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ScienceDirect

Energy Procedia 140 (2017) 314–324

Energy Procedia

www.elsevier.com/locate/procedia

AiCARR 50th International Congress; Beyond NZEB Buildings, 10-11 May 2017, Matera, Italy

Cost-optimal approach to transform the public buildings into nZEBs: an European cross-country comparison

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Abstract

A cross-country comparison of the *RePublic_ZEB* project results is presented. The paper reports on the energy efficiency measures and on the options considered for the refurbishment of the public buildings taken as representative of the building stock in the countries involved in the project. The nZEB solutions are compared in terms of adopted energy efficiency measures; moreover, the nZEBs are quantitatively defined through a set of energy, economic and environmental parameters. The paper aims at giving an overview on the meaning of nZEB in the European context, and on its energy and economic feasibility for real public existing buildings.

Peer-review under responsibility of the scientific committee of the AiCARR 50th International Congress; Beyond NZEB Buildings.

Keywords: Energy refurbishment; public building; cost-optimality; nZEB definition.

1. Introduction

Since it was coined already seven years ago, the term "nZEB" is nowadays spread anywhere and all the building sector is focused on it. In literature most of the research is focused on the investigation of suitable technologies for the nearly zero-energy target. In Ascione et al. [1] several different envelope solutions are investigated in such a way as to understand the best trade-off between summer and winter performance of the nZEBs in Mediterranean climate. Phase change materials, photovoltaic-thermal collectors, adjacent sunspaces and innovative daylighting control are the integrated technologies implemented in a computer model to assess the overall energy and economic

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Peer-review under responsibility of the scientific committee of the AiCARR 50th International Congress; Beyond NZEB Buildings
10.1016/j.egypro.2017.11.145

performance of multi-zone nZEBs [2]. In Pikas et al. [3] design guidelines for high performance office building facades are proposed, looking at alternative measures to achieve the nZEB level.

But, do these researches consider the same meaning of "nZEB"?

The definition of nZEB is reported in the European Directive 2010/31/EU [4], but the national implementation of this concept by EU Member States is variegated and sometimes still not accomplished. Moreover, the EU Directive gives a general definition of nZEB that is enforceable both to new and existing buildings, but technical barriers and constraints often make a deep renovation impracticable and the nZEB target is therefore unreached. BPIE summarizes in a comprehensive fact-sheet the status at April 2015 of different approaches and indicators used by EU Member States for the nZEB definition of new and existing buildings [5]. Moreover, in Erhorn et al. [6] the Concerted Action highlights that: at least 9 Member States translate the "very high energy performance" of the nZEB into one of the top energy classes of the energy performance certificate, while in other countries that means a reduction in between 10-25% and 50-60% of the 2014 energy requirements; the *RER* varies from 0% to 50%, but few countries set specific minimum renewable energy contributions in kWh m^{-2} or let the value implicit, applying "indirect" requirements; the nZEB energy performance is sometimes defined by means of only the primary energy amount, but in other cases additional parameters include *U*-values, net and final energy for heating, cooling and possibly other energy uses and CO_2 emissions.

Nomenclature

A	area	[m^2]
COP	coefficient of performance	[-]
DHW	domestic hot water	[-]
EER	energy efficiency ratio	[-]
EP	energy performance	[kWh m^{-2}]
F_D	daylight factor	[-]
F_C	occupancy factor	[-]
GC	global cost	[€]
PN	lighting power density	[W m^{-2}]
RER	renewable energy ratio	[%]
U	thermal transmittance	[W $m^{-2}K^{-1}$]
V	volume	[m^3]
W	peak power	[kW]
τ_s	solar transmittance coefficient	[-]
η	energy efficiency	[-]

Subscripts

C	cooling	op	opaque wall
coll	collectors	p	peak
ctr	control	P	primary
env	envelope	r	roof
g	gross	ren	renewable
gl	overall	s	solar
gn	generation	tot	total
H	heating	ve	ventilation
nren	non-renewable	W	domestic hot water
op	opaque wall	w	window

