] and control | 3.5 manual 3.5 manual – – |
| Heat recovery         | Efficiency [%] | 0 (absent) 80 – – |

a Here, the actual average air changes per hour due to infiltrations are provided. They refer to three different permeability classes of windows (i.e., 2, 3, and 4), as defined by the European standard EN 12207 (CEN 2000)

In order to define packages of measures able to increase the energy performances of the reference cases, technologies and techniques from the following groups were taken into account:

- Building envelope: measures that deal primarily with the reduction of heat transmission and improved air tightness of the building envelope with the objective of reducing transmission losses and losses from (uncontrolled) air-exchange.
- Space heating: an active system is usually necessary to meet the demand for heating. This demand can be met by efficient and/or renewable energy systems (e.g., condensing boilers, heat pumps, and thermal solar panels) in conjunction with suitable storage, distribution, and emission systems.
- Domestic hot water: DHW is often produced with the same system used for space heating, but it can also be supplied by combined systems (e.g., when integrating solar energy systems with a generator using fuel or electricity) or
separate systems. High-efficient storage and dis-
tribution systems are crucial for reducing heat
losses along all the chain.

– **Ventilation systems:** mechanical ventilation sys-
tems allow having control on the air change
rates necessary for IAQ and can also limit losses
from air-exchange if heat recovery systems are
installed. Ventilation and heat recovery can have
both a centralized or decentralized layout, with
the latter sometimes easier to implement in ret-
rofit work.

– **Cooling:** heat protection and passive cooling
systems such as shading devices, night ventila-
tion coupled with exposed mass, can help to
reduce or avoid cooling needs to be met by
active systems. Normally, these techniques are
not considered in previous cost-optimal analy-
sis, but their potential is relevant in many
climates. Cooling, heat protection, and passive
cooling systems can be considered in different
ways, such as shading devices, night ventila-
tion, and automated control as function of the day-
lighting illuminance levels and with objectives of

A relevant aspect of any cost-optimal calculation
is the number of building variants that it can eval-
uate; on one hand, a low number allows very de-
tailed calculations of the energy performances; on
the other, a high one improves the characterization
of the problem. In this case, to increase the number
of variants evaluated, with a reasonable level of
detail, a three-step procedure was adopted for the
primary energy demand calculations. In particular:

1. **Opaque envelope elements**
   - *U* value of external walls [W/m² °K]: 0.46–2.59
   - *U* value of Roof [W/m² °K]: 0.39–4.14
   - *U* value of Basement [W/m² °K]: 0.53–3.97

2. **Window systems**
   - *U* value of Windows [W/m² °K]: 2.71–5.86
   - Infiltration air change rate per hour [1/h]: 0.49–1.3

3. **Passive cooling strategies**
   - Solar shading device: Ext./Internal blinds—fixed slat angle
   - Control: Manual—Automated
   - Night change ventilation rate [1/h]: 0–5
   - Lighting load [W/m²]: 18 (15° manual); 12 (5° manual)

4. **Heat recovery**
   - Efficiency [%]: 0 (absent); 80

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*Lighting load [W/m²] in service rooms*
Secondly, the related final energy demands were calculated applying simplified dynamic calculations and/or efficiency factors to each variant of the thermal sub-systems and with further calculations for RES systems, pumps, fans, and other auxiliary systems. Finally, the net primary energy demand values were obtained applying appropriate primary energy conversion factors (PEFs), for which a dedicated study was developed, and (if applicable) subtracting the weighted contribution from solar renewable energy exported to the grid.

Combining the detailed dynamic simulations to obtain energy needs with the simplified design of thermal plants, more than 25 thousand building variants were defined, for each building type and each weather condition. In principle, this amount of data ensures the possibility of clearly recognizing the cost-optimal levels (minimum global cost for each value of net primary energy demand), as the lower profile of the “cloud” of points in the domain Energy-Cost. Multi-stage optimization approaches were not adopted to avoid limiting the economic competition between refurbishment measures related to different sub-systems of the building (e.g., between thermal insulation and RES systems).

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### Table 10 Summary of the boundary conditions of the simulations carried out

| EnergyPlus version | 7.2 |
|--------------------|-----|
| Surface convection algorithm | Adaptive convection algorithm |
| Heat balance algorithm | Conduction transfer function |
| Solar Distribution | Full interior and exterior with reflections |
| Terrain | City |
| Zone thermal system | Zone HVAC: ideal loads air system + design specification: outdoor air |
| Zone control | Humidistat and thermostat |
| Daylighting object | Daylighting: controls |
| Infiltration and ventilation objects | Zone infiltration/ventilation: design flow rate + zone refrigeration door mixing |
| Thermal bridge adjustment | Narrow sub-surfaces (as small part of the external walls) were added for modeling lintels, columns and other main thermal bridges. A no mass material was associated to these geometric areas and its fictitious U-value was calculated on the basis of available thermal bridge repertoires (Pascual Buisán et al. 2012). |

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### Table 11 Ranges of efficiency coefficient considered for the sub-systems alternatives

| Sub-system | Seasonal efficiency factor |
|------------|---------------------------|
| Generation systems | In heating mode | In cooling mode |
| Gas boiler (%) | 80 | – |
| Condensing gas boiler (%) | 95–104<sup>a</sup> | – |
| Air to water reversible heat pump (with high SCOP/SEER) | 1.44–2.91<sup>b</sup> | 0.6–3.20<sup>b</sup> |
| Ground source reversible heat pump (with high SCOP/SEER) | 1.55–3.89<sup>b</sup> | 0.63–4.45<sup>b</sup> |
| District heating connection (%) | 100 | – |
| Biomass boiler (%) | 90 | – |
| Emission systems | – | – |
| Insulated radiant floor (%) | 97–99<sup>c</sup> | 97 |
| Radiator (%) | 92–95<sup>c</sup> | – |
| Fancoil/split (%) | 94–96<sup>c</sup> | 98 |
| Air diffuser (%) | 90–94<sup>c</sup> | 97 |
| Distribution systems | – | – |
| Not insulated pipes (%) | 92–95<sup>a</sup> | 92–95 |
| Insulated pipes (%) | 99 | 99 |
| Control systems | – | – |
| Climatic control system (%) | 86–80<sup>a</sup> | 90 |
| Climatic + room indoor control system (%) | 98–95<sup>a</sup> | 98 |

<sup>a</sup> Depending on the emission system  
<sup>b</sup> Calculated for each building variant and climate according to standard EN 14825 (2012)  
<sup>c</sup> Depending on the emission power system

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**Energy performance of building envelope**

The selection of the energy efficiency measures is a critical choice since a very high number of packages can be established aggregating them. For this study, which provides a very wide application, the most typical and applicable renovation measures were selected and especially, those on the envelope (evaluated by dynamic simulation) were aggregated in several packages. Specifically, four packages of envelope measures were composed, combining the insulation of all the opaque envelope elements; the substitution of window systems (including glasses and frames); the heat protection and passive cooling strategies (including solar protections, night natural ventilation, and lighting); and the heat recovery strategy. As shown in Tables 8 and 9, in addition...
to the levels of the base cases, three levels of insulation, two types of windows, two passive cooling combinations, and one heat recovery strategy were identified for each building type and in each climate in accordance with the national experts’ indications. Because these variants were defined as real retrofit measures (i.e., addition of an insulation layer of a certain commercial thickness and substitution of the window), the values of parameters depend on the starting characteristics of the reference models, which are different for every climatic context (as shown in Table 7).

