Comparing cost-optimal and net-zero energy targets in building retrofit

Marco Ferreira, Manuela Almeida, Ana Rodrigues and Sandra Monteiro Silva

Department of Civil Engineering, University of Minho, Campus de Azurém, Guimarães, Portugal
E-mails: marcoferreira@civil.uminho.pt, malmeida@civil.uminho.pt, anarocha32846@yahoo.co.uk and sms@civil.uminho.pt

The recast of the European Union’s Energy Performance of Buildings Directive introduced the concept of nearly zero-energy buildings, requiring its adoption from 2021 by all new buildings and existing ones submitted to major renovations. European Union member states must also ensure minimum energy requirements for buildings in order to achieve cost-optimal levels during their life cycle. Cost optimality and nearly zero-energy buildings are important concepts in European Union energy policies. These concepts are related, but one is more focused on costs, while the other is more concerned with low energy consumption and on-site-renewable energy harvesting. If these approaches result in major differences in the selection of the best package of retrofit measures, then the transition from the cost-optimal concept to nearly zero-energy buildings might be problematic. To assess the most cost-effective solutions to achieve net-zero, a building in Porto, Portugal, was analysed. This determined not only the most cost-effective retrofit solutions but also compared these net-zero solutions with those resulting from the cost-optimal calculation. Both approaches lead to similar results, indicating that the transition between ‘cost optimality’ to ‘nearly zero-energy buildings’ could occur in Portugal.

Keywords: building renovation, cost optimization, energy efficiency, nearly zero-energy buildings, net-zero, retrofit

Introduction

The reduction of greenhouse gas (GHG) emissions, as required by the Kyoto protocol, has become an important goal for the European Commission (EC). Therefore, policies have been created to make sure that European Union (EU) member states do their best to achieve gradually the values established by the protocol (European Commission, 2006).

GHG emissions have different origins, such as industry, transport, buildings, agriculture etc., but the building sector is responsible for roughly 40% of the energy consumption and 32% of the GHG emissions in Europe (Boermans, Hermelink, Schimschar, Grözinger, & Offermann, 2011). These numbers make buildings an important target for the reduction of GHG emissions (EC, 2012a). Therefore, the improvement of buildings’ energy performance is an important part of the EU energy 2020 (European Parliament and the Council of the European Parliament, 2010) and 2030 targets (EC, 2014). This also informs the roadmap for moving towards a competitive low-carbon economy in 2050 (EC, 2011).

In an effort to tackle this problem, the recast of Energy Performance of Buildings Directive (EPBD-recast) (European Parliament and the Council of the European Parliament, 2010) introduced the concept of nearly zero-energy buildings. For new buildings, this implies a very high level of energy performance and low energy demand that must be supported by renewable energy sources harvested on-site, after the end of 2020 (Boermans et al., 2011).

The nearly zero-energy buildings’ performance is achieved by: reducing the energy needs of buildings through passive approaches (improving insulation levels, optimizing solar gains, using external shading systems and night cooling etc.); selecting efficient appliances and systems (lighting, heating, cooling, ventilation systems); and on-site production of renewable energy to reduce the remaining (very low level of energy consumption) non-renewable energy use. Solar thermal and photovoltaic (PV) systems as well as geothermal and biomass energy sources are the most common renewable energy sources used in buildings.
The EU targets for 2020 are a 20% reduction in energy consumption, a 20% reduction in GHG emissions and a 20% increase in renewable energy use (European Parliament and the Council of the European Parliament, 2010). By 2030, the EU is committed to reducing domestic GHG emissions by 40% when compared with the 1990 level (EC, 2014). This target will ensure that the EU is on a cost-effective track towards meeting its objective of cutting emissions by at least 80% by 2050. The EC also proposes an objective of increasing the share of renewable energy to at least 27% of the EU’s energy consumption by 2030 (EC, 2014).

However, despite these efforts, the EU will only achieve its goals with an intervention that includes the existing building stock, as the replacement rate of existing buildings by new energy-efficient ones is very small (1–2% per year) in all its member states (EC, 2011). There is a presumption and need for these requirements to be applied not only to new buildings but also to the existing ones.

The EPBD-recast also requires that buildings have to be cost-effective during their life cycle and establishes a method for cost-optimal calculations. This method is intended to guide member states in the process of establishing minimum energy requirements for buildings and buildings components (Boermans et al., 2011; EC, 2012b). This is still an ongoing process in almost all EU member states as many countries are late in delivering this information that was due in 2012.

Therefore, ‘cost optimality’ and ‘nearly zero-energy buildings’ are two fundamental concepts within the current EU policy related to the energy performance of buildings and consequently related to climate change mitigation and non-renewable resources consumption. While cost optimality is mainly focused on costs, nearly zero-energy buildings are focused on low energy consumption levels and on-site use of renewable energy.