In this heterogeneous context, the *RePublic_ZEB* project [7] addresses the refurbishment of the public building stock towards the nZEB target in the countries of the South-East of Europe. The main goal of the project is to support the development and the promotion on the market of technical retrofit solutions suitable for the nearly zero-energy target renovation of the public building stock. To achieve this goal, reference buildings are defined and the energy assessment of the current public building stock is carried out. Some of the preliminary results of the applied methodology for identifying the cost-optimal levels of the energy performance requirements are shown in Aelenei et al. [8], the Italian contribution to the project is presented in Corrado et al. [9]; the present work aims at giving an overview on the possibilities and barriers that the EU countries involved in *RePublic_ZEB* met towards the cost-effective refurbishment of the existing reference public buildings into nearly zero-energy ones.

2. Method

2.1. Requirements of nZEBs

In order to overcome the differences among the involved countries in the level of implementation of the EPBD recast [4], a common target for the nZEB was adopted within the *RePublic_ZEB* project. A refurbished building is considered nearly zero-energy when the following requirements are met: its energy performance is lower than that of the cost-optimal solution (it is more energy efficient than the cost optimal building); the differential Global Cost (ΔGC) with reference to the building before the refurbishment is negative (the renovation is cost-effective); the national minimum requirements for nZEB are fulfilled. Among these requirements there may be a minimum value of the Renewable Energy Ratio (*RER*) (e.g. for public buildings in Italy, $RER_{W} > 55\%$, $RER_{H+C+W} > 55\%$ [10].

Thus, the nZEB definition is neither fixed nor unique, but specific for each country although based on the same assumptions on energy performance and cost-effectiveness.

2.2. Energy performance and global cost calculation

A common tool was developed and used by most of the *RePublic_ZEB* partners, to assess the energy performance and the global cost of the nZEBs retrofit solutions. The tool is based on the Italian technical specification UNI/TS 11300 series [11], which implements the following European standards: EN ISO 13790 [12] on the energy need for space heating and cooling; EN 15316 series [13] and EN 15243 [14] on the energy requirements of the technical systems for the air conditioning and ventilation; EN 15193 on the energy demand for lighting [15]. The tool was modified at country level in order to implement national options, boundary conditions and input data.

The energy performance of the nZEB is expressed as the overall non-renewable primary energy demand divided by the conditioned area ($EP_{gl,nren}$). The overall primary energy refers to the heating, cooling, DHW, ventilation and lighting services. It is calculated according to ISO 52000-1 [16]. $EP_{gl,nren}$ is used to compare different nZEBs solutions, together with the *RER*, that is the ratio of the renewable primary energy to the total primary energy:

$$RER = \frac{E_{P,ren}}{E_{P,tot}} \quad (1)$$

where $E_{P,tot}$ is the sum of the renewable ($E_{P,ren}$) and of the non-renewable ($E_{P,nren}$) primary energy use.

The common tool used in *RePublic_ZEB* allows to calculate the *EP* of the building and to associate the referred global cost that is determined according to the financial approach of the Commission Delegated Regulation No. 244/2012 [17]. That methodology is based on the net present value (global costs, *GC*) calculation, carried out according to standard EN 15459 [18]. The overall costs include the initial investment, the sum of the annual costs for each year (energy, maintenance, operation and any additional costs), the extraordinary replacement of systems and components, the final value, and the costs of disposal, as appropriate.

Moreover, a sequential search-optimization technique was implemented in the tool [19], in such a way as to set the optimal levels of minimum energy performance requirements towards nZEB, in accordance with [17] and the accompanying Guidelines [20]. In that process, different sets of retrofit measures are compared and the one reaching the lowest global cost over the considered calculation period is defined as the cost-optimal solution. Finally, the optimal set of retrofit measures is modified in order to comply with the nZEB requirements.

3. Calculation

3.1. The reference buildings

Table 1. List of the reference buildings considered in the *RePublic_ZEB* project.