Wishing to reduce the number of simulations, 36 of the possible 72 combinations of packages were selected renouncing to study seldom found renovation variants, such as those that provide a high-performance improvement of certain elements without a simultaneous action on the others (e.g., the installation of an insulating layer of 20–25 cm, at the same time maintaining the original single-panes glazing). In this way, a total of 1440 models (36 variants per 4 building types per 10 climates) were defined and their energy needs for heating/cooling and energy use for lighting were calculated by the EnergyPlus simulations.

For obtaining building envelope configurations fully comparable in terms of indoor comfort performances, the energy needs for all the building

Table 12 Primary energy factor (PEF) considered for the present study

| Carrier                                | ES  | IT  | RO  | AT  | FR  | CZ  | DE  | FI  |
|----------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Electricity                            | 1.89| 2.05| 2.53| 1.65| 2.72| 3.14| 2.45| 2.69|
| Gas                                    | 1.00| 1.00| 1.00| 1.00| 1.00| 1.00| 1.00| 1.00|
| Biomass (total PEF: renewable + non-renewable part) | 1.25| 1.50| 1.50| 1.08| 1.50| 1.20| 1.50| 1.50|
| District heating                       | 1.20| 1.20| 1.20| 1.00| 1.20| 1.40| 1.20| 0.70|

Table 13 Average and standard deviation (on all target countries) of cost of technologies (material, labor, general expenditure, and business profit) for the different variation steps

| Packages                       | Building parameter | Type of building | Base renovation level average ± st. dev. | Variation step 1 average ± st. dev. | Variation step 2 average ± st. dev. | Variation step 3 average ± st. dev. |
|--------------------------------|--------------------|------------------|------------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| Opaque envelope elements       | Walls [€/m²]        | Res.             | 32 ± 23                                  | 64 ± 20                             | 72 ± 22                             | 80 ± 23                             |
|                                |                    | Non-res.         | 31 ± 22                                  | 59 ± 19                             | 70 ± 24                             | 86 ± 26                             |
|                                | Roof [€/m²]         | Res.             | No renovation⁻                         | 27 ± 12                             | 32 ± 11                             | 42 ± 12                             |
|                                |                    | Non-res.         | 51 ± 20                                  | 54 ± 48                             | 67 ± 50                             | 80 ± 52                             |
|                                | Basement [€/m²]      | Res.             | No renovation⁻                         | 37 ± 24                             | 43 ± 24                             | 52 ± 25                             |
|                                |                    | Non-res.         | No renovation⁻                         | 52 ± 27                             | 60 ± 29                             | 69 ± 30                             |
| Window systems                 | Window [€/m²]       | Res.             | 64 ± 29                                  | 277 ± 74                            | 332 ± 96                            | –                                   |
|                                |                    | Non-res.         | 64 ± 26                                  | 276 ± 69                            | 329 ± 84                            | –                                   |
| Passive cooling strategies     | Solar shading device and control [€/m² of windows] | Res.             | 201 ± 119                                | 325 ± 130                           | –                                   | –                                   |
|                                |                    | Non-res.         | 199 ± 113                                | 319 ± 124                           | 335 ± 126                           | –                                   |
|                                | Night ventilation system [€/m² of windows] | Res.             | Absent                                   | 228 ± 58                            | –                                   | –                                   |
|                                |                    | Non-res.         | Absent                                   | 119 ± 114                           | 222 ± 56                            | –                                   |
|                                | Lighting and control [€/m² of floor]     | Res.             | –                                       | –                                   | –                                   | –                                   |
|                                |                    | Non-res.         | 33 ± 12                                  | 39 ± 15                             | 69 ± 18                             | –                                   |

⁻ The rehabilitation of the finishing material of the roof do not have an influence on the thermal energy needs, because there is a unconditioned zone between the roof and the heated spaces

⁻ In school building, last slab in contact with unconditioned space; in office, roof in contact with conditioned space

⁻ Variant 1: repair and restoration existing windows

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variants were calculated assuming the same indoor conditions for each typology, specifically, the same operative temperature and relative humidity setpoints, 20 °C in winter and 26 °C in summer (latent control not applied) for the residential types and 20 °C and 25% in winter and 26 °C and 60% in summer for the non-residential buildings. The same was done for the values of minimum air change (at maximum occupation rate), coherently with the occupation levels and the ventilation design rates proposed by EN 15251 (CEN 2007b) for very low-polluted buildings, 0.5 h⁻¹ in the residential buildings, 0.8 h⁻¹ in the office, and 1.6 h⁻¹ in the school.

About the tool employed for this first step of calculation, it is useful to specify the algorithms used, the boundary condition selected, and the choices made to overcome some limitations of the software (as the evaluation of the thermal bridges). An overview of these aspects is shown in Table 10.

### Energy performance of thermal systems

The thermal systems (including all the main sub-components) were evaluated by simplified calculation methods derived from the Italian EPB standard UNI TS 11300-2 (UNI 2008) and several European reference standards: EN 15243 (CEN 2007a), EN 15316 (CEN 2007c), and EN 14825 (CEN 2012). In this way, it was possible to associate to each envelope variant a large number of alternative (and feasible) thermal plants. They were designed combining five heating and cooling generator types, two distribution variants, four heating and cooling emission systems, and two heating/cooling control options. These alternatives were considered in all