If the differences between cost optimal and nearly zero-energy buildings approaches result in major differences in the selection of the best package of retrofit measures, then the transition from the cost-optimality concept to nearly zero-energy buildings may not occur.

Despite the efforts, even in countries that are considered as examples in implementing energy-efficiency measures (e.g. Germany), homeowners are thermally retrofitting their houses at a considerably slower rate and depth of thermal improvement than has been planned and expected in German federal policy for the residential sector (Galvin, 2014).

According to Galvin (2014), this can be partly explained due to mismatches between policy, the nature of existing residential buildings and by the normal financial aspirations of homeowners.

Austrian, Belgian, Dutch, French, British and German studies show the existence of differences between the calculated heating energy consumption of homes (and the energy rating) and the measured heating energy consumption (Cayre, Allibé, Laurent, & Osso, 2011; Haas & Biermayr, 2000; Hens, Parijs, & Deurinck, 2010; Kelly, 2011; Sunikka-Blank & Galvin, 2012; Tigchelaar & Menkveld, 2011).

Although it is generally recognized that energy efficiency is the cheapest way of reducing carbon emissions, the renovation of existing buildings is an opportunity to improve the energy performance of buildings that is frequently missed (BPIE, 2011). This happens due to the higher initial costs but also because of the lack of know-how and awareness (from owners, tenants and stakeholders) regarding cost-effectiveness of the energy retrofit measures (Battiaux, Gram-Hansen, Fonseca, Ozoliņa, & Christensen, 2014), especially if a life cycle cost approach is considered and ancillary benefits of energy retrofit measures are taken into account.

The challenge is thus to develop and select cost-effective strategies for increased efficiency and deployment of renewable energy to achieve the best building performance (less energy use, fewer carbon emissions, overall added value achieved by the retrofit) at the lowest effort (investment, life cycle costs, intervention in the building, users’ disturbance) in retrofit procedures.

In building retrofit, meeting nearly zero-energy targets mainly by reducing the energy demand of the building, increasing the energy performance of the building envelope, will not be easy or cost-effective. Taking costs into consideration, cost optimality is often achieved at levels far from nearly zero-energy levels (BPIE, 2013; Kurnitski, 2013). From there it is often more cost-effective to use renewable energy sources (if economically available) than to strive for reducing energy demand.

At the same time, in many cases the use of renewable energy sources is not only cost-effective but also leads to significant reductions in emissions and in non-renewable energy use, even if the effects on total primary energy use are small.

In this context, the aim of this paper is to analyse the most cost-effective packages of retrofit measures for achieving a building with zero energy balance and to compare these packages with those resulting from the calculation of cost-optimal levels. The zero energy balance means that the building only uses energy from renewable sources or, if using non-renewable...
energy, it also harvests on-site energy from renewable sources equivalent to the non-renewable energy used. This definition, for grid-connected buildings, is commonly referred as net-zero energy building and it is used in this study because the nearly zero-energy building definition contains uncertainties regarding the meaning of ‘nearly’ (allowed distance to zero) and the boundary for the balance.

A typical multifamily building is chosen for this study. It is representative of the Portuguese housing stock and was built in the 1990s at the time of the implementation of the first thermal regulation. An investigation of the trade-offs between a retrofit for a net-zero energy balance and a cost-optimal retrofit without energy use restrictions is relevant to achieve a smooth transition from cost-optimal levels to nearly zero-energy buildings. This investigation is also important as it might provide insights into the elaboration of national plans to promote nearly zero-energy buildings through an appropriate financial support mechanism and the creation of clear legal instruments.

Methods for calculating cost-optimal and net-zero

The cost-optimal calculations are based on the cost-optimal method introduced by the EC Delegated Regulation (EU) No. 244/2012 of 16 January 2012, supplementing Directive 2010/31/EU of the European Parliament and of the Council on the Energy Performance of Buildings (EC, 2012a, 2012b).

In accordance with this method, the first step in determining the cost-optimal solutions for a net-zero primary energy use and zero-carbon emissions retrofit entails an assessment of different retrofit measures for the building envelope (insulation, etc.) and the building systems. Single-retrofit measures are combined into coherent combinations (or packages) of retrofit measures. The application of each package creates a retrofit scenario for that building. Different retrofit scenarios have been tested, involving improvements in the building envelope and the replacement of the heating, cooling and domestic hot water (DHW) systems. For each retrofit scenario, the non-renewable primary energy use is calculated, as well as the net present value (NPV) of the global costs (including investment costs, maintenance costs and energy-related costs) for the calculation period.

The core of the method is the identification of the cost-optimal level of the building’s energy performance. This can be achieved by comparing different retrofit scenarios. Based on the non-renewable primary energy calculations and on the global costs for each of the retrofit scenarios, graphics (e.g. Figure 1) can be created to evaluate and compare the tested scenarios. Each point in the graphic represents one of the building retrofit scenarios. The lowest point corresponds to the cost-optimal level of the energy performance for the building under analysis.