No.	Country	Building use	V_g [m^3]	A_{env}/V_g [m^{-1}]
1	BULGARIA	Student hostel	22 247	0.32
2		School	11 583	0.42
3		Office	4 252	0.55
4		Hospital	8 106	0.57
5	CROATIA	Office continent	11 059	0.44
6		Office coast	7 987	0.46
7		Education continent	-	-
8		Education coast	-	-
9	FORMER YUGOSLAV REPUBLIC OF MACEDONIA	Office	384	0.33
10		School	14 466	0.16
11	GREECE	School	6 247	0.31
12		Office	24 426	0.25
13	HUNGARY	Office	6 940	0.34
14		Kindergarten	1 718	0.63
15		Student hostel	22 509	0.27
16	ITALY	Social housing	22 845	0.37
17		School	39 760	0.31
18		Office	20 638	0.23
19	PORTUGAL	Social housing	180	0.87
20		Office	8 479	0.18
21	ROMANIA	Office	8 730	0.33
22		School	6 470	0.51
23	SLOVENIA	Office	3 769	0.43
24		Kindergarten	4644	0.66
25		School	13367	0.44
26		Health-care facility	12 035	0.50
25		Home for elderly people	12 923	0.33
28	SPAIN	Office	19 450	0.17
29		Hospital	33 366	0.36
30	UK	Office	3 986	0.54

Among the countries involved in the *RePublic_ZEB* project, a total of 30 reference buildings were considered. The chosen buildings are representative of the public building stock for several different building uses, as listed in Table 1. Each reference building was analyzed and the input data suitable for the energy performance evaluation were collected [21].

3.2. The Energy Efficiency Measures

The refurbishment consists of a major renovation; the energy efficiency measures (*EEMs*) concern both the fabric and the technical systems; these are defined at country level, according to the most appropriate technologies suitable to reach the project goals. In Table 2 is reported the list of *EEM* available in the tool; for each reference building, the list has been modified in such a way as to consider the suitable technical solutions for the transformation into nZEB [22].

Table 2. List of Energy Efficiency Measures *EEMs* and referred thermal parameter and unit.

No.	EEM	Parameter
1	External wall thermal insulation	U_{op}
2	Wall vs unconditioned spaces	$U_{op,u}$
3	Roof/last floor thermal insulation	U_r
4	Ground/first floor thermal insulation	U_f
5	Window thermal insulation	U_w
6	Solar shading system	τ_s
7	Chiller	*EER*
8	Generator for heating and appropriate emission system	$\eta_{gn,Pn,H}$ or *COP*
9	Generator for DHW	$\eta_{gn,Pn,W}$ or *COP*
10	Combined generator for heating, DHW, and appropriate emission system	$\eta_{gn,Pn,H+W}$ or *COP*
11	Heat pump for heating, DHW, cooling, and appropriate emission system	*COP* *EER*
12	Thermal solar system	A_{coll}
13	PV system	W_p
14	Heat recovery ventilation system	η_{ve}
15	Heating control system	η_{ctr}
16	Lighting system	*PN*
17	Lighting control system	F_D (F_C)

The *EEMs* from 1 to 4 define the opaque envelope thermal insulation. *EEMs* 5 and 6 considers the windows replacement and the solar shading devices respectively. *EEM* 7 stands for the replacement/installation of the technical system for cooling (e.g. splits). The *EEMs* from 8 to 11 involve the replacement and upgrading of technical systems for space heating, DHW, combined space heating/DHW and combined space heat-ing/cooling and DHW respectively (e.g. replacement of the heat generator) and take into account technologies like condensing boiler, biomass generator, district heating, air-to-air and air-to-water heat pumps. *EEMs* 12 and 13 concern the energy production from renewables (i.e. solar collectors and PV panels), while *EEM* 14 the heat recovery of ventilation system. Finally, an advanced control for space heating (*EEM 15*) and the lighting system replacement (*EEM* 16 and 17) are considered.

The tool allows the consider up to five energy efficiency options (*EEOs*) for each *EEM*, representing different levels of performance: e.g. the *EEOs* referred to the measure of external wall thermal insulation (*EEM* No. 1) consist of different post-retrofit *U*-values. Each *EEO* also corresponds to a suitable technology and its referred cost that include the material as well as the extra-costs for lathing and technical systems adjustment.