| Table 14 Average and standard deviation (on all target countries) of cost of sub-systems alternatives (material, labor, general expenditure, and business profit) |
|-----------------|-----------------|-----------------|
| **Sub-system** | **Unit**        | **Average ± st. dev.** |
| Generation systems | | |
| Gas boiler | €/kW | 151 ± 72 |
| Condensing gas boiler | €/kW | 194 ± 90 |
| Air to water reversible heat pump (with high SCOP/SEER) | €/kW | 524 ± 209 |
| Ground source reversible heat pump (with high SCOP/SEER) | €/kW | 1009 ± 325 |
| District heating connection | €/dwelling | 642 ± 240 |
| Biomass boiler | €/kW | 541 ± 108 |
| Emission systems | | |
| Insulated radiant floor | €/m² of floor | 92 ± 68 |
| Insulated radiant floor + local dehumidifier | €/m² of floor | 141 ± 68 |
| Radiator | €/m² space conditioned | 45 ± 31 |
| Fancoil/split | €/m² space conditioned | 54 ± 27 |
| Air diffuser | €/m² space conditioned | 73 ± 30 |
| Distribution systems | | |
| Insulated pipes (low) | €/m of pipe | 8 ± 4 |
| Insulated pipes (medium) | €/m of pipe | 12 ± 6 |
| Control systems | | |
| Climatic control system | €/unit | 996 ± 456 |
| Climatic + room indoor control system | €/number of rooms | 311 ± 168 |
| Solar systems | | |
| Photovoltaic panels | €/m² of solar panel | 2782 ± 386 |
| Solar thermal system | €/m² of solar panel | 812 ± 378 |

9 As discussed in several previous studies (Nicol and Humphreys 2010; Deuble and de Dear 2012; Pagliano and Zangheri 2010; Carlucci 2013), other choices (e.g., the adaptive comfort target for naturally ventilated buildings) are also possible and it may be one of the ways to reduce the energy needs for cooling with respect to those estimated in this study, while offering comfortable living and working conditions to occupants.
selected contexts with some exceptions: the gas generation and the radiant floor systems were not applied in Finland, and the district heating option was not considered in Spain, due to their very low diffusion (also in the main urban areas).

In the assessment of the final energy demands, several auxiliary design calculations were also needed. Specifically, the seasonal efficiency factor of heat pumps was calculated applying the hourly method described in the standard EN 14825 (CEN 2012). The energy demand for DHW was estimated with the method EN 15316-3-1 (CEN 2005) and considering the number of occupants already used (as thermal gains) in the dynamic simulations.

Where applicable, the energy consumption of circulating pumps (ST included) was calculated assuming their efficiency equal to 80%, estimating the pressure losses in function of the size and complexity of the different buildings and deducing the operation times from the simulation results (hourly energy needs). For the building variants in which a mechanical ventilation system was implemented, a simplified dimensioning of fan consumptions was based on an efficiency value of 60% and, in the presence of a heat exchanger, the pressure losses were increased of 300 Pa. For fancoils and splits, a specific fan power of 0.7 kW/m$^3$/s was used. In designing the power of the auxiliary systems, a safety factor of 1.2 was used.

References on the variants of thermal system are provided in Table 11.

Energy from RES

In Europe, solar energy is one of the most favorable RES (European Commission 2006) and the most
applied one to the building sector. The sun source was considered available on the roof of all building types, and four alternatives of solar systems were taken into account: (i) both solar thermal (ST) and photovoltaic (PV) absent; (ii) only solar thermal, designed to cover 50% of the energy need for hot water; (iii) only PV panels, installed on the 50% of the roof free surface (north exposition excluded) and designed to cover not more than the yearly primary energy demand of the building; and (iv) the combination of the two systems (with the previous sizing rules). A flat plate solar thermal collector 10 and a photovoltaic panel of monocrystalline silicon 11 were selected as reference technologies and fixed for all applications. A performance decay of 1% per year was applied for both technologies.

In line with the EU Commission Decision 2013/114/UE and the standard EN 15603 (CEN 2008), the renewable contribution from heat pumps and biomass generation systems was evaluated considering the first as “on-site generation from on-site renewables” and the second as “on-site generation from off-site renewables”.

The electricity generated by photovoltaic systems and exported to the grid was converted in primary energy applying the same primary energy factors used to convert the electric final demand (see below).

**Primary energy of the building variant**

To obtain the (net) primary energy demand from the final levels, appropriate primary energy factors for each considered carrier were used (Table 12). For the primary energy factors of fossil sources, biomass, and district heating, the reference values provided by the national experts were applied. Otherwise, for electricity, a dedicated analysis was developed by Enerdata using the Prospective Outlook on Long-term Energy Systems (POLES) model. 12 Price and power mix projections were derived from two scenarios of the world energy systems simulated with the POLES model, using historical data up to 2011: a “Reference” scenario and an “Ambitious” climate scenario, with the same macroeconomic context and main differences on the carbon policies.

The “Reference” scenario assumes that, once the global recession is over, business as usual behavior is resumed rather quickly. Only on-going and already planned climate policies are taken into account, including the 20% emissions reduction in the European Union by 2020. It is assumed that no consensus is reached at international level and, after 2020, it is assumed that additional energy and climate policies are adopted (EU reduces its emissions in 2050 by 50% compared to 1990 levels). Without a global agreement, these low-intensity and non-coordinated policies result in soaring CO2 emissions across the world and in emerging economies in particular. The future fuel mix is dominated by fossil fuels.

The “Ambitious” climate scenario shows a clear transition towards a long-term decarbonisation, with more ambitious efforts on energy efficiency and a real emergence of renewable technologies. Negotiations between advanced and emerging economies on climate change are eventually successful,

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10 With: overall heat loss coefficient \( U_L = 3.5 \) W/m² K; absorbance of the receiver \( \alpha = 0.95 \); transmittance of the cover systems \( \tau = 0.85 \).

11 With peak power factor of 0.15 kW/m².

12 https://ec.europa.eu/jrc/en/poles
and an international consensus is progressively reached. Europe goes beyond its −20% target by 2020, and the OECD and emerging countries meet their Copenhagen objectives. A new international agreement is adopted to reach the 2050 targets, i.e., a trajectory limiting the global temperature increase at around 2 to 3 °C by the end of the century (IPCC 2007), which implies reducing world emissions by a factor 2 by 2050 compared to 1990 levels, and by a factor of 4 for developed countries.