The period of building life used in this analysis is 30 years, which corresponds with the EC Delegated Regulation, taking into account the replacement of the building systems after their lifetime according to EN 15459 and considering its residual value in the end of the period.

The calculations of the energy needs followed the Portuguese regulation for the thermal performance of residential buildings (Portugal, 2006) in accordance with ISO-13790 (ISO, 2008). The primary energy was calculated considering the conversion factors of 2.5 kWhPE/kWh for electricity and 1 kWhPE/kWh for natural gas (Portugal, 2013a), biomass and thermal energy from solar panels. For the calculation of the non-renewable primary energy, the contribution of the on-site renewable energy systems (solar thermal, solar electrical and biomass) is deducted from the total amount of primary energy use, which is according to Portuguese regulation (Portugal, 2013c). In the results, average values per m² refer to the conditioned net floor area (NFA).

The indoor comfort conditions considered were an absolute minimum of 20°C for air temperature in winter and an absolute maximum of 25°C for air temperature and 50% for relative humidity in summer, in accordance with the Portuguese thermal performance of residential buildings regulation (Portugal, 2006).

The costs of the retrofit measures and the related maintenance costs were calculated using Cype software which generates prices for construction works. The energy costs are based on Portuguese energy prices and the estimation of the evolution of the energy prices for the calculation period follows the scenario given by EC (2012b). Table 1 presents the electricity and natural gas prices for each year of the calculation period.
The global costs of each retrofit scenario refer to the NPV of the capital costs for the initial retrofit works and replacements during the considered period of 30 years, the maintenance costs and the energy costs, with a discount rate of 6%, in accordance with the EC Delegated Regulation.

Following this method, cost-optimal calculations were performed for the different retrofit scenarios which included a combination of the building-integrated technical systems (BITS) with different envelope retrofit measures. The different retrofit scenarios considered in this study reached more than 80 different combinations.

After these cost-optimal calculations, the required contribution from PV energy was calculated to reach the zero energy level. The PV contribution is based on the EC’s Photovoltaic Geographical Information System (PVGIS)\(^6\) and the location (Porto, 41.18N, −8.68E) to determine PV efficiency and output.

### Case study

The case study is a multifamily building located in Matosinhos, a suburb of Porto, on the north-west coast of Portugal. The building was chosen to be representative of the multifamily building stock: it reflects 20% of the multifamily building stock in Portugal (INE, 2012) due to the climate zone where it is located, its geometry and energy performance. It was built in the 1990s, shortly before the first Portuguese thermal regulation came into effect. It is a semi-detached building with its facades oriented to the north-east, south-east and south-west. It has five floors with two apartments per floor and a half-buried basement used as a garage.

The building has a reinforced concrete structure and concrete floor slabs. There is no insulation in the building envelope, as was common practice at the time. The exterior walls are cavity wall construction (two masonry leaves with an air gap) then covered with ceramic tiles; the windows are single glazed with

### Table 1  Electricity and natural gas prices for each year of the calculation period

| Year | Electricity (cents) | Natural gas (cents) | Year | Electricity (cents) | Natural gas (cents) | Year | Electricity (cents) | Natural gas (cents) |
|------|---------------------|---------------------|------|---------------------|---------------------|------|---------------------|---------------------|
| 1    | 20.81               | 8.36                | 11   | 25.25               | 10.86               | 21   | 25.89               | 12.09               |
| 2    | 21.36               | 8.79                | 12   | 25.55               | 11.03               | 22   | 25.69               | 12.16               |
| 3    | 21.91               | 9.23                | 13   | 25.85               | 11.20               | 23   | 25.50               | 12.24               |
| 4    | 22.45               | 9.45                | 14   | 26.15               | 11.33               | 24   | 25.30               | 12.31               |
| 5    | 22.89               | 9.68                | 15   | 26.18               | 11.47               | 25   | 25.10               | 12.39               |
| 6    | 23.33               | 9.90                | 16   | 26.20               | 11.60               | 26   | 24.91               | 12.46               |
| 7    | 23.77               | 10.13               | 17   | 26.23               | 11.73               | 27   | 24.71               | 12.54               |
| 8    | 24.21               | 10.36               | 18   | 26.26               | 11.86               | 28   | 24.51               | 12.62               |
| 9    | 24.64               | 10.53               | 19   | 26.29               | 11.94               | 29   | 24.31               | 12.69               |
| 10   | 24.94               | 10.69               | 20   | 26.09               | 12.01               | 30   | 24.12               | 12.77               |

