Comparison of nZEB indicators for hotel renovations under different European climatic conditions

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Abstract
Hotels hold an important role in the energy efficiency policies of the European Union (EU), as they are typically ranked among the top energy consumers in the non-residential sector. However, a significant amount of the energy used in hotels is wasted, leaving ample room for enhancing energy-efficiency and resource conservation. Indeed, energy refurbishment of the hotel building stock is crucial in order to reach the nearly zero energy building (nZEB) status imposed by EU Directives for energy efficiency, and also an important pillar to achieve the energy targets for 2030 and the transition towards climate-neutral levels by 2050.

A typical 4-star hotel in operation in Faro (Portugal) was used as a case study in order to establish energy performance indicators for nZEB hotels in three European cities, taking into account the influence of the climatic context, the technical feasibility and cost effectiveness of the best energy retrofit packages. The study started after the calibration of the building energy model by means of an energy audit and measured data, in order to have a baseline model that represents well the actual energy use of the hotel in the reference location. The building energy model was developed by using DesignBuilder/EnergyPlus software. The validated model was then used to assess the effect of the best retrofit interventions (energy efficiency measures and active solar systems) in order to set minimum energy performance requirements and to reach cost-optimal levels and nZEB levels for refurbished hotels. A significant energy-saving potential was found for the cost-optimal benchmarks, and the obtained nZEB levels can be achieved under technically and economically conditions for the selected cities: Faro, London and Athens.

Keywords: zero energy buildings; hotels; renewables; climatic dependence; economic analysis

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1. INTRODUCTION
A significant part of the building stock in Europe is obsolete, inefficient and in need of extensive retrofitting to improve its energy-environmental performance. As a result, buildings currently represent about 40% of the final energy consumption in the European Union (EU) and 36% of the greenhouse gas emissions. This makes energy efficiency strategies and renewable energy in this sector crucial to meet the EU long-term energy and climate objectives set by the low carbon roadmap 2050. Moreover, the energy consumption of the EU building stock, besides climatic conditions and utilization, significantly depends on its age. At least 35% of the EU building stock (residential and service sectors) is over 50 years old, more than 40% of the building stock was built before 1960 and 90% before 1990, when building energy regulations were extremely limited or inexistant [1–3]. It should be noted that in many existing buildings, the envelope was deteriorated and the technical systems were degraded in terms of efficiency, which means that such buildings require higher levels of energy consumption to maintain comfortable indoor environments. Clearly, the renovation of the existing building stock can lead to significant energy savings—under economically feasible conditions—and can play a key role in the EU’s clean energy transition.

In order to reach the long-term emission objectives and decarbonize the building stock, the European performance of buildings...
directive (EPBD) recast [4] introduced the nearly zero energy building (nZEB) concept. This concept was initially directed to new buildings, to be built from 2021 on, but it was soon understood that the same approach should be extended to existing buildings, which was consolidated in the 2018 EU directive reformulation. The requirement pointed to a cost-effective transformation of all existing buildings into nZEBs. In this perspective, EU member states should create a long-term strategy aimed at renovating their national building stocks, turning them into highly energy efficient and decarbonized buildings by 2050 [5]. An nZEB refers to a grid-connected building and may be defined as a building that over a given period (e.g. a year) is nearly neutral when energy conservation and efficiency measures are successfully combined with on-site (or nearby) renewable energy systems. Moreover, the term ‘nearly’ can be used in reference to a building that produces ‘slightly less’ energy than the energy it needs to assure indoor environmental comfort. However, this quantification of ‘nearly’ varies according to the building context, in particular with the climatic conditions and building categories. In that respect, an nZEB can be described as a building that uses a primary non-renewable energy value higher than zero (balance) but not higher than a limiting value established at national level. This threshold value takes into account the local climatic context and is determined through a proper combination of efficient technological measures, which may or may not be based on optimum costs (i.e. the best relation between energy performance and global intervention cost) [4, 6]. However, no uniform nZEB definition has been clearly configured in EU countries.

In general terms, the nZEB definition in Europe—expressed by numerical targets of primary energy use (main indicator)—shows a wide variability among member states and reflects different national and regional calculations and energy flows. The maximal primary energy consumption varies between 0 and 270 kWhPE/(m²·year) for the non-residential sector (depending on the type of building). For residential buildings, the nZEB primary energy indicator ranges from 30 to 95 kWhPE/(m²·y), with most countries aiming at establishing energy consumptions not higher than 50 kWhPE/(m²·y) [7]. Furthermore, these nZEB indicators take into account the energy use for heating, ventilation and air conditioning (HVAC) systems (heating, cooling, ventilation and pumping), sanitary hot water (SHW) and lighting. Several member states also include appliances and central services [7, 8]. Concerning renewable energy integration in buildings, only some EU countries have defined a specific minimum share (between 25% to 56%) [9].