Under these assumptions, the residential domestic prices of oil and gas are projected to increase by respectively 5.9 and 5.2% per year in the ambitious scenario over the period 2010–2030. In the reference scenario, the progression will be lower because of lower carbon tax. The average electricity price will increase by 2% per year in the ambitious scenario and by 0.8% per year in the reference one. The electricity price is expected to peak in 2030 at around $3400/toe in the ambitious scenario and at $2500/toe in the reference scenario.
Table 16  Identification of the cost-optimal (“C-opt”) and NZEB targets, and selection of technological benchmarks (financial perspective 2011, “Reference” scenario)

| Climate and building type | Targets                | Benchmarks                        |
|---------------------------|------------------------|-----------------------------------|
|                           | (Net) primary energy   | Energy need for heating\(^a\)     | Energy need for cooling [kWh/m\(^2\)/year] | RES contribution\(^b\) [kWh/m\(^2\)/year] | Initial Investment difference with respect to BRL [%] |
|                           | [kWh/m\(^2\)/year]    | [kWh/m\(^2\)/year]               |                                           |                                           |                                                      |
|                           | BRL C-opt NZEB C-opt NZEB C-opt NZEB C-opt NZEB C-opt NZEB C-opt NZEB C-opt NZEB C-opt NZEB |                           |
| Seville (ES) SFH          | 156 25 < 10 −14 1     | 6 3 48 24 83 57 36 64            |
|                           | AB 127 35 < 25 −28 −23 | 11 3 15 12 79 68 32 17          |
|                           | Office 225 145 < 10 −5 16 | 18 4 88 37 74 58 51 110        |
|                           | School 189 83 < 10 −8 8 8 | 20 6 58 25 117 81 20 124       |
| Madrid (ES) SFH           | 236 43 < 10 −18 −1     | 30 15 32 11 107 91 66 84       |
|                           | AB 182 49 < 30 −28 −24 | 23 15 6 5 37 86 50 24          |
|                           | Office 298 124 < 10 −14 20 | 59 15 49 19 122 72 56 134     |
|                           | School 262 80 < 10 −10 6 | 71 17 21 9 179 90 40 110      |
| Rome (IT) SFH             | 193 41 < 10 −11 4      | 19 11 39 12 98 89 30 62        |
|                           | AB 157 69 < 35 −21 −9  | 7 10 24 8 40 36 23 40          |
|                           | Office 296 72 < 20 −8 13 | 12 11 37 37 3 70 27 103        |
|                           | School 357 101 < 10 −4 9 | 13 9 28 29 0 95 42 102        |
| Milan (IT) SFH            | 346 50 < 20 −26 2      | 27 27 0 0 43 116 51 126        |
|                           | AB 260 98 < 40 −53 −13 | 35 21 0 0 15 109 −6 72         |
|                           | Office 400 76 < 10 −20 −7 | 16 8 15 14 0 61 34 107        |
|                           | School 357 86 < 10 −17 −4 | 11 7 12 12 0 64 46 119        |
| Bucharest (RO) SFH        | 392 149 < 40 −19 33    | 54 33 24 4 0 154 40 181        |
|                           | AB 307 125 < 75 −27 −9  | 43 43 20 3 12 39 28 96          |
|                           | Office 379 198 < 30 −27 −8 | 80 37 48 11 38 131 1 90        |
|                           | School 381 237 < 15 −34 −1 | 108 28 23 7 8 162 −29 106     |
| Vienna (AT) SFH           | 451 97 < 30 −51 −28    | 38 30 0 0 0 98 −2 48           |
|                           | AB 344 103 < 55 −57 −32 | 52 38 0 0 13 113 −18 31        |
|                           | Office 525 75 < 10 −43 −18 | 9 11 17 5 5 49 11 70          |
|                           | School 540 77 < 15 −45 −33 | 8 12 9 0 8 47 10 57          |
| Paris (FR) SFH            | 363 126 < 30 −29 −14    | 49 36 0 0 0 177 39 89          |
|                           | AB 336 99 < 55 −27 −13  | 30 30 0 0 18 173 196 296       |
|                           | Office 493 180 < 10 −47 −35 | 80 14 15 0 188 39 9 58        |
|                           | School 452 222 < 10 −35 −10 | 110 7 6 3 324 62 34 134       |
| Prague (CZ) SFH           | 519 159 < 55 −4 33      | 65 58 0 0 0 58 201 374        |
|                           | AB 303 164 < 100 −103 722 | 0 0 38 38 8 134 79 111       |
|                           | Office 615 118 < 25 −42 −34 | 19 26 10 0 4 40 79 111        |
|                           | School 579 110 < 10 −38 −12 | 28 35 0 0 8 72 154 305       |
| Berlin (DE) SFH           | 348 85 < 40 −30 −36    | 36 30 0 0 37 130 39 114        |
|                           | AB 319 161 < 70 −38 −29 | 47 47 0 0 22 189 31 45         |
|                           | Office 442 68 < 15 −40 −29 | 13 17 9 0 28 87 62 89        |
|                           | School 398 49 < 20 −22 −2 | 23 26 0 0 50 58 128 198       |
| Helsinki (FI) SFH         | 203 76 < 65 −6 −4      | 80 72 0 0 42 42 100 110        |
|                           | AB 195 219 < 95 −19 −13 | 52 52 0 0 0 29 162 163        |
|                           | Office 371 109 < 35 −56 −34 | 31 28 0 0 27 27 72 131        |
|                           | School 339 179 < 30 −47 −25 | 48 20 0 0 0 55 70 154        |

\(^a\) If present, the reduction due to heat recovery strategies is taken into account

\(^b\) From thermal panels, PV systems and heat pumps, if present. This amount includes self-consumed and exported electricity
Calculating the global cost

The global costs associated to each building variant were estimated over a period of 30 years, including the capital costs (initial investment) for renovation, the costs for the substitution of building elements with a lifetime lower than 30 years, the annual maintenance costs, the operating energy costs, the disposal costs, and the final value of considered technologies. Considering a financial perspective, the applicable taxes were considered and all cost items were discounted to 2011 with real interest rates typical of the contexts taken into account and based on the EUROSTAT statistics. The equation of global cost can be written as (Eq. 1):

\[
C_G(\tau) = C_I + \sum_f \sum_{i=1}^\tau \left( C_{a,f}(j) \times R_d(i) \right) - V_{f,j}(\tau) \tag{1}
\]

with \(C_G(\tau)\) the global cost referred to the starting year \(\tau_0\), \(C_I\) the initial investment costs, \(C_{a,f}(j)\) the annual cost for component \(j\) at the year \(i\), \(R_d(i)\) the discount rate for year \(i\), and \(V_{f,j}(\tau)\) the final value of component \(j\) at the end of the calculation period.

The costs over the calculation period were discounted by means of the discount factor \(R_d\), which is calculated as (Eq. 2):

\[
R_d(p) = \left( \frac{1}{1 + \frac{r}{100}} \right)^p \tag{2}
\]

where \(p\) is the number of years of the period and \(r\) is the real interest rate.

The cost database, on which the calculation was done, was populated involving national experts who have provided data for the costs of materials, building elements, and related labor. The experts referred mainly to two types of references: existing national (or regional) databases derived from large market-based data gathering and analysis of available data from recent renovation projects and standard commercial offers. In these data collection activity, the main complementary works associated to each refurbishment action were taken into account (e.g., renovation of the doorsteps due to interventions on the floors and suspended ceiling modification associated with the installation of an air distribution system).

