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Nearly-Zero Energy Buildings: Cost-Optimal Analysis of Building Envelope Characteristics

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Abstract

Energy consumption in the building sector continues to increase in the entire world and therefore, the determination of cost-optimal solutions towards nearly zero-energy buildings is a serious challenge. The present study is focused on the optimal thermal features of the building envelope, including thermal insulation on wall, roof and ground floor as well as the optimal window properties, in order to achieve nearly-zero energy buildings in the climate conditions of Cyprus. A systematic and robust scientific procedure was adapted in order to determine levels of energy performance leading to minimum life-cycle cost. Energy simulations of different reference test-cell buildings were performed, based on the external envelope's surface to total building volume ratio, and the cost-optimal performance levels were calculated in accordance with Regulation 244/2012/EU, taking into consideration three different climate areas of Cyprus – the cities of Limassol and Nicosia and the mountainous area of Saittas. Both the optimal thermal transmittance coefficient of the external envelope elements and the optimal window properties for each reference test-cell building were calculated. The results demonstrate that the cost-optimal energy performance levels of reference test-cell buildings in Cyprus are considerably higher than the national minimum requirements. Moreover, a linear correlation was found between the optimal (mean) thermal transmission coefficient and the study area, a result that underlines the necessity of forming three independent climate zones in Cyprus instead of one that exists today.

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Keywords: Nearly Zero Energy Building (nZEB); Building envelope; Cost-Benefit analysis; Thermal insulation; Glazing properties; EnergyPlus

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Nomenclature

$c_g(\tau)$ global cost referred to starting year τ_o
c_i initial investment cost
$c_{\alpha,i}(j)$ annual cost for component j at the year i (including running and replacement costs)
$V_{f,\tau}(j)$ final value of component j at the end of the calculation period
$R_d(i)$ discount rate for year i
r real discount rate for year i
U_g thermal transmittance of glazing
U_f thermal transmittance of frame
g total solar energy transmittance
τ_v light transmittance

1. Introduction

The building sector contributes greatly to global energy demand [1]. More specifically, buildings account for approximately 40% of the final energy consumption and three-quarters of global GHG emissions [2]. At this point, the influence of the building envelope cannot be underestimated on the building's energy needs, since in 2010, 37% of the total primary energy in the United States was utilized for buildings' heating and cooling [3]. It is therefore evident that there is a close relationship between building energy consumption and the building envelope.

In order to address this issue, the European Union published the Energy Performance of Building Directive 2002/91/EC (EPBD) which eventually evolved in the recast Directive 2010/31/EU. The EPBD recast focuses on the improvement of building energy performance by setting minimum requirements for buildings and building components and establishing nearly-zero energy buildings (nZEB) as a political target [4]. In addition to nZEB policy, EPBD recast goes a step further and sets a comparative methodology framework with a view to achieving cost optimal performance levels for buildings. The legal framework for the cost-optimal methodology has been published in the delegated regulation 244/2012/EU and leads to the lowest cost in accordance with the estimated economic life-cycle [5].

Along with the European legal framework, researchers focused on the cost-optimal approach, both by studying new and existing constructions. Becchio et al. presented a study investigating the different cost-optimal solutions of building and technical systems for nZEBs in Italy [6]. Bojic et al. found the optimum thickness of the insulating layer for both polystyrene and mineral wool through the development of a life-cycle cost sensitive analysis [7]. Hamdy et al. studied the combination of energy efficient measures with the parallel implementation of alternative renewable energy systems in a single family house located in Finland [8]. In addition, Kurnitski et al. presented a scientific procedure to identify nZEB energy performance levels along with the cost-optimal solutions by means of building simulation of a reference house and an office building located in Estonia [9].

The objective of the present study is to investigate and analyze the optimal energy performance levels under a cost-optimal approach in line with EBPD recast and nZEB requirements. The introduced method is applied to find the efficient combination comprising the above main aspects by using reference buildings in the form of test-cells in Cyprus. In particular, the methodology structure of the study is designed with the view of identifying the optimal thermal characteristics of the building envelope (e.g. building envelope U-values) the implementation of which lead to adequate near zero energy performance. The energy and economic assessment for each reference test-cell building is achieved by using the national requirements and energy framework as well as by taking into account the local climate conditions.