Among existing serviced buildings that need energy-saving actions, hotels have proven to be highly energy consuming, especially the 4- and 5-star segment. In fact, they typically include a vast diversity of functional zones with different utilization profiles, ranging from guest rooms, meeting rooms and auditoriums to restaurants, wellness areas and services areas (kitchen, laundry, offices, etc.). These zones with several functions are all consuming energy in varying levels [10, 11]. In that respect, the technical systems have a major role with a large potential for energy savings; those savings will have a positive impact in terms of real estate valorization (i.e. added value in the form of lower operating costs, higher incomes, increased occupancy rate and improvement of indoor comfort). Thus, an improvement of the energy performance of the existing hotel stock—in particular for 4- and 5-star hotels due to the required comfort levels and diversity of services provided to guests—is crucial to the European strategy to ensure that future climate and energy targets are reached.

Energy consumption in hotels significantly varies between types of hotels (i.e. building, resort) and is affected by hotel category, geographical location (i.e. urban, rural or mountain), customer profile (i.e. difference in behavior and preferences) and is strongly influenced by climatic zone and seasonal operation (summer or winter period) [12, 13]. In addition to the climate, this variation is also related to other aspects such as building size, age of the facility, thermal quality of the building envelope, technical systems, operation and maintenance services and also depends on occupancy rate, income, energy cost and diversity of activities.

A number of international studies analysed the energy use intensity (EUI) of hotels. For example, some references indicate an average annual energy use between 20 to 90 kWh/guest-night [14–16]. In Europe, the average energy consumption varies between 240 to 300 kWh/(m²·y). According to the European climate, the EUI in the Mediterranean climate is in the range of 272 to 364 kWh/(m²·y); in the UK (representing the Oceanic climate), the average EUI is 495 kWh/(m²·y); in Stockholm (Nordic zone), the average EUI is not higher than 379 kWh/(m²·y) [10, 17]. However, these energy indicators give only a gross indication of building efficiency and therefore should be treated with caution, since they can hide underlying problems with individual end uses of energy [18, 19].

Concerning the main energy end uses, Balantia-Creara [20] collected energy consumption data from 55 hotels in Spain during energy audits. The results showed that the end uses associated with HVAC systems and SHW represent 55% of the total consumption (on average). Besides, the energy use related with the services areas (such as kitchens, laundries, office-equipment) may reach 35% of the total. Energy consumption in kitchens and laundries vary considerably, depending on the size of the restaurant facilities and the amount of laundry that is processed on site. This justifies the need to include global energy consumption in the nZEB definition. Furthermore, Pinto et al. [21] demonstrated that in several hotels the main energy consumption is related to SHW and concludes that this energy service accounts for ~20% of the primary energy consumed in a hotel during the summer season.

In the nZEB context, the importance of the hotel sector was reflected through a dedicated EU-funded project for nearly zero energy hotels [22]. In the light of this, Tsoutsos et al. [23] indicated benchmarks of primary energy use for the European climate zones. These benchmarks range between 71 kWhPE/(m²·y) in the Southern zone and 134 kWhPE/(m²·y) in the Nordic zone for new hotels. In the Oceanic zone and Continental zone, the energy performance targets are 115 and 80 kWhPE/(m²·y), respectively. These reference values were increased by 30% for refurbished hotels (150 and 104 kWhPE/m²/y).
In a previous work by the authors, Cunha and Oliveira [24], nZEB energy performance indicators were calculated for hotel rehabilitations, using as a reference a 4-star hotel under operation in Faro (Portugal). In this work, the aim is to extend the previous study to assess the performance and energy indicators to different European climates, using as a basis the same reference hotel. Two additional different climates were considered, using two cities that represent different European climatic zones [25]: Athens (Mediterranean zone) and London (Oceanic zone). For that, three main tasks were defined:

- considering real operating conditions and using the simulation model that was previously validated through an energy audit, obtaining simulation results for the three cities considered and comparing the energy performance results;
- defining sets of energy rehabilitation solutions with higher impact, taking into account technical limitations and quantifying nZEB indicators for the different climates;
- analysing the economic viability of the rehabilitation solutions, using two different criteria: the optimum cost level and the return on investment.

2. METHODOLOGY

This study is focused on the energy consumption that corresponds to regulated consumptions in hotel buildings, which allow maintaining thermal comfort and air quality in functional areas (clients and services). Therefore, in the calculation of nZEB indicators, the following regulated final energy uses were considered: HVAC systems, SHW, lighting and elevators. The consumptions associated to other intensive uses, such as kitchens and laundries and other various equipment, will not be included in the energy balance to obtain the nZEB levels.