References on the cost data collected are provided in Tables 13 and 14 for all technologies already introduced above. About this, it is important to notice that significant deviations among countries were observed for some technologies. This reflects the economic differences of the contexts considered, from which the cost of labor mainly depends, but also the lack of harmonization between the national references used.

Also, in the global cost calculations, several assumptions were needed and, instead of using the estimated long-term energy price developments proposed by the Commission Guidelines (European Parliament 2012a, b), the POLES scenarios were applied also for foreseeing the energy prices over the calculation period. They are shown in Fig. 4.

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13 It has to be noticed that this calculation period was used for both residential and non-residential building types, in order to obtain comparable results. This choice introduces a difference with respect to the methodology described in the Commission’s Guidelines, which sets at 20 years, the calculation period for non-residential buildings.

14 http://epp.eurostat.ec.europa.eu/
Table 17  Envelope transmittances of the benchmarks selected in the cost-optimal and NZEB areas for each building type and climate. For opaque surfaces, $U$ values greater than 0.6 W/m² K refer to the original (not renovated) elements.

| Climate and building type | Envelope thermal transmittance [W/m² °K] |
|---------------------------|------------------------------------------|
|              | Cost-optimal | NZEB         |             | Window | Wall | Roof | Basement | Window |             |             |             |             |
|              | Wall | Roof | Basement | Window | Wall | Roof | Basement | Window |             |             |             |             |
| Seville (ES) | SFH  | 0.31 | 0.33 | 0.31 | 2.60 | 0.31 | 0.33 | 0.31 | 1.71 |             |             |             |             |
|              | AB    | 0.31 | 0.33 | 0.31 | 5.83 | 0.22 | 0.23 | 0.22 | 1.69 |             |             |             |             |
|              | Office | 1.37 | 1.29 | 1.54 | 2.72 | 0.16 | 0.13 | 0.20 | 2.11 |             |             |             |             |
|              | School | 0.46 | 0.53 | 0.55 | 5.85 | 0.28 | 0.21 | 0.31 | 2.10 |             |             |             |             |
| Madrid (ES) | SFH  | 0.31 | 0.23 | 0.50 | 2.60 | 0.18 | 0.12 | 0.22 | 1.71 |             |             |             |             |
|              | AB    | 0.31 | 0.23 | 0.50 | 2.58 | 0.18 | 0.12 | 0.22 | 1.69 |             |             |             |             |
|              | Office | 1.37 | 1.29 | 1.54 | 2.72 | 0.16 | 0.13 | 0.20 | 2.11 |             |             |             |             |
|              | School | 1.37 | 2.19 | 2.57 | 2.71 | 0.16 | 0.13 | 0.21 | 2.10 |             |             |             |             |
| Rome (IT)   | SFH  | 0.30 | 0.32 | 0.32 | 2.60 | 0.22 | 0.23 | 0.23 | 1.71 |             |             |             |             |
|              | AB    | 0.30 | 0.32 | 0.32 | 1.69 | 0.22 | 0.23 | 0.23 | 1.69 |             |             |             |             |
|              | Office | 0.27 | 0.20 | 0.29 | 2.11 | 0.15 | 0.13 | 0.21 | 2.11 |             |             |             |             |
|              | School | 0.27 | 0.20 | 0.29 | 2.10 | 0.15 | 0.13 | 0.21 | 2.10 |             |             |             |             |
| Milan (IT)  | SFH  | 0.17 | 0.12 | 0.23 | 1.71 | 0.17 | 0.12 | 0.23 | 1.71 |             |             |             |             |
|              | AB    | 0.22 | 0.18 | 0.32 | 1.69 | 0.17 | 0.12 | 0.23 | 1.69 |             |             |             |             |
|              | Office | 0.27 | 0.20 | 0.29 | 0.77 | 0.13 | 0.13 | 0.21 | 0.77 |             |             |             |             |
|              | School | 0.27 | 0.20 | 0.29 | 0.77 | 0.13 | 0.13 | 0.21 | 0.77 |             |             |             |             |
| Bucharest (RO) | SFH | 0.22 | 0.18 | 0.30 | 1.03 | 0.18 | 0.12 | 0.22 | 1.03 |             |             |             |             |
|              | AB    | 0.18 | 0.12 | 0.22 | 1.03 | 0.18 | 0.12 | 0.22 | 1.03 |             |             |             |             |
|              | Office | 1.34 | 1.01 | 1.10 | 2.11 | 0.12 | 0.10 | 0.19 | 0.77 |             |             |             |             |
|              | School | 1.34 | 0.70 | 1.10 | 2.10 | 0.12 | 0.10 | 0.19 | 0.77 |             |             |             |             |
| Vienna (AT) | SFH  | 0.22 | 0.17 | 0.33 | 1.71 | 0.17 | 0.12 | 0.23 | 1.03 |             |             |             |             |
|              | AB    | 0.17 | 0.12 | 0.23 | 1.03 | 0.17 | 0.12 | 0.23 | 1.03 |             |             |             |             |
|              | Office | 0.15 | 0.15 | 0.27 | 0.77 | 0.11 | 0.11 | 0.20 | 0.77 |             |             |             |             |
|              | School | 0.16 | 0.16 | 0.27 | 0.77 | 0.16 | 0.16 | 0.27 | 0.77 |             |             |             |             |
| Paris (FR)  | SFH  | 0.32 | 0.22 | 0.57 | 1.71 | 0.18 | 0.12 | 0.24 | 1.71 |             |             |             |             |
|              | AB    | 0.18 | 0.13 | 0.24 | 1.69 | 0.18 | 0.13 | 0.24 | 1.69 |             |             |             |             |
|              | Office | 1.06 | 1.65 | 3.44 | 2.11 | 0.12 | 0.11 | 0.22 | 0.77 |             |             |             |             |
|              | School | 1.17 | 1.57 | 1.74 | 2.11 | 0.13 | 0.11 | 0.21 | 0.77 |             |             |             |             |
| Prague (CZ) | SFH  | 0.22 | 0.17 | 0.30 | 1.03 | 0.17 | 0.12 | 0.22 | 1.03 |             |             |             |             |
|              | AB    | 0.63 | 0.65 | 1.24 | 2.66 | 0.17 | 0.11 | 0.22 | 1.03 |             |             |             |             |
|              | Office | 0.15 | 0.09 | 0.22 | 0.78 | 0.15 | 0.09 | 0.22 | 0.78 |             |             |             |             |
|              | School | 0.16 | 0.10 | 0.22 | 0.77 | 0.16 | 0.10 | 0.22 | 0.77 |             |             |             |             |
| Berlin (DE) | SFH  | 0.21 | 0.17 | 0.29 | 1.03 | 0.16 | 0.12 | 0.21 | 0.70 |             |             |             |             |
|              | AB    | 0.16 | 0.12 | 0.23 | 0.70 | 0.16 | 0.12 | 0.23 | 0.70 |             |             |             |             |
|              | Office | 0.16 | 0.14 | 0.27 | 0.77 | 0.11 | 0.10 | 0.19 | 0.77 |             |             |             |             |
|              | School | 0.16 | 0.15 | 0.27 | 0.77 | 0.11 | 0.10 | 0.19 | 0.77 |             |             |             |             |
| Helsinki (FI) | SFH  | 0.17 | 0.12 | 0.48 | 1.03 | 0.17 | 0.09 | 0.48 | 0.70 |             |             |             |             |
|              | AB    | 0.17 | 0.10 | 0.48 | 1.03 | 0.17 | 0.10 | 0.48 | 0.70 |             |             |             |             |
|              | Office | 0.09 | 0.09 | 0.16 | 0.78 | 0.13 | 0.12 | 0.21 | 0.78 |             |             |             |             |
|              | School | 0.14 | 0.12 | 0.23 | 0.77 | 0.10 | 0.09 | 0.17 | 0.77 |             |             |             |             |
Where PV systems were installed, two different economic values were associated to the self-consumed and the exported electricity: the market price was used to the self-consumed energy (i.e., an avoided electric consumption); a lower value was considered for the exported electricity instead (i.e., the 35% of the market price). Taking into account that this differentiation does not have an impact on the energy performance calculations (because a different primary energy factor was not used for the exported electricity), it was assumed that 50% of electricity yearly generated was self-consumed in the building by the electric loads of thermal systems and lighting. The remaining 50% was evaluated as exported to the grid. The influence of this simplifying
as the minimum (net) primary energy level within the interval (often quite large) with a global cost lower than the absolute minimum one increased by 3%. Otherwise, the NZEB target was obtained incrementing by 10 kWh/m$^2$/year the minimum primary energy achieved by the best building variant (from the energy point of view). The incremental factors (3% for global cost, 10 kWh/m$^2$/year for NZEB, as well as those discussed below) are not provided by the Commission Guidelines or by other references. They were defined so as to be suitable for defining targets accessible to different retrofit options.