2. Methodology

2.1. Defining the energy design variables

According to the methodology, the combination of two main energy design variables related to building envelope was examined in order to obtain the optimal energy performance levels: the thermal transmittance of external building elements including wall, roof and ground floor, as well as the thermal characteristics of the external fenestration. The thermal transmittance coefficient is determined by the thermo-physical properties and thickness of the materials used to construct the element as well as the internal and external thermal resistances accounting the convention resistances on the element's surface. In the entire market there are a large number of thermal insulation materials. In the current study, extruded polystyrene was selected as the most common thermal insulation material used in Cyprus by means of the following thicknesses: 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18 and 20 cm. The second energy variable of the analysis was the thermal characteristics of the external openings comprising glazing and frame. It is obvious that the glazing thermo-optical properties have a significant influence on the total building energy demand and their optimization is considered essential [10]. In particular, in the current analysis, the examined external openings' thermal characteristics were as follows: thermal transmittance of glazing U_g, thermal transmittance of frame U_f, total solar energy transmittance g, and light transmittance τ_v.

2.2. Defining the multi-phases optimization model

The analysis of each reference test-cell building has been divided in three phases: the energy assessment, the cost-optimal assessment and the optimal energy performance level calculations.

2.2.1. Energy assessment of reference test-cell buildings

The energy assessment was conducted by means of the dynamic energy simulation software EnergyPlus. Developed by the research laboratories of the U.S. Department of Energy since 2001 [11], EnergyPlus was used to simulate the energy behavior of several buildings and evaluate their annual heating and cooling needs. In the present study the energy assessment of the reference test-cell buildings was divided in two parts. In the first part, the main variable considered was the external insulation thickness of the external wall, roof and ground floor separately. Following a systematic procedure, the annual heating and cooling needs of each reference test-cell buildings were calculated by only changing the insulation thickness from 3 cm to 20 cm, while the thermo-optical characteristics of the external openings remained constant. In the second part, the energy simulations were conducted using as main variable the opening's thermo-optical characteristics as they were presented earlier, while the thermal characteristics of external building components remained constant and equal to the previously calculated optimal insulating thickness on each reference-test cell building.

2.2.2. Cost-optimal assessment of reference test-cell buildings

The methodological framework of the European Regulation 244/2012/EU was performed for calculating the Net Present Value (NPV) and evaluating the cost-optimal energy performance levels of reference test-cell buildings. The cost-optimal energy design variable was determined by using the following formula:

$$c_g(\tau) = c_i + \sum_j [\sum_{i=1}^{\tau} \left(c_{a,i}(j) x R_d(i) \right) - V_{f,\tau}(j)] \qquad (1)$$

where, $c_g(\tau)$ corresponds to the global cost referred to starting year τ_o; c_i is the initial investment cost; $c_{\alpha,i}(j)$ is the annual cost for component j at the year i (including running costs and replacement costs); $V_{f,\tau}(j)$ is the final value of component j at the end of the calculation period; $R_d(i)$ is the discount rate for the year i, which can be written as:

$$R_d(p) = \left(\frac{1}{1 + r/100} \right)^p \qquad (2)$$

where p $(p=i)$ is the number of years from the starting period and r corresponds to the real discount rate.

According to the European Regulation 244/2012/EU, the calculation period of the global energy performance associated cost was set to 30 years since the study referred to new constructions. Due to the need for defining the optimal energy design variable in each reference test-cell building, a life cycle cost-optimal analysis with a real discount rate of 6%, was carried out, leading to the minimum Net Present Value (NPV) according to the guidance of the draft regulation. To obtain the minimum NPV, straightforward calculations were set up as follows:

- *Operation Cost (C_o)*: The operation cost included both material and labor costs of the design variable.
- *Maintenance Cost (Cm):* The maintenance cost, which includes annual costs for inspection, cleaning, adjustments, repairs and consumable items, was set to be equal to existing market cost. Specifically, it was determined as 75.00 €/a for the thermal insulation and 6.00 €/piece for the external openings.
- *Energy Cost (C_e):* Energy cost was considered for space heating and cooling. In accordance to the needs of cost-optimal assessment analysis, two typical conventional systems, which are widely used in Cyprus, were proposed for heating and cooling; an oil-fired burner-boiler system for heating and an air-to-air split type heat pump system for cooling. In order to calculate the annual final energy consumption of each reference test-cell building, the heating energy need was divided by the boiler's energy efficiency (η_{boiler} = 0.92), the efficiency of the distribution system (η_d = 0.94), and the efficiency of the emission system (η_{em} = 0.89). In addition, the electricity consumption of the heat pumps in order to provide space cooling was retrieved by the annual cooling needs of each reference test-cell building using a seasonal energy efficiency ratio (SEER = 5.3). Finally, the calculated amounts of final energy consumption were multiplied by the current Cypriot final energy costs which were: 0.089 €/kWh_t for heating oil and 0.20 €/kWh_e for electricity. It is worth mentioning that as this analysis was run for a period of 30 years, a mean annual energy inflation rate per year was applied equal to 3.3% for heating oil and 3.6% for electricity, respectively.