The nZEB levels will be defined through an energy efficiency indicator—$\text{IEE}_{\text{nZEB}}$—which represents the annual primary energy specific consumption (in kWh/PE), obtained by dividing all regulated primary energy consumptions by the total floor area ($A_p$). The primary energy total consumption corresponds to the sum of all building energy vectors ($E_{r,i}$), subtracting the production of energy from renewable sources for own consumption ($E_{\text{ren},i}$), converted to primary energy through the use of conversion factors ($F_{p,i}$) — see equation 1, Cunha and Oliveira [24].

$$\text{IEE}_{\text{nZEB}} = \frac{1}{A_p} \sum_{i} \left[ F_{p,i} \cdot \sum_{n=\text{ng}} \left( \sum_{k} \frac{f_{n,k} \cdot Q_n}{\eta_{n,k}} + \sum_{k} f_{n,k} \cdot \gamma_{n,k} \right) \right]$$

$$- \frac{1}{A_p} \sum_{i} (E_{\text{ren},i} \cdot F_{p,i})$$

Each energy vector $i$, including those of renewable origin, is associated to a system $k$, with an efficiency $\eta_{n,k}$, totally or partially satisfying ($f_{n,k}$) the useful energy ($Q_n$), of the different $n$ uses, in this case regulated uses ($r$), including the lighting, ventilation/pumping and lift systems, here represented by $\gamma_{n,k}$.

The nZEB levels and indicators ($\text{IEE}_{\text{nZEB}}$) start from the energy performance of the reference or base scenario, which was simulated and validated through an energy audit carried out at the existing reference hotel. After that, different simulations with DesignBuilder, an interface of EnergyPlus [26] were performed using different rehabilitation options, including changes in existing energy systems (efficiency of energy equipment and control) and introduction of renewable energy systems. This allowed a comparison between the reference/base situation and the different rehabilitation options. The different options were simulated and analysed for three different locations and climatic conditions: Faro (reference study—Southwestern European zone), London (Oceanic zone) and Athens (central Mediterranean zone).

One may note that, besides the climate, the energy performance of buildings also depends on utilization patterns and cultural/societal habits. This is particularly true in residential buildings. However, it is not the typical case of international hotels that usually follow standardized practices and have a large number of international staff and residents. Therefore, the same utilization patterns were used for the three climates considered.

In the economic viability analyses performed, minimum energy efficiency requirements were defined, taking into account technical and economic constraints. The requirements were defined by imposing $\text{IEE}_{r} \leq 70\% \text{IEE}_{r,\text{baseline}}$, where IEE$_{r}$ is the annual specific primary energy regulated consumption, and the baseline value corresponds to the corresponding specific energy consumption without any rehabilitation.

3. CHARACTERISTICS OF THE REFERENCE HOTEL AND BASELINE SCENARIOS

The reference 4-star hotel is located in Faro (Portugal, coordinates in Table 1), at an altitude of 3 m. The local climate can be classified as a Mediterranean temperate climate type, although with an Atlantic Ocean influence; it is characterized by warm winters and moderately hot summers — Table 1 shows some representative climatic data.

A detailed energy audit was carried out in the reference hotel, as described in Cunha and Oliveira [24]. The main energy vectors and real operating conditions were identified, which served to adjust and calibrate the simulation model. The same conditions and basic construction characteristics were maintained as baseline scenarios (building without rehabilitation) for each of the considered locations/climates. The same energy systems and control characteristics were used in the different baseline scenarios. The effect of the studied rehabilitation measures could then be compared with those baseline scenarios.

The dynamic simulation model was developed with DesignBuilder, an interface of EnergyPlus [26], as described in Cunha and Oliveira, (2020). The necessary climatic data files were obtained from LNEG (National Laboratory for Energy and
Table 1. Main climatic data for the simulated locations.

| Location | $T_{\text{min}}$ [°C] | $T_{\text{max}}$ [°C] | HDD [°C-day] | CDD [°C-day] | Irrad [kWh/m².day] |
|----------|------------------------|------------------------|--------------|--------------|-------------------|
| Faro, 37.25 N, 8.0 W | 4.5 | 34.9 | 899 | 787 | 5.09 |
| London, 51.15 N, 0.18 W | −5.9 | 31.3 | 3118 | 101 | 2.77 |
| Athens, 37.90 N, 23.73 E | 2.0 | 37.2 | 1254 | 1036 | 4.57 |

$T_{\text{min}}$: minimum temperature, $T_{\text{max}}$: maximum temperature, HDD/CDD: heating/cooling degree-days base 18.5°C, Irrad.: daily average global solar irradiance.