To provide exemplary technological benchmarks (i.e., packages of exemplary retrofit options satisfying the targets), a portion of the Energy-Cost domain was studied for both targets. These areas are limited inferiorly by the lower frontier of cost-energy cloud (i.e., the profile of cost-optimality), and they were defined applying a range of $\pm 5$ kWh/m$^2$/year in net primary energy and an upper limit of cost equal to the minimum global cost for the specific target increased by 10%. These factors were chosen for identifying areas populated by a number of building variants neither too small nor too big (i.e., about 20–50).

To apply the EPBD principle of priority of efficiency solutions involving the building envelope, the building variants within these areas were further filtered. Firstly, only the cases with energy needs for heating and cooling lower than the minimum value incremented by 10 kWh/m$^2$/year were considered. Then, the resulting variants were statically analyzed to recognize the more frequently occurring technologies. If the result obtained was not representative of any real variant present in the studied area, priority was given firstly to the most recurrent envelope combination and then to those relative to thermal systems and RES technologies.

Results and discussion

Main results

The main aim of this study is to find possible targets of (net) primary energy representative of the cost-optimal and nearly zero-energy levels and to provide examples
of the associated complete retrofit solutions (i.e., technological benchmarks), for all climates (10) and building types (4).

In accordance with the methodology described in the previous section, 40 data sets were plotted on the Energy-Cost plane, obtaining 40 characteristic clouds. For example, Fig. 6 shows the results obtained in terms of annual (net) primary consumption (x-axis) and global costs (y-axis) for the apartment block in Vienna.

The analysis of clouds allows deriving some key references. Table 16 provides an overview of results obtained for each building type in each climate. The section “Targets” shows the energy levels associated to three characteristic points of every cloud (i.e., base refurbishment level, cost-optimal target, and NZEB target), as well as the percentage difference between the global costs calculated for the targets with respect to the BRL. The section “Benchmarks” shows the main energy performance of the specific building variants (i.e., retrofit solutions) selected within the cost-optimal and NZEB areas, as well as the percentage difference between the investment costs of these variants with respect to the BRL. All these results refer to the financial perspective with base year 2011 and to the “Reference” scenario discussed above.

About the targets shown, it is interesting to observe that the cost-optimal levels imply an average reduction of 66% in primary energy and of 27% in global costs, with respect to the base refurbishment levels. Maximum values of net primary energy for the NZEB targets 18 of 40, 75, and 100 kWh/m² were recognized as obtainable respectively for the South, Central, and North European areas. Often (27 times out of 40), the NZEB levels result economically more advantageous (lower global costs) than the base renovation Levels, especially in the Central-North Europe.

About the investment costs—the main barrier to the widespread diffusion of efficient refurbishments—it has to be noticed that their average increases with respect to the BRL for the cost-optimal and NZEB targets are respectively of 50 and 115%. However, some results demonstrate the possibility to reduce the base refurbishment investment costs, moving towards cost-optimal solutions. For instance, this is the case of the residential types located in Milan and Vienna, where the improvement of the building envelopes allows avoid the expenditure related to the installation or substitution of an active cooling system.

Interesting are also the cases of the apartment blocks located in Spain (Seville and Madrid), where the NZEB benchmarks have a lower investment cost of the cost-optimal ones. However, in spite of the fact they also have lower energy running costs, the global