2.2.3. Optimal energy performance level calculations

The last stage of the optimization method was the calculation of energy performance levels of the examined reference test-cell buildings. The calculations followed the methodological framework of the Building Insulation Guide, which is issued by the Energy Service of the Ministry of Energy, Commerce, Industry and Tourism of Cyprus [12]. Through the above mentioned guidance, the thermal transmittance coefficients were calculated for the external building components, including external walls, roof and ground floor as well as for the external openings.

3. Defining reference test-cell buildings

3.1. Geometrical parameters of building envelope

There is a close connection between geometrical parameters of the building envelope and its energy performance level. In fact, the exterior exchange surface is defined by the building shape and primarily the thermo-physical properties of the building envelope determine the loss or gain of thermal energy [13]. According to the European Committee for Standardization proposal, there is a significant parameter describing the shape of a building: the compactness ratio, which is defined as the ratio of the thermal external envelope area (A_e) in m^2 to the total building volume (V) in m^3 [14]. To meet the needs of the current analysis, the following A_e/V ratio values were selected: 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, and 1.2. Moreover, each reference test-cell building was located in a freestanding plot, in which the main façade was oriented due south. Besides, the proportion of the external openings in each surface was based on a common bioclimatic practice applied in Cyprus where they should not exceed the 50% of the southern area, 30% of the eastern area, 10% of the northern area and 10% of the western area.

3.2. Construction layers of the reference test-cell elements

The energy optimization analysis has led to the choice of particular construction layers, including the vertical elements (external wall) and the horizontal ones (roof and ground floor). Both vertical and horizontal elements were considered common to all modeled reference test-cell buildings apart from the thermal insulating layer and the thermo-optical characteristics of the external windows, which were defined as the energy design variables of the analysis. The details of the construction layers of the reference test-cell building elements are as shown in Table 1.

Table 1. Construction layers of reference test-cell elements.

External wall		Roof		Ground floor	
Layer description	Thickness [mm]	Layer description	Thickness [mm]	Layer description	Thickness [mm]
Plaster (cement-lime mortar)	150	Extruded polystyrene	-	Marble tiles	20
Extruded polystyrene	-	Asphalt membrane	70	Cement mortar	20
Brick masonry	200	Lightweight concrete	40	Lightweight concrete	40
Plaster (cement-lime mortar)	150	Reinforced concrete	150	Reinforced concrete	150
		Lime plaster	20	Extruded polystyrene	-

3.3. Input conditions of thermal zone

The thermal properties of the envelope, the internal heat gain of people, appliances and lighting were assigned to the reference test-cell buildings through the EnergyPlus software. In particular, all the reference test-cell buildings had the same thermal zone schedules as long as the optimization analysis examined the two specific design variables already mentioned. Due to the fact that the final results of the energy assessment refer to total annual heating and cooling loads, the year was divided into summer and winter periods: summer refers to the period from May to September and winter from October to April. Hence, two separate schedules for the desired indoor temperature, air ventilation and infiltration, and lighting were used for summer and winter respectively, whereas the schedules for appliances and people space occupancy remained constant all over the year (Table 2). It is worth mentioning that the indoor desired conditions are selected in accordance to EN 15251 [15] suggestions, while the time schedule profiles are created based on local practice.

Table 2. Indoor desired conditions and internal gains.