Table 2. Characteristics of the reference hotel building and energy modeling boundary conditions.

| Building type | Existing hotel (4-star) |
|---------------|-------------------------|
| Reference location | Faro, Portugal, 37.25 N, 8.0 W |
| Use | 365 days/year, business and leisure |
| Occupancy rate | 66% (annual average), Summer > 80%, Winter ≈ 45% |
| Total floor area/shape factor ($F_{\text{shape}}$) | 8954 m² (including service areas and guest areas)/$F_{\text{shape}}$: 0.28 m²⁻¹ |
| Total facade area | External walls: 2886 m²; outside glazings: 1159 m² |
| Average ceiling height/WWR | 2.9 m/window-wall ratio: 6–38% |
| External walls U-value | 0.96–1.7 W/(m².C), post-1960 construction without insulation |
| Roof U-value | 2.6 W/(m².C), terrace without insulation |
| Floor U-value | 3.10 W/(m².C), without insulation |
| Windows U-value ($U_w$) | 2.20–6.25 W/(m².C), aluminium frame without thermal break, double glazing and single glazing in some parts |
| Windows, global solar factor ($g_T$) | 0.16–0.38, internal shading protection (light colour) |
| Occupancy | Rooms: 11.65 m²/occupant; remaining area: 28.22 m²/occupant |
| Lighting | Global density: 5.2 W/m² (51% fluorescent tubular, 35% fluorescent compact, 12% LED and 2% halogen) |
| Equipment | 3.8 W/m² (on average), laundry: 577 W/m² (100% electrical), kitchen: 536 W/m² (40.6% natural gas and 59.4% electricity) |
| Utilization patterns | Under real operating conditions, based on the survey made during the audit and monitored data concerning the electrical energy demand |
| Heating and cooling source plants | Natural gas boiler (2 × 465 kW, efficiency of 90%): heating; air-cooled chiller (2 × 264 kW, energy efficiency ratio of 2.66): cooling, system shut off: November–March |
| SHW | 2 storage tanks (5000 L), connected to 2 plate heat exchangers (2 × 300 kW) fed by the gas boilers |
| Mechanical ventilation/terminal units | Air handling units (with cooling/heating coils)/terminal units: 2-pipes fan coil units |
| Operating period/temperature setting | According to the hotel occupation period/set points: 22°C for heating and 24°C for cooling |
| Final/primary energy conversion factors, by energy vector $i$ ($F_{pi}$) | Electricity (el): 2.5 kWh$\text{PE}$/kWh$\text{el}$, natural gas (ng): 1 kWh$\text{PE}$/kWh$\text{ng}$ |

*Excluding gym and shops: under autonomous management, not considered in this work.
*Sensible and latent heat gains per person, based on the metabolic activity in each space [27].

Geology of Portugal), for Faro and IWEC (International Weather for Energy Calculations), for London and Athens. Table 1 presents representative climatic data for the three locations.

Concerning the reference hotel construction and operating characteristics, Table 2 presents a summary of the baseline conditions. The hotel was built in 1966 and had a first major renovation at the end of the 1990’s. It has a total floor area of 9986 m², with rooms and related circulation area corresponding to 41% of the total area, divided in eight stories. The main façades are southeast and northeast oriented—see Figure 1.

Heating and cooling are achieved through a centralized system using two tubes and fan-coil units: heating with hot water produced in two natural gas boilers, and cooling with cold water produced in two air-water compression chillers. The same equipment provides water to the air handling units that filter and deliver conditioned fresh air to the indoor spaces.

Internal energy loads reflect the operating dynamics of the hotel, considering the different zones: for instance, guest rooms with night and early morning use and service zones and offices with diurnal use. Lighting and ventilation loads are consistent with occupation.

4. INFLUENCE OF THE CLIMATIC CONDITIONS: SIMULATION RESULTS

4.1. Baseline models

The simulation model allowed to separate consumptions by end-use for all baseline scenarios (locations). The corresponding annual energy consumption results are shown in Figure 2, for the three locations, considering both regulated and non-regulated
energy uses. The baseline (regulated) consumptions are 118.8 kWh/(m².y) in Faro, 200.1 kWh/(m².y) in London and 149.7 kWh/(m².y) in Athens.

One may note that the energy consumption for space heating/cooling strongly depends on the climate, representing 31% of the regulated consumption in Faro, 50% in London and 39% in Athens. In London, heating alone represents 38% of the total energy consumption (regulated and non-regulated), in Faro this only represents 9%. Note that the heating degree days in London are 3.5 times higher than in Faro (Table 1). Cooling has a similar weight in Faro and Athens (9%), with only 2% in London.