3.3. The assumptions

The building energy use for space heating/cooling is calculate by means of the quasi-steady-state method as specified in the Italian technical standards that implement EN ISO 13790 [11], based on a monthly balance between thermal losses and gains. The monthly values of the climatic data are set at national level. In order to allow a comparison among buildings that differ in use and management, a continuous operational schedule for the heating/cooling systems has been considered; the heating season length is set at national level while the cooling season is not fixed.

The *EP* is expressed in terms of overall non-renewable primary energy ($EP_{\mathrm{gl,nren}}$) and *RER*. The primary energy factors are defined at national level according to the specific regulations. The electricity from PV panels is considered on a monthly basis as a reduction of the electricity demand; the exported electricity is not considered.

The following assumptions are used for the *GC* calculation: period of 30 years; 3% real interest rate; electricity and natural gas costs fixed at national level [23]; energy trend scenarios developed with the PRIMES model according to the European Commission [24]; annual maintenance costs variable from 0% to 4% of the investment cost depending on the technology; technical lifespan of building elements fixed at 20 years, of technical systems variable from 15 to 20 years.

4. Results

Through the application of the above presented calculation process, up to 107 retrofit solutions suitable for the nZEB target were investigated (from 2 to 4 nearly zero-energy retrofit solutions for each reference building), among over 9600 different combinations of *EEMs* options generated by the cost-optimization tool.

The cross-country comparison reported in [25] pointed out that it is not always possible to reach the nZEB target: it is often impossible to meet the minimum RER requirements, due to building contingencies and constrains such as impossibility to install PV/solar panels on the building components, or unavailability of renewable sources on-site. Moreover, many retrofit solutions reach the nZEB energy target as set in the *RePublic_ZEB* project (*EP* lower than that of the cost-optimal solution), but those were not cost-effective because of the high investment costs. Only 67 packages of retrofit measures over 107 considered can be correctly considered suitable for the nZEB goal as those satisfy the energy performance and *RER* requirements , and are cost effective.

Figure 1 shows the overall total primary energy performance index of the nZEB retrofit solutions, subdivided into the non-renewable part (in red), and the renewable part (in green). Each bar of the histogram refers to a retrofit solution; those are listed for countries, according to the building use in Table 1. It has to be noticed that the nZEBs are generally characterized by a non-renewable primary energy around 70 kWh m^{-2}: some countries like Bulgaria, Hungary, Italy and Portugal reach lower values, around 40 kWh m^{-2}. The Bulgarian nZEBs are the most energy savings (less than 20 kWh m^{-2}), while the Spanish, Greece and the Slovenian seem to be more energy-intensive. As regards the overall total energy performance of the nZEB solutions, values are generally around 120 kWh m^{-2}. Smart cases are those of the Bulgarian school and of the UK Victorian office. At the opposite, Greece, Spain, Croatia and the Former Yugoslav Republic of Macedonia, show higher values of $EP_{\mathrm{gl,tot}}$.

As regards the use of renewables, Figure 2 shows that most of the buildings reach a *RER* of 50%, and in many cases the energy covered by renewables is around 70% (Bulgaria, Croatia, UK). At the opposite, some cases like those of Hungary, Spain and UK show values of *RER* lower than 30%. It has to be noticed that the services considered in the *RER* calculation are not the same for all the countries: ventilation and in some cases lighting are not considered for instance in Italy and in Portugal, in Hungary and in Greece. Moreover, the values are due to the variety of national requirements concerning the minimum *RER*: the highest value of 55% in Italy and Bulgaria, on the opposite 10% in Romania; 30% and 25% in Croatia and Hungary respectively, while UK, Spain Portugal Greece and Macedonia don't have any prescription about that. A special case is represented by Slovenia for which the national law provides a 25% share of *RER* in total final energy consumption to ensure the functioning of systems in the building, so heat and electricity for ventilation, heating, cooling, hot water and lighting.