Input data	Period	Daily Schedules				
Indoor Temperature	Winter	22 °C (7:00-21:00)			20 °C (22:00-6:00)	
	Summer	25 °C (8:00-21:00)			27 °C (22:00-7:00)	
Ventilation & Infiltration	A year	0.8 ach (0:00-23:00)				
Appliances (1000 W)	A year	75% (7:00)	40% (8:00-11:00)	50% (12:00-14:00)	35% (15:00-21:00)	10% (22:00-06:00)
People (1/30 m^2)	A year	100% (07:00)	25% (8:00-14:00)	50% (15:00-20:00)	80% (21:00-23:00)	100% (24:00-6:00)
Lighting (5 W/m^2)	Winter	50% (07:00)	0% (08:00-17:00)	75% (18:00-21:00)	30% (22:00-23:00)	0% (24:00-06:00)
	Summer	0% (01:00-19:00)	65% (20:00-21:00)	30% (22:00-23:00)	15% (00:00)	

4. Definition of the design climatic conditions

Cyprus, as part of the Mediterranean region, has an intense climate with seasonal characteristics described by hot dry summers from mid-May to mid-September and moderately rainy winters from November to mid-March. For the energy multi-optimization process, two cities and a village were chosen, as representative of the different climate characteristics of the island: the city of Limassol, which is located in the south coast area and characterized by wet and hot climate; the city of Nicosia, the capital of Cyprus, located at the center of the island and has relatively warm and dry summers and mild winters; and Saittas, a typical mountainous village, which is located in the Troodos mountain terrain and characterized by mild summers and cold winters. Climate data, considering a typical meteorological year, were retrieved from the METEONORM ver.7.2 meteorological database and the climate details were given for each one of the selected locations.

5. Results and Discussion

5.1. Optimal thermal transmittance coefficients of external building components

An overview of the optimal thermal transmittance coefficients calculated using the methodological framework of the Building Insulation Guide for specific external components is shown in Table 3.

Table 3. The optimal thermal transmittance coefficients of external building components.

A_e/V	Limassol			Nicosia			Saittas		
	Ground floor	Roof	External wall	Ground floor	Roof	External wall	Ground floor	Roof	External wall
0.2	0.28	0.36	0.37	0.28	0.34	0.33	0.20	0.29	0.27
0.3	0.28	0.38	0.37	0.27	0.34	0.33	0.24	0.29	0.27
0.4	0.30	0.38	0.37	0.29	0.34	0.33	0.25	0.29	0.27
0.5	0.34	0.38	0.37	0.32	0.34	0.33	0.27	0.29	0.27
0.6	0.34	0.38	0.39	0.32	0.34	0.35	0.29	0.29	0.28
0.7	0.37	0.38	0.39	0.37	0.34	0.35	0.31	0.29	0.28
0.8	0.40	0.38	0.39	0.38	0.36	0.35	0.33	0.30	0.28
0.9	0.44	0.38	0.39	0.41	0.36	0.35	0.35	0.30	0.28
1.0	0.45	0.38	0.39	0.42	0.36	0.35	0.37	0.30	0.30
1.1	0.49	0.38	0.39	0.45	0.36	0.35	0.39	0.30	0.30
1.2	0.51	0.38	0.39	0.47	0.36	0.35	0.40	0.30	0.30

The results are presented taking into consideration the examined building components, namely ground floor, roof and external wall by the corresponding A_e/V ratio and distinguishing between the three climate areas. In fact, the results were derived using as a main energy design variable the thermal transmittance of the studied components and particularly considering thirteen different values of insulation thickness. Following the multi-stage optimization process for each specific case presented in Table 3, comprising energy simulation and assessment as well as cost-optimal analysis, the optimal insulating thickness was defined and then the optimal thermal transmittance coefficient was calculated.

From the comparative point of view, there is a linear correlation between optimal thermal transmittance coefficients and the A_e/V ratio. Specifically, while A_e/V ratio values increase from 0.2 to 1.2, the values of optimal thermal transmittance coefficients for ground floor, roof and external walls are raised from 0.28 $W/(m^2 \cdot K)$ to 0.51 $W/(m^2 \cdot K)$, 0.36 $W/(m^2 \cdot K)$ to 0.38 $W/(m^2 \cdot K)$ and 0.37 $W/(m^2 \cdot K)$ to 0.39 $W/(m^2 \cdot K)$, respectively. Important considerations regarding the significant distributions of the optimal energy performance levels can be drawn from these results. The values of optimal thermal transmittance coefficients derived from the analysis show a linear reduction moving from the outward to the inward area of Cyprus. It is therefore evident that there is a differentiation of the values moving from one area to another; this suggests that there is a need for the creation of a spatial energy map of Cyprus. In this case, it is possible to create three energy performance climate zones: the coastal area resulting from the Limassol analysis, the mainland zone resulting from the analysis of Nicosia and the mountainous zone resulting from the analysis of Saittas.