The end-uses that comprise SHW, lighting, ventilation and pumping have similar values, due to similar utilization patterns. From these results, one may conclude that when looking at the different energy vectors (sources), there is an increase in the weight of natural gas use for colder climates.

4.2. Selected energy retrofit packages

Several energy retrofit packages were considered but only the best integrated rehabilitation options were simulated, taking into account the experience gained in the previous study [24].

Table 3 represents the different packages of rehabilitation measures (PCKₐ), which include measures to reduce internal gains (R1), measures to improve the efficiency of existing energy systems (R2) and measures to include renewable energy systems (R3). Note that all packages include the adequate insulation of opaque elements and the replacement of existing windows by energy efficient windows, with air-filled double glazing, solar control and/or low-e coatings and PVC frame.

The first package in Table 3, PCK10, includes R1 and R2 measures such as improving lighting efficiency, a total reformulation of the ventilation system and use of efficient devices to reduce hot water consumption.

Figure 3 represents final and primary energy consumptions for all simulated packages.

The best packages that include R1 and R2 measures only are PCK21 and PCK23—introducing chillers and boilers with higher efficiencies. These lead to a reduction in primary energy consumption of 38% in Faro, 43% in London and 41% in Athens. The primary energy consumptions achieved are 135–139 kWhₚₑ/(m².y) in Faro, 161–164 kWhₚₑ/(m².y) in London and 150–158 kWhₚₑ/(m².y) in Athens. This corresponds to achieving the minimum energy efficiency requirements set (IEEᵣ ≤ 70% IEEᵣ,baseline), which were IEEᵣ,Faro ≤ 153 kWhₚₑ/(m².y), IEEᵣ,London ≤ 196 kWhₚₑ/(m².y) e IEEᵣ,Athens ≤ 179 kWhₚₑ/(m².y).

The introduction of renewable energy systems (R3), considered the installation of two types of solar energy systems: solar thermal (ST) for SHW and photovoltaic system (PV) to generate part of the hotel electrical consumption. In both cases, two options were considered: one for systems with regular efficiency (A) and another for systems with improved efficiency (B). The collector areas took into account the available space in the reference hotel and are equal to 63 m² for the ST systems and 371–384 m² for the PV systems. For the PV systems, it was assumed that 80% of the generated electricity is used in regulated consumptions.
Table 3. List and description of the selected packages (PCK) of retrofit interventions and shares of renewable energy.

| Energy retrofit measures                          | PCK10 | PCK13 | PCK15 | PCK17 | PCK19 | PCK21 | PCK23 | PCK30 | PCK31 | PCK32 | PCK33 | PCK38 | PCK39 | PCK40 | PCK41 |
|--------------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| R1 LED lights                                     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     |
| Readjustment of outdoor air flow rate in accordance with the Portuguese building code—requirements for ventilation | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     |
| R2 Regulation of space heating and cooling—set points: 21°C–25°C | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     |
| Regulation of space heating and cooling—set points: 20°C–26°C | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     |
| Water saving devices (to reduce water and SHW consumption—guest rooms) | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     |
| Efficient ventilation system with variable volume fans (category SFP2, EN 13779; <750 W/(m³/s)) | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     |
| Heating recovery systems (minimum 73% energy recovery for balanced airflow) | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     |
| Demand controlled ventilation: ventilation rate controlled by air quality | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     |
| Cooling system—higher leaving chilled water temperature (Tout): 10°C | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     |
| Efficient air-cooled chiller (EER = 3.73 | | | | | | | | | | | | | | | |
| outdoor temperature: 35°C/water outlet: 10°C) | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     |
| Efficient air-cooled chiller (EER = 3.62 | | | | | | | | | | | | | | | |
| outdoor temperature: 35°C/water outlet: 10°C) | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     |
| Condensing gas boiler (nominal η = 97.6%) | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     | x     |
| for space heating and SHW | | | | | | | | | | | | | | | |
| R3 ST system A: collector area = 63 m²; | x     | x     | | | | | | | | | | | | | | |
| south-oriented, 45° tilt angle | optical efficiency (η0) = 0.73; \(a_1 = 4.12 \text{W/m}^2\cdot\text{C} \), \(a_2 = 0.0140 \text{W/m}^2\cdot\text{C}^2\) | | | | | | | | | | | | | | | |
| ST system B: collector area = 63 m²; | x     | x     | | | | | | | | | | | | | | |
| south-oriented, 45° tilt angle | optical efficiency (η0) = 0.794; \(a_1 = 3.86 \text{W/m}^2\cdot\text{C} \), \(a_2 = 0.0310 \text{W/m}^2\cdot\text{C}^2\) | | | | | | | | | | | | | | | |
| PV system A: 60 kW; collector area = 384 m²; | x     | x     | | | | | | | | | | | | | | |
| southwest-oriented, 30° tilt angle | solar panel efficiency = 15.73%; polycrystalline 305 Wp | | | | | | | | | | | | | | | |
| PV system B: 68 kW; collector area = 371 m²; | x     | x     | | | | | | | | | | | | | | |
| southwest-oriented, 30° tilt angle | solar panel efficiency = 18.45%; monocrystalline 300 Wp | | | | | | | | | | | | | | | |
| Share of renewable energy in the regulated use (%) | | | | | | | | | | | | | | | |
| IEE_{Faro}/IEE_e | Faro | 22% | 25% | 22% | 25% | 22% | 24% | 22% | 25% |
| IEE_{London}/IEE_e | London | 10% | 11% | 11% | 12% | 10% | 11% | 11% | 12% |
| IEE_{Athens}/IEE_e | Athens | 18% | 20% | 18% | 21% | 18% | 20% | 18% | 20% |