Some discrepancies arise from the cross-county comparison of the results. Firstly, in some countries there is no official definition of a nZEB. Thus, most of the partners proposed suitable retrofit solutions just according to the definition of nZEB adopted in the project. Other inconsistencies arise because some countries (e.g. Former Yugoslav Republic of Macedonia, Slovenia, Hungary) do not have official values of primary energy factors, specifically as regards the renewable primary energy. In these cases it was left to each national partner to decide whether using the conversion factors as reported in ISO 52000-1, or considering the non-renewable primary energy factors already available at country level without specifying the renewable energy demand. Finally, the energy performance deeply depends on weather conditions, which may be different among the considered countries; thus, a comparison is often difficult.

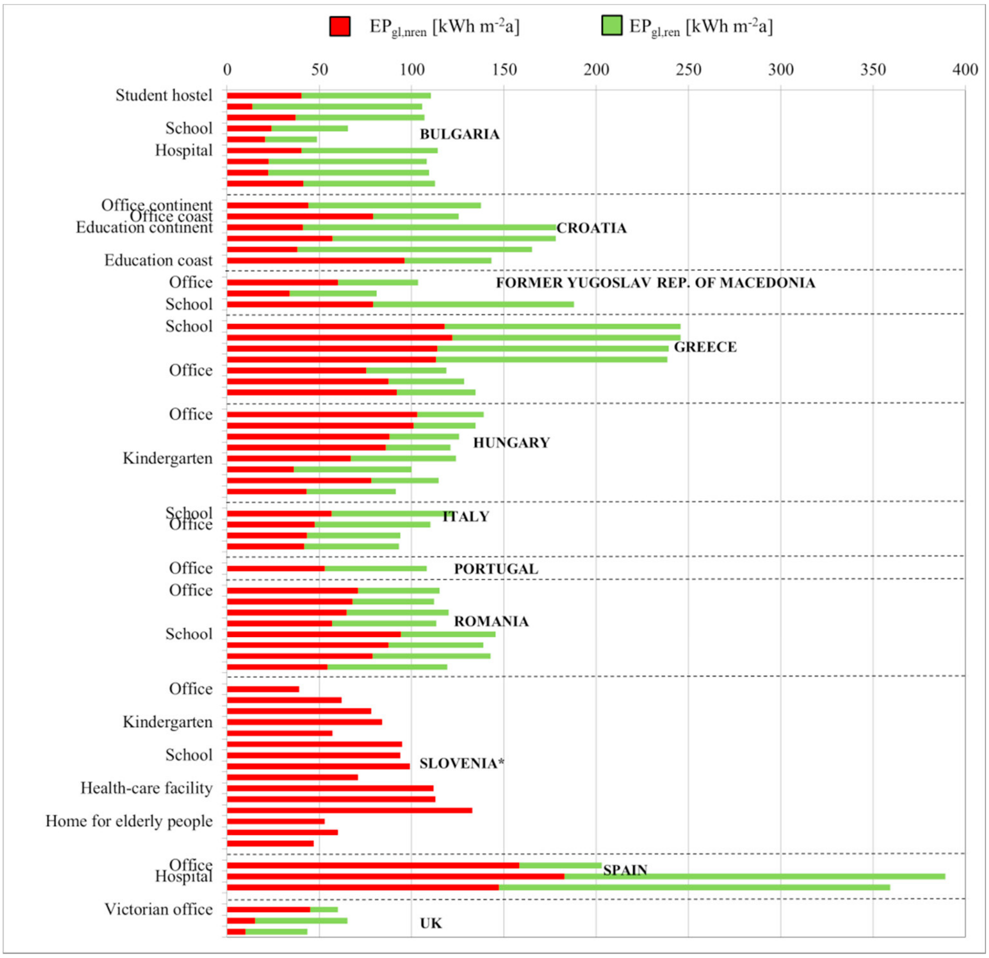
Figure 3 shows the differential global costs of the nZEBs referred to the building before the refurbishment. Only the cost-effective solutions are shown, i.e. those that have a negative differential global cost over the 30 years-period considered. The highest saving is that of the Italian school, and refers to a very energy-intensive building before the retrofit: in similar cases, the nZEB refurbishment leads to a very high energy saving and so to a significant energy cost reduction. The negative values of the differential global costs are generally in between 100 and 200 € m^{-2}; Slovenia reaches higher values. As regards the positive values, that means the retrofit is not cost-effective, those solutions should not be considered. These cases are characterized by a really high global cost, meaning that the building is not appropriate for an nZEB renovation, or that the technologies chosen for the retrofit are energy saving but very expensive in terms of initial investment and/or maintenance. It is pointed out that the calculations consider a continuous operation of the heating/cooling systems, according to the standard calculated rating approach. The real energy consumptions of the buildings are generally lower than the standard energy demands. Thus, the energy performance, the global cost as well as the pay-back period here reported should be adjusted, especially in case of intermittency of the heating system.