5.2. The optimal thermal characteristics of external openings

This sub-section presents the results of the multi-stage optimization analysis carried out in order to determine the optimal energy performance characteristics of external openings. The analysis was carried out using as main energy design variable the thermal characteristics and properties of the studied external openings and particularly considering eight different scenarios, comprising glazing and frame (Table 4).

On this basis, it was evident that scenario no. 4 was clearly the proper cost-optimal scenario for all A_e/V ratio values as well as for all examined climate areas. Taking into consideration the above mentioned glazing and frame features and using the methodological framework of the Building Insulation Guide, the optimal mean thermal transmittance coefficient for the external openings was calculated equal to 1.67 $W/(m^2{\cdot}K)$. This value seems to be significantly lower than the 2.25 $W/(m^2{\cdot}K)$ that it is indicated by the 366/2014 local decree and prescribes the minimum national energy performance level for achieving nearly zero energy buildings.

Table 4. Thermo-optical characteristics of the windows.

Scenario	U_g	U_f	g	τ_v	Investment Cost[1]	
					Frame (€/item)	Glazing (€/m^2)
Baseline	5.8	5.8	0.9	0.9	250	22
1	2.8	2.8	0.8	0.8	405	30
2	2.8	2.0	0.5	0.6	405	37
3	2.0	2.0	0.5	0.6	490	37
4	2.0	1.6	0.5	0.8	490	47
5	2.0	1.6	0.3	0.5	490	52
6	1.6	1.6	0.5	0.8	508	47
7	1.6	1.6	0.3	0.5	508	52

[1]Investment cost represents the actual prices paid by the customers including all applicable taxes.

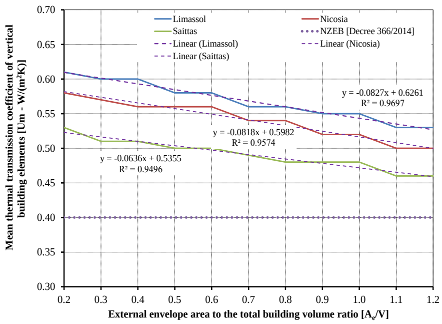

Fig. 1: The optimal mean thermal transmittance coefficients for vertical building elements [Um] in relation to the external area to total building volume ratio [A_e/V].

5.3. The optimal mean thermal transmittance coefficients for vertical building elements

The last part of the multi-stage optimization methodology is the definition of the optimal mean thermal transmittance coefficients for vertical building elements. Using the results shown in Table 3 and in sub-section 5.2, for external walls and openings respectively, and following the methodological framework of the local Building Insulation Guide, the optimal mean thermal transmittance coefficients regarding to A_e/V ratio were calculated as illustrated in Figure 1.

The results are comparable with the maximum mean thermal transmittance coefficient, 0.40 W/(m^2·K), provided by the local decree 366/2014. By reviewing the results of the mean thermal transmittance coefficient derived through the multi-stage optimization methodology (Figure 1), it can be observed that they are comparatively higher than the one indicated by the 366/2014 decree. It is also obvious that there is a linear correlation between the calculated optimal mean thermal transmittance coefficient and the A_e/V ratio when moving gradually from a ratio of 0.2 to 1.2. The analyzed optimal mean thermal transmittance coefficient displays a falling trend, which is similar for all studied climate areas.

6. Conclusions

The main conclusions drawn from the multi-stage simulation-based optimization method in order to find the cost-optimal and nearly-zero energy performance characteristics for nearly zero energy buildings in Cyprus using a range of reference test-cell buildings, could be summarized as follows:

1. There is a linear correlation between optimal mean thermal transmittance coefficient of the vertical building elements and the A_e/V ratio, since an increase in the ratio leads directly to a rise in the mean thermal transmittance coefficient.
2. It is considered essential to create a spatial energy map of Cyprus due to the significant fluctuation of the optimal calculated performance characteristics of the building elements, when moving from the southern coastal areas to the mainland areas of Cyprus.
3. The optimal defined mean thermal transmittance coefficient for external windows is 1.67 W/(m^2·K) and is considered significantly lower than the one indicated by the 366/2014 decree for all studied A_e/V ratios and climate areas.
4. The optimal mean thermal transmittance coefficients for vertical building elements, comprising external walls and openings, are comparatively higher than the ones indicated by the 366/2014 decree.

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