Note: reduction of internal loads: R1; efficiency of energy systems: R2; active solar energy systems: R3.
Combining R3 with R1 and R2 measures (PCK30 to PCK41) leads to primary energy consumptions of 101–106 kWh<sub>PE</sub>/(m<sup>2</sup>·y) in Faro, 142–144 kWh<sub>PE</sub>/(m<sup>2</sup>·y) in London and 119–124 kWh<sub>PE</sub>/(m<sup>2</sup>·y) in Athens.

In Faro, the average renewable energy contribution is 23% (IEE<sub>ren</sub> = 33.5–29.5 kWh<sub>PE</sub>/m<sup>2</sup>/y), while in London it is equal to 11% (IEE<sub>ren</sub> = 18.6–16.7 kWh<sub>PE</sub>/m<sup>2</sup>/y) and in Athens 19% (IEE<sub>ren</sub> = 30.9–27.2 kWh<sub>PE</sub>/m<sup>2</sup>/y).

The above indicated values of 101–106 kWh<sub>PE</sub>/(m<sup>2</sup>·y) for Faro, 142–144 kWh<sub>PE</sub>/(m<sup>2</sup>·y) for London and 119–124 kWh<sub>PE</sub>/(m<sup>2</sup>·y) for Athens, should then be considered as indicative values to be used in the 4- and 5-star hotel stock, in the context of hotel rehabilitations (nZEB indicators), when there is an available area to install the considered solar systems.

Considering the values presented in section 1, with average energy intensities in the range of 272 to 364 kWh/m<sup>2</sup>/y for hotels in Mediterranean climates and 495 kWh/m<sup>2</sup>/y for UK hotels, the above values (nZEB indicators) represent a significant reduction of more than 60% in the final energy consumption, compared to those averages. But the comparison should be carefully made, as the average values may include non-regulated consumptions.

One may compare the nZEB indicators obtained in this work under rehabilitation context, with the nZEB benchmarks for new hotels given by Tsoutsos et al. [23] for different European climatic zones (71 kWh<sub>PE</sub>/m<sup>2</sup>/y in Southern Europe and 115 kWh<sub>PE</sub>/m<sup>2</sup>/y for the Oceanic zone), which should be increased by 30% for refurbished hotels (to 93 and 150 kWh<sub>PE</sub>/m<sup>2</sup>/y, respectively). The Faro value is only about 10% higher (101 against 93), and the value obtained for London is only about 5% lower (142 against 150) in comparison with the indicated benchmarks. In any case, there is a fair agreement between them. For Athens the difference is higher (119 versus 93).

5. ECONOMIC VIABILITY ANALYSES

In this section, the economic viability of the rehabilitation packages/solutions will be analysed, using two different criteria: the optimal cost level and the return on investment.

According to the optimal cost level, the best solution/package is the one with an energy performance that leads to the lowest life cycle cost (LCC) during a period until the next major renovation (n<sub>y</sub>, taken as 20 years), taking into account the initial cost, maintenance and energy costs during the period.

The return on investment period (RI) is the period of time needed to recover the investment on the package, through the savings made during this period. An additional requirement was fixed: RI ≤ 75%n<sub>y</sub>.

The calculation methodology is shown in Cunha and Oliveira [24].