Note: cents are in Euro currency

### Table 2  Case study building: thermal characteristics

| Element             | \(U\)-value before renovation \((W/m^2\cdot\text{K})\) | \(U\)-value reference values \((W/m^2\cdot\text{K})\)\(^a\) | \(U\)-value reference values \((W/m^2\cdot\text{K})\)\(^b\) | \(\eta\) (efficiency) |
|---------------------|-----------------------------------------------------|-----------------------------------------------------|-----------------------------------------------------|---------------------|
| Exterior walls       | 1.08                                                | 0.60                                                | 0.50                                                | –                   |
| Windows             | 4.80                                                | 3.30                                                | 2.90                                                | –                   |
| Roof                | 1.88                                                | 0.45                                                | 0.40                                                | –                   |
| Floor               | 2.50                                                | 0.45                                                | 0.40                                                | –                   |
| Domestic hot water (DHW) | –                                                   | –                                                   | –                                                   | 0.80                |
| Heating             | –                                                   | –                                                   | –                                                   | 1                   |

Notes: \(^a\)According to 2006 national thermal regulation

\(^b\)According to 2013 national thermal regulation

191
aluminium frames; the floors are lightweight slabs; and the roof is composed of corrugated metallic plates placed over the lightweight slab. Each apartment has an electric heater for DHW and there are no central heating or cooling systems, just portable electric heaters and fan coils, which is the common situation in this type of dwelling (INE & DGEG, 2011). Table 2 summarizes the thermal characteristics of the building in terms of the $U$-value of the different elements of the envelope and of the efficiency of the used systems. It also shows the reference $U$-values prescribed in the Portuguese thermal regulation (Portugal, 2006, 2013b).

The calculated energy needs of this building before renovation are the following:

- Heating needs: 94.75 kWh/m²/year
- Cooling needs: 2.96 kWh/m²/year
- DHW needs: 30.74 kWh/m²/year

These needs correspond to a primary energy use of 335.05 kWhPE/m²/year taking into consideration the previously presented conversion factors. The energy needs used for the cost-optimal analysis were a weighted average of the energy needs of the 10 apartments that constitute the building under analysis.

### Identification of different energy-related retrofit measures

For this study, different retrofit scenarios were considered according to the previously presented method. The building under analysis has not had any previous renovation, thus the base scenario (to which all the others will be compared) includes maintenance works such as facade cleaning, the replacement of damaged tiles and the replacement of the BITS for DHW, heating and cooling in order to restore the building functionality without improving its energy performance.

Table 3 summarizes the different combinations of retrofit packages considered in this study to improve the building envelope. For the exterior walls, the retrofit measures consisted in the application of an external thermal insulation composite system (ETICS) with different thicknesses of expanded polystyrene (EPS). For the roof, the retrofit measure consisted in placing extruded polystyrene (XPS) boards of different thicknesses on the roof slab. For the floor, in order to avoid interfering with the living conditions, the retrofit measure considered was the application of XPS boards underneath the floor slab. The insulation thicknesses considered varied from 30 to 120 mm. For the window frames, polyvinylchloride (PVC) was the chosen material due to its cost-effectiveness, always with double-glazing. The combination of different retrofit measures for the elements of the envelope together with different combinations of BITS led to different retrofit packages.

The analysed BITS were heating, ventilation and air-conditioning (HVAC) with multi-splits, a heat pump with fan coils, a gas heater, a gas boiler, an electric heater and a biomass boiler. These BITS may serve for one or more purposes. For example, the heat pump was analysed by taking into consideration its contribution to heating, cooling and DHW, while the gas heater was just considered for DHW.

Table 4 shows how the different combinations of BITS considered in the study performed, indicating their efficiency or coefficient of performance (COP).

### Table 3 Packages to improve the energy performance of the building envelope

| Package | Wall insulation | Roof insulation | Floor insulation | Window replacement |
|---------|----------------|----------------|------------------|--------------------|
| 0 (base scenario) | Maintenance | Maintenance | Maintenance | Maintenance |
| 1 | Maintenance | Maintenance | Maintenance | PVC frames and double-glazing |
| 2 | Maintenance | Maintenance | 30 mm XPS | PVC frames and double-glazing |
| 3 | 40 mm EPS | Maintenance | 30 mm XPS | PVC frames and double-glazing |
| 4 | 40 mm EPS | 40 mm XPS | 30 mm XPS | PVC frames and double-glazing |
| 5 | 50 mm EPS | 50 mm XPS | 50 mm XPS | PVC frames and double-glazing |
| 6 | 60 mm EPS | 60 mm XPS | 60 mm XPS | PVC frames and double-glazing |
| 7 | 80 mm EPS | 80 mm XPS | 80 mm XPS | PVC frames and double-glazing |
| 8 | 100 mm EPS | 100 mm XPS | 100 mm XPS | PVC frames and double-glazing |
| 9 | 120 mm EPS | 120 mm XPS | 120 mm XPS | PVC frames and double-glazing |

Note: EPS = expanded polystyrene; PVC = polyvinylchloride; XPS = extruded polystyrene
The combination of measures to improve the building envelope from 1 to 9 (Table 3) with BITS from A to G (Table 4) leads to different retrofit packages. The contribution and impact of solar thermal systems were also considered. As solar thermal panels only affect DHW, in most cases this made the retrofit packages less cost-effective, therefore the solar thermal contribution was only considered in packages complementing electric heaters for DHW. In the case of the electric heater, the significant reduction of electricity use by the solar thermal panels makes the investment cost-efficient.