5. Conclusion

The paper presents a method to investigate retrofit packages of measures suitable for transformation of buildings into nZEBs through the application of the cost-optimality methodology. The research is part of the European project *RePublic_ZEB*, on the refurbishment of the public building toward the nearly zero-energy target.

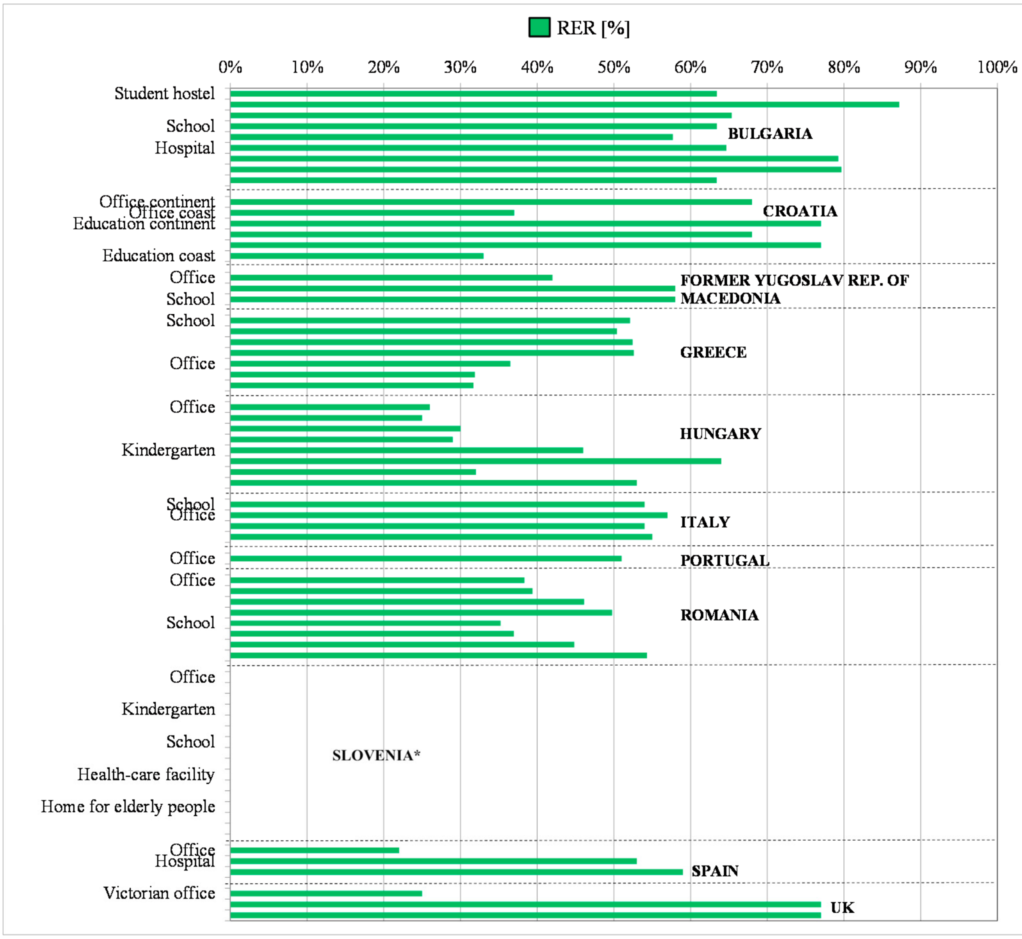
Thirty reference buildings were considered, with different end uses, geometries and thermal characteristics, representing the public building stock in the countries involved in the project. On these buildings, several different packages of retrofit measures were applied and those suitable for the nearly zero-energy purpose and at the same time cost-effective were defined.