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18 These maximum values are always associated to the apartment block type that shows a lower energy saving potential due to geometric limits (e.g., lower available roof surface for solar systems).
Table 19  Influence of the boundary conditions on the cost-optimal targets, in terms of percentage difference in (net) primary energy with respect to the reference condition (financial perspective with starting year 2011 and “Reference” scenario)

| Climate and building type | Financial perspective | Macroeconomic perspective |
|---------------------------|-----------------------|--------------------------|
|                           | “Ambitious” (%)       | “Reference” (%)          | “Ambitious” (%)          |
| Seville (ES) SFH          | −13                   | 19                       | −13                      |
| AB                        | −8                    | 7                        | −8                       |
| Office                    | =                     | =                        | −10                      |
| School                    | −22                   | =                        | −20                      |
| Madrid (ES) SFH           | −19                   | 10                       | −37                      |
| AB                        | −12                   | =                        | −16                      |
| Office                    | =                     | =                        | 29                       |
| School                    | =                     | =                        | −36                      |
| Rome (IT) SFH             | −20                   | 7                        | −35                      |
| AB                        | −13                   | =                        | −30                      |
| Office                    | −68                   | 10                       | −74                      |
| School                    | −19                   | =                        | −43                      |
| Milan (IT) SFH            | −13                   | =                        | −21                      |
| AB                        | −17                   | −8                       | −17                      |
| Office                    | −70                   | −15                      | −88                      |
| School                    | −25                   | =                        | −33                      |
| Bucharest (RO) SFH        | −36                   | =                        | −49                      |
| AB                        | −7                    | =                        | =                        |
| Office                    | −72                   | =                        | −63                      |
| School                    | −50                   | =                        | −30                      |
| Vienna (AT) SFH           | −9                    | −9                       | −17                      |
| AB                        | −10                   | =                        | −14                      |
| Office                    | −26                   | −6                       | −22                      |
| School                    | −25                   | =                        | −14                      |
| Paris (FR) SFH            | −25                   | −10                      | −16                      |
| AB                        | −24                   | =                        | −15                      |
| Office                    | −73                   | =                        | −16                      |
| School                    | −58                   | −33                      | −36                      |
| Prague (CZ) SFH           | −14                   | =                        | −45                      |
| AB                        | =                     | =                        | =                        |
| Office                    | −19                   | =                        | −36                      |
| School                    | =                     | =                        | −43                      |
| Berlin (DE) SFH           | −12                   | =                        | =                        |
| AB                        | −7                    | =                        | −7                       |
| Office                    | −22                   | =                        | −18                      |
| School                    | −11                   | 79                       | 19                       |
| Helsinki (FI) SFH         | −14                   | −9                       | −14                      |
| AB                        | =                     | =                        | =                        |
| Office                    | =                     | =                        | −13                      |
| School                    | −8                    | −40                      | −26                      |

“=” no relevant variation (range between ± 5%)
costs are slightly higher than the cost-optimal retrofit solution. This can be explained by analyzing the other cost items considered in the calculation. As shown in Fig. 7, the NZEB benchmarks have higher replacement and maintenance costs, also because of retrofit solutions with lower lifespan (e.g., fancoils) compared to more expensive alternatives (e.g., radiant floor). This type of result is due to the contingent proximity between the cost-optimal and NZEB areas for these Spanish cases, but it is also symptomatic of the methodology applied (i.e., non based on multi-stage optimization techniques).

In general, the NZEB area appears characterized by medium-high and high recurrences of efficiency and RES technologies in all countries and for both the building destinations. For instance, a typical NZEB building has a well-insulated envelope (including insulation layers of 10–30 cm and double or triple low-e windows), efficient generators (e.g., condensing boiler or ground source heat pump or district heating) in some case assisted by heat recovery strategies, and renewable solar systems installed (normally both thermal and photovoltaic). More details are provided below in Tables 17 and 18 for each building and climatic condition.

Otherwise, the cost-optimal benchmarks are more heterogonous. Various are the retrofit solutions able to reach this target, that overall is characterized by the competition between the deepest actions regarding envelope, thermal systems, and solar renewable systems. Figure 8 provides a qualitative overview of cost-optimal benchmarks which are classified in function of their strengths. As expected, it is difficult to minimize the global costs applying a high-performance envelope, very efficient generators, a heat recovery strategy, and a PV plant at the same time. This occurs only for the single-family houses located in Milan, Berlin, and Helsinki, which lie in the intersection of all sets.

Filtering also on the energy needs for heating and cooling (as discussed above), more than half (23 cases) of the benchmarks obtained are characterized by
medium-high levels of insulation (10–20 cm) and by double or triple glazing low-e windows. In 16 cases, the deep grade renovation of envelope is coupled with the installation of an efficient generators (condensing boiler or ground source heat pump or connection to district heating). Only for four residential building variants, there is also the presence of heat recovery strategies and photovoltaic generation. Among these, it is interesting the case of the single house in Milan, where the cost-optimal variant results those with the best envelope solutions\(^\text{19}\) because it avoids the need for active cooling systems. Differently, for other South European types (particularly in the Spanish contexts, where the saving potential of envelope strategies is lower and the solar radiation is higher), the cost-optimal level can be represented by medium-low envelope renovations compensated by photovoltaic systems.

About the thermal systems, normally, both cost-optimal and NZEB targets require the substitution of the original thermal generators with more efficient technologies and the insulation of distribution pipes. Particularly, in the cost-optimal area, the penetration of simple system layouts is favored (e.g., reversible heat pump coupled to a single distribution and emission system). Otherwise, the mechanical ventilation strategies (often associated to heat recovery) can get into economic competition with envelope and RES solutions, also in the NZEB area.\(^\text{20}\) Medium-low temperature emission systems for heating often occur both in the NZEB and cost-optimal areas. In some climate contexts, biomass and district heating systems occur with low frequency in the benchmark areas. This might be due also to difficulties in defining the actual primary energy factors, the investment costs (due to different installation conditions), and the energy prices (due to private negotiation).

RES technologies represent a key strategy to reach the zero-energy target in all the analyzed contexts (e.g., also for the residential buildings of Berlin). Moreover, the more efficient lighting strategies appear always a good intervention to reach NZEB area, especially in office buildings.

Being a crucial aspect of the EPBD framework, in order to provide more detailed information about the features of the selected retrofit solutions, the thermal transmittances obtained for the main envelope elements are presented in Table 17 and qualitative indications of thermal systems adopted are shown in Table 18, for both the cost-optimal and NZEB areas.

### Sensitivity analysis

In compliance with the EU cost-optimal Regulation\(^\text{21}\) (European Parliament 2012a, b), it is interesting to study the influence of some key input data on the main calculation results. As discussed above, in the present study, the macroeconomic perspective was also evaluated and two energy price scenarios (“Ambitious” besides “Reference”) were considered.

\(^{19}\) With automatized night natural ventilation and high-performance solar shading systems, as well as high insulation levels and very low infiltrations during the day.

\(^{20}\) In this study, the penetration of mechanical ventilation with or without heat recovery, is compared with a good user behavior of occupants, who correctly open windows when air changes are needed, avoiding excessive openings. This helps to obtain natural ventilation solutions in the cost-optimal and sometimes also in the minimum net primary energy area more often with respect to mechanical ventilation. Clear real time signals on IAQ and training of occupants, in this way, could be a cost-effective strategy to reduce the initial investment, annual, and energy costs, without reducing the indoor air quality.