Results
Cost-optimal calculations
Analysing the different retrofit scenarios, those with the lowest global costs within each group of BITS combination for heating, cooling and DHW were identified. Based on the costs of each retrofit scenario and on the calculated non-renewable primary energy use, and following the above method, the retrofit scenarios are graphically expressed by each of the markers of the following figures.

Figure 2 shows the global costs for the analysed solutions for each retrofit scenario. Each marker represents a different combination of BITS and within each BITS combination there are different combinations of measures to improve the building envelope. Figure 2 also shows the non-renewable primary energy (NRPE) (i.e. fossil fuel) use in each of the retrofit scenarios.

For each combination of BITS, there is a cost-optimal solution, which is the lowest point of each group of markers. But considering all packages of combinations between BITS and measures to improve the building envelope, the cost-optimal solution is the lowest point in Figure 2, which means the combination of the BITS E with the combination of measures to improve the building envelope.
building envelope number 5, which corresponds to a gas boiler for heating and DHW and 50 mm envelope insulation and PVC window frames with double-glazing (the solution marked with an arrow in Figure 2).

Table 5 shows the thermal characteristics of the building before renovation, the reference U-values of the building components as indicated in the national thermal regulation, and its thermal characteristics after the application of the cost-optimal retrofit package.

It is evident that the thermal characteristics of the cost-optimal retrofit package are better (for walls and windows) or close (for floor and roof) to the reference values defined in the national thermal codes.

The global cost for each retrofit scenario is the NPV of all costs during the defined economic life cycle of the building, including investment costs and costs related to the use of the building. Investment costs include the initial costs for implementing the package of retrofit measures (measures to improve the energy performance of the building envelope, measures to install BITS and measures related to the use of renewable energy systems) and also the NPV of the costs related to the replacement of building elements with a lifetime smaller than the defined economic life cycle of the building after the retrofit.

Residual values for building elements with lifetimes longer than the economic life cycle are also taken into account. Energy costs refer to the NPV of the energy bills for each year of the economic life cycle and maintenance costs refer to the NPV of annual costs with the maintenance of each building element and system.

Figure 3 shows the disaggregated costs for each of the retrofit scenarios. The combinations with higher global costs are the packages with a biomass boiler for heating and DHW (systems F) and the less expensive are the packages with a gas boiler for heating and DHW (systems E). Both situations do not consider the cooling needs because the introduction of equipment only to deal with cooling is not usual in residential Portuguese buildings and the low cooling needs in most of the country makes such an investment generally unjustified. The biomass boiler for heating and DHW and the biomass boiler for heating, combined with the electric heater for DHW, have high investment costs in the system itself and in maintenance over the 30-year life cycle considered in this study.

Within the retrofit packages with a gas boiler for heating and DHW, the highest costs are related to energy costs once the gas boiler is not very efficient. However, all the other costs are lower, resulting in a cost-optimal solution.

Between the packages of measures using systems that can also provide cooling, the cost-optimal combination of systems is HVAC for heating and cooling and a gas heater for DHW.

According to the EU regulation, for the cost-optimal calculations, renewable energy is subtracted from the total primary energy that the building needs. However, it is also interesting to understand what will be the total amount of primary energy that the building requires to supply its energy needs. An analysis of the cost-optimal curves including both renewable and non-renewable primary energy (Figure 4) shows that whatever the combination of BITS considered, the shape of the different curves is very similar. In the same way, their lowest points, which indicate the cost-optimal packages related to each combination of BITS, refer to the same combination of measures to improve the energy performance of the building envelope. As an example of this, a comparison can be made between the packages of measures using a gas boiler for heating and DHW (the curve with the lowest global costs in Figure 4) and the packages of measures using a biomass boiler for heating and DHW (the curve with the highest global costs in Figure 4). This comparison shows two curves that are almost parallel, moving within a very similar range of primary energy use (between 75 and 135 kWh/m²/year) and with its lowest markers corresponding to the same package of retrofit measures for the building envelope (which is combination 5 from Table 3).