Results show that a retrofit towards the nearly zero energy target is technically feasible in most of the cases. The refurbishment leads to a high reduction of the non-renewable primary energy consumption. Nevertheless, the costs of such retrofit measures are still too high to make the process attractive. Results should be useful for giving suggestions and guidelines to the authorities involved in the process of the public building renovation.



* Not possible to calculate the renewable energy demand. Primary energy factors not available.

Fig. 1. Non-renewable and renewable primary energy performance index ($EP_{gl,nren}$) of the nZEB solutions.



* Not possible to calculate the renewable energy demand. Primary energy factors not available.

Fig. 2. Renewable Energy Ratio (*RER*) of the nZEB solutions.

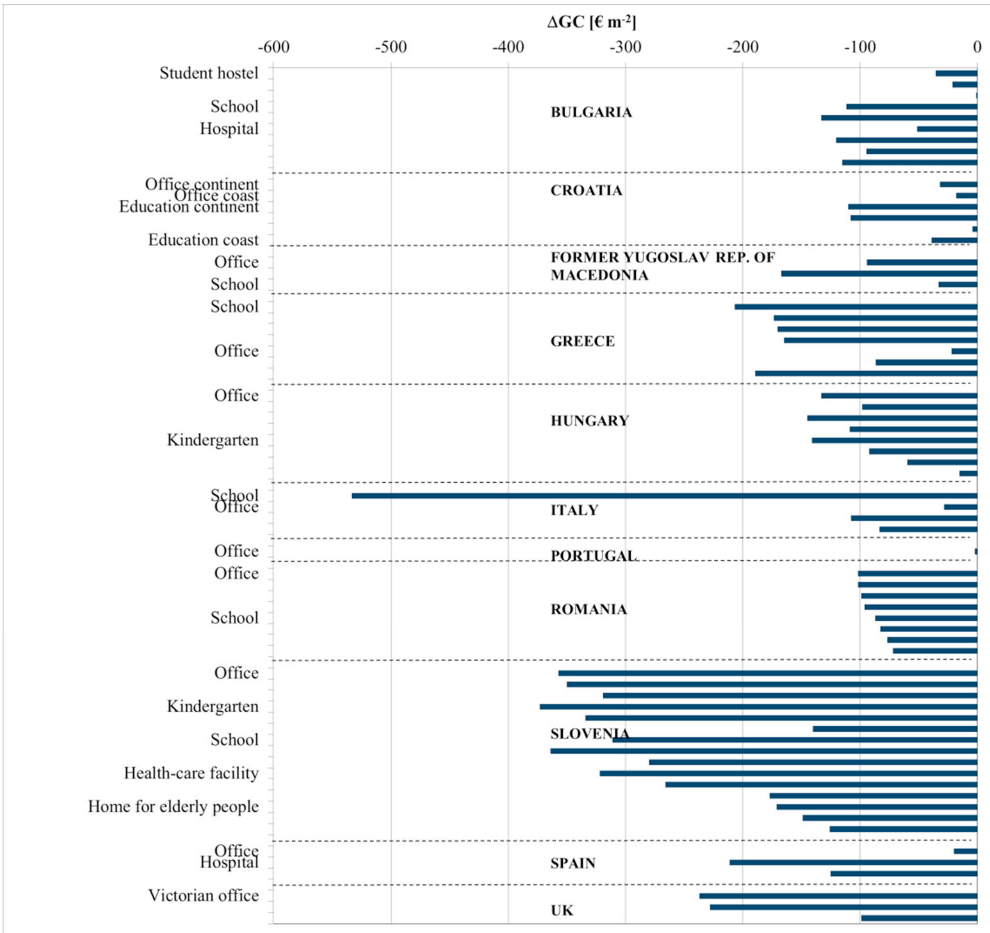


Fig. 3. Differential Global Cost (ΔGC) of the nZEB solutions.

Acknowledgements

This work is based on the IEE Project *RePublic_ZEB*, financed by the European Commission through grant agreement no. IEE/13/886/SI2.674899.

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