The calculation of investment costs was made by consultation of different suppliers. Maintenance costs were estimated as a percentage of investment costs (EN 15459, 2007). In the base scenario, maintenance costs correspond to 20% of the operational energy cost. Energy costs for natural gas and electricity were taken for Faro according to the real costs obtained during the energy audit to the hotel [24] and for London and Athens using the Eurostat information for non-domestic users with the corresponding consumption levels [28, 29]; for natural gas they were 0.0510€/kWh<sub>ng</sub> in Faro, 0.0282€/kWh<sub>ng</sub> in London and 0.0393€/kWh<sub>ng</sub> in Athens and for electricity, 0.1058€/kWh<sub>el</sub> in Faro, 0.1373€/kWh<sub>el</sub> in London and 0.1057€/kWh<sub>el</sub> in Athens. For other financial parameters, the following values were assumed: annual inflation rate (i) of 2%, annual energy inflation rate (e) of 3%, return on investment rate (i<sub>r</sub>) of 5%.
Figure 4. Cost-benefit analysis for the selected locations (1% - 5%, 2% - 2%, 3% - 3%): (a) optimal cost method, (b) RI method.

Figure 4 shows the results for the two economic criteria in the three locations. Figure 4a represents the optimal cost results (LCC in €/m²), while Figure 4b represents the RI results. In the graphs of Figure 4a, values below the blue line correspond to profitable solutions (LCC below the baseline scenario).

The following conclusions may be drawn from Figure 4a:

- the optimal cost package in Faro and Athens is PCK13, with an IEE of 149 kWhPE/m²/year and a specific LCC of 304€/m² in Faro (reduction of 32% compared to base scenario) and with an IEE of 170 kWhPE/m²/year and LCC of 310€/m² in Athens (reduction of 34% compared to base scenario);
- in London, the optimal cost also corresponds to PCK13, with IEE equal to 179 kWhPE/m²/year and with a LCC of 358€/m² (reduction of 36% from base scenario); however, due to the high heating load, satisfied by natural gas, if the specific cost
of natural gas increases, option PCK19 (with more efficient boilers) may become better;
• optimal solutions correspond to \( I_{Ee} \leq 70\% \ I_{EE, baseline} \);
• concerning the packages that use solar energy systems, the best one is PCK33 (with ST B and PV B options), with an \( I_{Ee,nZEB} \) of 101 kWh\( m^2/y \) and LCC of 311\( €/m^2 \) in Faro, 142 kWh\( m^2/y \) and 376\( €/m^2 \) in London and 119 kWh\( m^2/y \) and 318\( €/m^2 \) in Athens.

In Figure 4b, one may note that all packages/solutions comply with the requirement of \( RI \leq 75\% \ n_y \leq 15 \) years. Three different ranges may be identified, according to the strategies used and climatic conditions:
• a first range, with \( RI \leq 4 \) years, in all locations, guaranteed with more efficient lighting, optimization of HVAC set-points, water saving devices and efficient ventilation with demand controlled by air quality (CO2); note that the optimal package for the three locations (PCK13) is included in this range;
• a second range with \( RI \leq 6 \) and 10 years (may be a bit higher in Faro), characterized by the introduction of more efficient chillers and condensing boilers; an economic benefit results from the climate severity—higher heating needs in London and higher cooling needs in Athens, compared to Faro;
• a third range with \( RI \leq 10 \) and 12 years, this range combines the use of solar energy with the previous energy efficiency measures (second range); the best nZEB indicator—\( I_{Ee,nZEB} \) from PCK33—has an \( RI \leq 10 \) and 11 years in Faro and Athens and about 12 years in London.

The application of the RI criterion shows that the higher the energy consumption, and the higher the reduction in energy cost due to the energy efficiency retrofit packages (ranges 1 and 2), the higher the economic interest of those measures. The return on investment in Athens and London is slightly faster than in Faro. On the other hand, the introduction of solar energy systems guarantees a higher return on investment in the Mediterranean climate due to the higher potential for renewable energy production.

Table 4 summarises the main energy and economic indicators.

| Solutions | \( I_{Ee,nZEB} \) \([kWh/m^2/y]\) | LCC \([€/m^2]\) | RI \([years]\) |
|-----------|-----------------|----------------|---------|
| Baseline scenario | 219\( ^a \)/280\( ^a \)/256\( ^c \) | 342\( ^b \)/402\( ^b \)/353\( ^c \) | - | - |
| \( I_{Ee} \leq 70\% \ I_{EE, baseline} \) | 151\( ^a \)/179\( ^a \)/172\( ^c \) | 305\( ^b \)/359\( ^b \)/311\( ^c \) | \( \geq 4^c \), \( > 3^c \), \( > 3^c \) | PCK10\( ^b,c \) |
| Optimal solution (\( I_{EE} \)) | 149\( ^a \)/179\( ^a \)/170\( ^c \) | 304\( ^b \)/358\( ^b \)/310\( ^c \) | \( \geq 4^c \), \( > 3^c \), \( > 3^c \) | PCK13\( ^b,c \) |
| Best nZEB (\( I_{EE,nZEB} \)) | 101\( ^b \)/142\( ^b \)/119\( ^b \) | 311\( ^b \)/357\( ^b \)/318\( ^b \) | \( \geq 11^b \), \( \geq 12^b \), \( < 11^b \) | PCK33\( ^b,c \) |

\( ^a \) Faro, \( ^b \) London, \( ^c \) Athens

### 6. CONCLUSIONS

This work has evaluated the climatic influence in the definition of nZEB performance indicators, for hotel buildings under renovation, using as a reference a 4-star hotel located in the South of Portugal (Faro, Southwestern Europe zone). The other climates/locations considered were London (Oceanic zone) and Athens (central Mediterranean zone).