### Table 5

| Element       | Before renovation | Reference values | Cost-optimal renovation package |
|---------------|-------------------|------------------|---------------------------------|
| Walls (U-value) | 1.08 W/m²°C       | 0.60/0.50 W/m²°C | 0.46 W/m²°C                    |
| Windows (U-value) | 4.80 W/m²°C     | 3.30/2.90 W/m²°C | 2.40 W/m²°C                    |
| Roof (U-value)  | 1.88 W/m²°C       | 0.45/0.40 W/m²°C | 0.54 W/m²°C                    |
| Floor (U-value) | 2.50 W/m²°C       | 0.45/0.40 W/m²°C | 0.52 W/m²°C                    |
| DHW            | Electric with 80% efficiency | – | Natural gas boiler with 93% efficiency both for heating and DHW |
| Heating        | Electric with 100% efficiency   | – | – |
| Cooling        | Not considered      | – | – |
| NRPE           | 335.05 kWh PE/m²/year | – | 84.87 kWh/ m²/year |

Notes: *According to 2006 and 2013 national thermal regulations

DHW = domestic hot water; NRPE = non-renewable primary energy
Figure 3  Disaggregated costs for the retrofit packages
These results show that major differences in global costs result mainly from the change of the energy vector and combination of BITS. Figure 4 also shows that for each combination of BITS, the improvement of the energy performance of the building envelope leads to significant reductions in the primary energy use but has less impact on changes in the global costs.

**Figure 4**  Global costs and total primary energy use for different packages of retrofit measures

**Figure 5**  Global costs and non-renewable primary energy (NRPE) for different retrofit scenarios without energy restrictions and for net-zero.  
*Notes:* See Figure 2 for an explanation of these packages. Zero NRPE is achieved with the use of photovoltaic (PV) panels (these packages are encircled)
Retrofit for a net-zero target

In order to compare cost optimality and the net-zero targets, previous results from the calculation of cost-optimal levels are now compared with the most cost-effective packages of retrofit measures to achieve a zero energy balance.

For this case study, the net-zero-energy level (which also corresponds to a zero emissions level) was achieved through the use of a biomass boiler for heating and DHW and through the utilization of PV panels in every other retrofit package. It was observed that the BITS hierarchy has not suffered major changes when compared with the cost-optimal calculations. As shown in Figure 5, where the packages of retrofit measures that lead to a zero balance of NRPE appear aligned over the y-axis, the packages of measures using a gas boiler for heating and DHW continue to be those with the lowest global costs (for the packages of measures leading to net-zero, only the packages with the lowest global costs for each combination of systems are presented in Figure 5).

Figures S1–S6 (in the Supplemental data online) show the results for each of the analysed BITS (A–G) combined with packages of measures 0–9. These retrofit packages are presented (1) without energy restrictions (i.e., a search for the lowest global costs regardless the value of energy use) and (2) with the energy restriction of net-zero for which the previous packages are combined with PV panels to generate the necessary amount of electricity.

Most scenarios do not present significant changes with the addition of PV panels. Despite the increase of the global costs, the cost-optimal solution for both combinations of systems (A and B) is the same with and without the PV panels. The cost-optimal solution corresponds to package 5, the one already described in Table 3.

Figures S3–S6 show the retrofit packages for the remaining combinations of BITS (C–G, with the exception of F once the original F BITS combination already delivered zero non-renewable primary energy use with a biomass boiler), where similar results are obtained in all of them. In fact, in all tested retrofit scenarios, the lowest global costs without energy restriction or with a zero NRPE balance are achieved.
with the same combination of measures on the building envelope for each combination of BITS.

The combination of retrofit measures for the building envelope that present the lowest global costs without energy restriction or with a zero NRPE balance is the same and corresponds to package 5 (50 mm insulation to walls, roof and floor, double-glazed windows with PVC frames).

**Sensitivity analysis and representativeness**

The presented analysis assumes the retrofit is undertaken by a non-public (i.e., private) client: costs include all taxes and subsidies and the discount rate presents a value that reflects a commercial, short-term approach to the valuation of investments (which traditionally reflects a private investor perspective). If a macroeconomic (or societal) perspective is assumed, then the costs do not include taxes and subsidies, the discount rate is lower (3%) and a monetization of CO₂ emissions⁷ can be included. This leads to a reduction of the costs gap between net-zero and cost-optimal solutions, but the main results and conclusion remain the same (Figure 6).

Returning to the private client perspective, in order to evaluate the robustness of the results, sensitivity analyses were performed for the discount rate and energy prices evolution. For the discount rate, instead of 6%, values of 4%, 3% (Figure 7) and 2% were tested; for the evolution of energy prices, instead of the base scenarios, a 3% yearly increase rate was tested (Figure 8). The results presented no relevant variations and the conclusions are the same.

Although this case study has been considered representative of nearly 20% of the multifamily building stock in Portugal by its typology, location, geometry and energy performance, other research (Ferreira, Pereira, Almeida, & Rodrigues, 2013a; Ferreira, Almeida, & Rodrigues, 2013b) on different residential buildings and locations led to the same main conclusion that the lowest cost net-zero can be achieved with the introduction of renewables on buildings that meet the cost-optimal levels or slightly more stringent energy performance levels, extending the representativeness of these results to the generality of the residential buildings in Portugal.