\(^{21}\) “Member States shall undertake an analysis to determine the sensitivity of the calculation outcomes to changes in the applied parameters, covering at least the impact of different energy price developments and the discount rates for the macroeconomic and financial calculations, ideally also other parameters which are expected to have a significant impact on the outcome of the calculations such as price developments for other than energy” (Article 3).
In order to provide a quantitative overview of the influence of these standpoints on the lower frontier (i.e., the optimal frontier) of the Energy-Cost clouds, the changes of the cost-optimal targets are reported in Table 19. In general, the higher energy price scenario (“Ambitious”) increases the global costs (mainly composed of initial investment and running costs due to energy) of the less efficient variants and leads to a lower value of net primary energy for the cost-optimal level. Not considering taxes and introducing the prices for CO₂ emissions, as required by the macroeconomic perspective, the global costs of the more efficient refurbishments decrease, moving again the cost-optimal target towards the NZEB one. These effects are shown for an exemplary case in Fig. 9.

The higher energy price scenarios increase the minimum global cost range and lead to a lower value of net primary energy for cost-optimal levels, as well as the increase of prices for CO₂ emissions (and eventual costs related to environmental damages or other externalities). In some cases, the cost-optimal profiles are very flat and this can imply that a moderate change of input data results in a significant variation of outputs.

As discussed by Boermans et al. (2011), the assumed development of energy prices is one of the most critical input data because many energy prices have a strong national (or regional or even local) influence and the forecasts have to take into account expected longer-term political and economic developments. Moreover, its overall influence on the final results is not necessarily linear, and indeed discontinuities can be observed. For instance, referring again to the identification of the cost-optimal target, this is the case of our school located in Paris and mostly the office in Milan (Fig. 10). Here, varying all energy prices (i.e., electricity and natural gas) by the same annual developments in the range −1/6%, the optimum selection procedure reveals a pronounced discontinuity between 2 and 3%. This effect is more relevant for those building types characterized by a cost-optimal frontier very flat.

Other calculation parameters for which a sensitivity analysis is recommended by the EC Regulation are the real interest rate and the calculation period. For these variables, a more linear dependency was observed, as shown in Fig. 11 for the example of the office located in Milan. As expected, the cost-optimal target increases with increasing real interest rate because the future economic savings (greater for low net primary energy levels) are more discounted at high interest rates. Otherwise, the target decrease with increasing the calculation period until the thirtieth year and slightly increase after, because of the periodic costs for replacement occurring at year 31,22 which are greater for the more efficient renovation packages.

Because of the assumption made on the self-consumption of the electricity generated on-site by the photovoltaic systems (set to 50% for all building types), it is interesting to evaluate the influence of this variable of the final results. As shown below for the critical case of the Milanese office (Fig. 12), a minor influence was observed, especially in the range 45–70%.

Conclusions

The first cost-optimal calculations of the European Member States23 have been recently evaluated by the European Commission (Boermans et al. 2015; Zirngibl and Bendzialova 2015), and it is quite evident that different interpretations of the procedure prescribed by the EPBD framework were adopted. The present large-scale study provides reliable references obtained under common boundary conditions and calculation assumptions for a representative sample of the EU-28 area. The quantitative results found here for the refurbishment sector are obviously depending on the typologies of selected buildings, but they allow a direct comparison between a high number of climatic and economic contexts across the EU.

Taking as reference the existing buildings of 60s–70s, the energy saving potential of found cost-optimal

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22 According to Standard EN 15459 (CEN 2007d), a lifetime of 30 years was considered to the majority of envelope technologies.

23 The MS’s reports are available on http://ec.europa.eu/energy/en/topics/energy-efficiency/buildings
targets are very relevant (36–88% in term of net primary energy) for all analyzed cases and the achieved NZEB levels resulted interesting also from an economic point of view: their global costs (over 30 years) are often lower than the respective base refurbishment levels (as defined in this study) and never greater than 33%.

While a further recast of EPBD has been announced and it is under approval, it is interesting to observe that the EPBD framework provides a useful guidance for cost-optimal calculations. However, to achieve a more uniform implementation in the Member States (or at least to improve the comparison possibilities), more detailed indications would be needed and some boundary conditions should be better defined. Taking into account the methodology developed within this study and the application to a quite large amount of building types and climatic/economic conditions, some suggestions can be provided.

The method used to calculate the energy demands associated to the building renovations provides a good compromise between detail and simulation effort, for this type of study. The preliminary choice to develop the analysis avoiding search-optimization techniques makes an easier comparison between retrofit options (sometimes competing among themselves) and allows an easier assessment of the influence of the main calculation parameters. However, the high number of building variants can complicate the analysis and interpretation of final results, which depend on many calculation factors.

The comparison of the retrofit variants in the primary energy/global costs domain allows identifying quite clearly some reference targets and technical solutions that can guide the development of new energy requirements and targeted policy. However, the clouds (or curves) obtained cannot show explicit information about the energy needs for the different energy end-uses of a building and the initial investment costs of a renovation action. Details about these aspects should be explicitly requested by the procedure and references about the priority of technologies taken into account for the selection of benchmark should be clarified.

While, for new buildings, it is quite simple to define a reference building variant (e.g., the one that meets the current energy requirements), this aspect is not fully regulated for existing buildings. For the calculation experience here reported, the concept of base refurbishment level was introduced to obtain homogeneous building variants (in terms of functionality, esthetic aspect, and comfort levels) and to recognize which costs could be omitted. This baseline has proved a useful reference for a direct evaluation of the results, and it should be proposed for further applications of the EPBD calculation framework.

As a function of the cost range chosen, the cost-optimal area can be very wide in terms of net primary energy range and the simple encouragement for the minimum target of (net) primary energy could represent a too soft indication that could introduce discrepancies between the analyses of the different Member States. The choice of the cost range should be standardized: in this study, an increment of 3% was applied on the minimum value of global cost.

The collection of consistent and reliable data for costs associated to the renovation actions is undoubtedly one of the most critical steps of this kind of analysis. Because erroneous data or non-homogeneous database may have a substantial influence on the final results, solid references should be defined and provided to Member States by the European Commission. As starting point, the national databases used for the first run of cost-optimal calculations done by the Member States, as well as those developed within parallel studies (as the one discussed here), should be considered.

The EU cost-optimal methodology focuses on the building variants of the lower frontier of the Energy-Cost clouds. Of course, this part of the graphs represents the most profitable solutions in terms of global costs, but also the variants with higher global costs might represent interesting solutions in terms of environmental value or energy efficiency solutions that might reach the cost-optimal area if supported with incentive policies. To evaluate this possibility, it is essential to define as much as possible the Energy-Cost clouds, rather than limiting the analysis to optimization procedures able to produce only the cost-optimal curve.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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