The main tool used was a simulation model, using DesignBuilder/EnergyPlus software, which was previously validated by...
The climatic influence was analysed by comparing energy consumption values and energy performance indicators (IEE: annual primary energy consumption per m²) for a large number of renovation packages, including measures to reduce internal gains, measures to improve the efficiency of existing energy systems and measures to include renewable energy systems. The combination of all measures leads to nZEB-type solutions.

The economic viability of the rehabilitation packages (PCK) was assessed using two different criteria: the minimum LCC and the return on investment (RI).

From the obtained energy and economic results, the following is highlighted:

• the multiple solutions/packages that do not include the introduction of renewables lead to regulated energy indicators of 135–139 kWhPE/m²/y in Faro, 161–164 kWhPE/m²/y in London and 150–158 kWhPE/m²/y in Athens;

Figure 5. Sensitivity analysis on the energy price variation (\(e = 1\%\)): (a) optimal cost method, (b) RI method.
Comparison of nZEB indicators for hotel renovations under different European climatic conditions

Figure 6. Sensitivity analysis on the energy price variation ($e = 6\%$): (a) optimal cost method, (b) RI method.

- for Faro, London and Athens, the optimal solution is PCK13, with $\text{IEE}_r=149 \text{ kWh}_\text{pe}/\text{m}^2/\text{y}$ and $\text{LCC}=304\text{€}/\text{m}^2$ in Faro, $\text{IEE}_r=179 \text{ kWh}_\text{pe}/\text{m}^2/\text{y}$ and $\text{LCC}=358\text{€}/\text{m}^2$ in London and $\text{IEE}_r=170 \text{ kWh}_\text{pe}/\text{m}^2/\text{y}$ and $\text{LCC}=310\text{€}/\text{m}^2$ in Athens;
- the nZEB levels vary between 101–106 kWh$\text{pe}/\text{m}^2/\text{y}$ in Faro, 142–144 kWh$\text{pe}/\text{m}^2/\text{y}$ in London and 119–124 kWh$\text{pe}/\text{m}^2/\text{y}$ in Athens;
- the option with the best nZEB indicator is PCK33 (with ST and PV systems): $\text{IEE}_{\text{nZEB}}=101 \text{ kWh}_\text{pe}/\text{m}^2/\text{y}$ and $\text{LCC}=311\text{€}/\text{m}^2$ in Faro, 142 kWh$\text{pe}/\text{m}^2/\text{y}$ and 376€/m$^2$ in London, 119 kWh$\text{pe}/\text{m}^2/\text{y}$ and 318€/m$^2$ in Athens;
- in the three climates/locations, the optimal solutions have a return on investment period (RI) equal or lower than 4 years and the nZEB interventions between 10–12 years.

The main conclusions from the analysis of the results are:

- the combination of all measures, including measures to reduce internal gains, measures to improve the efficiency of existing
energy systems and measures to include renewable energy systems, leads to global energy savings (in the regulated and non-regulated consumptions) of 23% in Faro, 30% in London and 26% in Athens;

- the optimal cost solution for the three locations/climates (PCK13) excludes the use of renewables and includes the following measures: optimization of HVAC set-points, installation of water management devices, use of more efficient lighting and complete redesign of the ventilation system;
- the nZEB levels (IEE_{nZEB}) are obtained with the additional economic viability requirement of RI ≤ 15 years;
- the higher the energy consumption, the faster the return on the investment;
- considering a reduction on the inflation of energy prices from 3% to 1%, the optimal cost solutions are the same; however, the RI period increases and is less favourable to the introduction of renewables, although the requirement RI ≤ 15 years is still verified;
- if the energy prices significantly increase (inflation from 3% to 6%), the optimal solutions are nZEB solutions in Faro and Athens; PCK39, with active ST and solar PV systems; in London, the optimal cost solution remains PCK13 due to the more severe climatic conditions.

nZEB levels are the goal to be pursued in future improvements and research. Results show that with the use of properly structured solutions, supported by energy efficiency measures, it is possible to accommodate the use of renewable energy systems in hotel renovations, leading to nZEB levels that are economically viable and adapted to the reality of the European hotel stock.

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