**Conclusions**

Different packages of retrofit measures to achieve a building with a net-zero energy balance were examined and compared with the retrofit packages needed to reach the cost-optimal levels. This study was performed for a typical multifamily building representative of the Portuguese housing stock, built shortly before the implementation of the first thermal regulation in 1990s.

Although the presented results only refer to a single building type and location, some general conclusions can be made about the cost-effectiveness of the combination of measures to improve the energy performance of the building envelope and of the heating, cooling and DHW systems and the use of on-site renewable energy to achieve a net-zero energy balance.
Without the restriction of reaching a net-zero energy balance, the cost-optimality level is found for packages of retrofit measures using natural gas only for DHW or for DHW and heating. If the natural gas grid is not available on-site, then the packages of retrofit measures using a multi-split HVAC system combined with solar thermal panels and backed up by an electric heater for DHW and also the packages using the heat pump for heating, cooling and DHW present very similar global costs. However, the differences in the non-renewable primary energy use are significant. In these cases of similar global costs, the retrofit packages with the lowest non-renewable primary energy associated with them should be chosen.

With the introduction of PV panels to generate electricity in a quantity that equals the non-renewable primary energy use, the hierarchy of cost-effectiveness from the several systems used for heating, cooling and DHW did not require major modifications. The cost-optimal solutions remain the same.

The impact of on-site renewable energy systems on the cost-effectiveness of the measures in the building envelope does not change significantly the hierarchy of the cost-effectiveness between the different packages of retrofit measures. However, there is a tendency for a reduced gap in global costs between the cost-optimal package of measures and those with better energy performance decrease, while differences in global costs between the most cost-effective retrofit scenario and those with worse energy performance increase.

The present results confirm the robustness of the cost-optimal method in the definition of the most cost-effective packages of retrofit measures in the building envelope. This allows very similar results to be reached for both a zero non-renewable primary energy goal and a cost-optimal goal.

These results indicate that the transition between the concept of ‘cost optimality’ and nearly zero-energy buildings can occur in Portugal without major difficulties. The lowest cost nearly zero-energy building can be achieved with the introduction of renewables on buildings that meet the cost-optimal levels.

These results also support the recent definition of nearly zero-energy buildings included in the 2013 Portuguese legislation on the thermal performance of buildings. It states the efficiency of a nearly zero-energy building should be consistent with the limits of economic viability obtained from the cost-optimal method.

Nevertheless, two aspects need to be taken into consideration:

- The cost-optimal levels for the energy performance of the building envelope will vary with the efficiency of the BITS for heating, cooling and DHW as well as with the costs of the retrofit measures.
(which in existing buildings can vary significantly depending on the specific characteristics and constraints of each building). Thus, the introduction of national thermal legislation for high-level envelope performance requirements may impose complex and costly interventions. In practice, this can lead to deviations from the cost-optimal levels. Lower levels of energy performance of the building envelope (or of some of its elements) can be offset by the use of more efficient systems and/or the integration of renewables. All the cost-optimal retrofit packages included the improvement of all envelope elements. It is essential to intervene in the largest possible number of elements of the envelope in order to ensure, in a passive way, minimum comfort levels and the reduction of risks. Therefore, for the retrofit of existing buildings, it will be necessary to adjust the cost-optimal energy performance levels to the real context of the building instead of imposing requirements from reference buildings.

- The use of renewables is crucial to achieving the net-zero level. Regardless of the different packages of retrofit measures used, an important difference in costs exists between the cost-optimal level and the net-zero level. Although the costs associated with the introduction of renewables can be reduced until 2020, the financing of this difference is a fundamental aspect that has to be politically safeguarded.

**Supplemental data**

Supplemental data for this article can be accessed at http://dx.doi.org/10.1080/09613218.2014.975412

**References**

Bartiaux, F., Gram-Hansen, K., Fonseca, P., Ozoliņa, L., & Christensen, T. H. (2014). A practice–theory approach to homeowners’ energy retrofits in four European areas. Buildings Research & Information, 42(4), 525–538. doi:10.1080/09613218.2014.900253

Boermans, T., Hermelink, A., Schimschar, S., Grozinger, J., & Offermann, M. (2011). Principles for Nearly Zero-Energy Buildings – Paving the way to effective implementation of policy requirements, Buildings Performance Institute Europe (BPIE).

BPIE. (2011). Europe’s Buildings Under the Microscope – A country-by-country review of the energy performance of buildings. ISBN: 9789491143014.

BPIE. (2013). Implementing the Cost-Optimal Methodology in EU Countries – Lessons learned from three case studies. ISBN: 9789491143083.

Cayre, E., Allibe, B., Laurent, M.-H., & Osso, D. (2011). There are people in the house! How the results of purely technical analysis of residential energy consumption are misleading for energy policies, in Proceedings of the ECREEE 2011 Summer Study on Energy Efficiency First: The Foundation of a Low-Carbon Society, pp. 1675–1683. European Commission. (2006). The European Climate Change Programme. European Communities. ISBN 92-79-00411-5.

Christensen, T. H. (2014). A practice–theory approach to understanding and improving energy performance of buildings. Energy and Buildings, 74, 403–410.

Hens, H., Parijs, W., & Deurinck, M. (2010). Energy consumption and rebound effects. Energy and Buildings, 42, 105–110.

Lino, R., Jordão, M., & Carvalho, P. (2013). Do Homes that are More Energy Efficient Consume Less Energy? A Structural Equation Model for the Residential Sector. University of Cambridge, Department of Economics, Cambridge Working Paper, 417.

Kurnitski, J. (2013). Technical definition for nearly zero energy buildings. The REHVA European HVAC Journal, 50 03/2013, 403–410.

Lino, R., Jordão, M., & Carvalho, P. (2013). Do Homes that are More Energy Efficient Consume Less Energy? A Structural Equation Model for the Residential Sector. University of Cambridge, Department of Economics, Cambridge Working Paper, 417.

Kurnitski, J. (2013). Technical definition for nearly zero energy buildings. The REHVA European HVAC Journal, 50 03/2013, 403–410.

Lino, R., Jordão, M., & Carvalho, P. (2013). Do Homes that are More Energy Efficient Consume Less Energy? A Structural Equation Model for the Residential Sector. University of Cambridge, Department of Economics, Cambridge Working Paper, 417.

Kurnitski, J. (2013). Technical definition for nearly zero energy buildings. The REHVA European HVAC Journal, 50 03/2013, 403–410.

Lino, R., Jordão, M., & Carvalho, P. (2013). Do Homes that are MoreEnergy Efficient Consume Less Energy? A Structural Equation Model for the Residential Sector. University of Cambridge, Department of Economics, Cambridge Working Paper, 417.

Kurnitski, J. (2013). Technical definition for nearly zero energy buildings. The REHVA European HVAC Journal, 50 03/2013, 403–410.

Lino, R., Jordão, M., & Carvalho, P. (2013). Do Homes that are More Energy Efficient Consume Less Energy? A Structural Equation Model for the Residential Sector. University of Cambridge, Department of Economics, Cambridge Working Paper, 417.

Kurnitski, J. (2013). Technical definition for nearly zero energy buildings. The REHVA European HVAC Journal, 50 03/2013, 403–410.
energy consumption. *Building Research & Information, 40*(3), 260–273. doi:10.1080/09613218.2012.690952
Tigchelaar, C., & Menkveld, M. (2011). *Obligations in the existing housing stock: who pays the bill?,* in Proceedings of the ECEE 2011 Summer Study on Energy Efficiency First: The Foundation of a Low-Carbon Society, pp. 353–363.

**Endnotes**

1The Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) definition for a net-zero-energy building proposed by Kurnitski (2013) is used here, with the exclusion of consumer appliances and lighting. (The Portuguese thermal regulation for residential buildings does not specifically consider the energy used for lighting. The retrofit of the envelope of existing buildings presents significant constraints for the improvement of use of natural lighting.)

2Ancillary benefits of retrofit measures beyond energy savings include lower noise levels and improved comfort from insulation and glazing, better indoor air quality and temperature control from new HVAC equipment, less operational maintenance or increased energy security against energy price fluctuations through deployment of renewable energy resources (BPIE, 2011).

3Although the Portuguese regulation for the thermal performance of residential buildings has suffered a recast with the publication of Decree-Law n. 118/2013, which came into force on 1 December 2013, the calculation of energy needs follows the previous regulation. Both regulations are in accordance with ISO-13790:2008, but the 2013 recast presents heating degrees-days based on 18°C for winter instead of the previous 20°C. For the purpose of this study, it was considered that the use of the 20°C base was more appropriate in order to allow comparisons with similar studies in other European countries, where the usual reference comfort temperature is 20°C.

4Total conditioned floor area inside the building envelope excludes the external and internal walls and vents, shafts, stairs, (unoccupied) attics, basements and garages. The area is reduced by partition walls but not by moveable or building-integrated furnishing.

5This is a parametric and interactive database that allows the user to obtain the price for building elements or systems according to the selected materials, equipment and construction processes. Independent bodies, including ASEMAS (Mutua de Seguros y Reaseguros a Prima Fija), Tecnopavimento and EuroAdoquin, periodically revise this database. For the software, see http://www.geradordeprecos.info/.

6See http://re.jrc.ec.europa.eu/pvgis/.

7€20/ton of CO₂e until 2025, €35/ton until 2030 and €50/ton beyond 2030 in line with current European Commission projected Emissions Trading Scheme (ETS) carbon price scenarios.