Multi-objective optimization to promote nearly zero-energy buildings in Portugal

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Abstract

The promotion of nearly zero-energy buildings (nZEB) became mandatory for the European Union since the recast of the Energy Performance of Buildings Directive, occurred on 2010.
Thus, Directive 2010/31/EU requires that, by 31 December 2020, all new buildings, or buildings undergoing major renovation, are buildings with reduced energy needs. The very low amount of energy required should be largely covered by energy from renewable sources. Moreover, Member States are required to set their own nZEB goal, establishing minimum requirements for the energy performance of buildings, which had achieved cost-optimal levels.
In this paper a multi-objective model is proposed to solve this problem through a genetic algorithm. This model is applied to a case-study (a dwelling located in Lisbon, Portugal), in order to determine a numerical indicator for the energy balance and to define the share of renewables considered suitable for residential buildings with the same localization.
From the application of the model to a reference dwelling and the analysis of its results, it was concluded that a numerical indicator for the energy balance of 29,58 $kWh_{ep}/(m^2.year)$ is suitable for an average residential building located in Lisbon and subject to major intervention works. Still, for the same building, the share of renewables should be at least equal to 48.5%.

Keywords: Energy Performance of Buildings Directive Recast, Nearly Zero-energy Buildings, Multi-objective optimization

1. Introduction

Nowadays, buildings account for 40% of total energy demand in the European Union. With the expansion observed in this sector, this value is expected to increase. Therefore, promoting energy efficiency by reducing energy demand and exploiting energy from renewable sources is an essential measure to reduce the energy dependence of the European Union (EU) and greenhouse gas emissions (Dir 2010/31 / EU).

The EU stated that by 2030, at least 27% of energy demand in EU must be covered by energy from renewable sources; at least a reduction of 40% on greenhouse gas emissions must be achieved (compared with the corresponding 1990's levels); and, there must be an improvement on energy efficiency of, at least, 27% (European Comission. 2016).

Consequently, the EU has been taking various actions in different areas so that these goals are met. Thus, the European Union launched the Energy Performance Building Directive Recast, in order to promote the creation of nearly zero-energy buildings (high energy performance buildings with a low energy consumption, whose residual energy needs are, as much as possible, covered by renewable energy, achieving these objectives being also economically feasible).

In Portugal, however, this policy implementation has not been completed yet. It is being planned and it is necessary to establish the numerical indicator for maximum primary energy demand allowed for new buildings and buildings undergoing major renovation, and for the minimum share of renewables (Ecofys, 2014).

The objective of the present paper is to analyse the implementation of EPBD Recast and develop a multi-objective optimization model to help the Portuguese decision on the minimum energy requirements for buildings, evaluating the application of energy efficiency measures by their cost-effectiveness levels. To do this a Genetic Algorithm (GA) model is proposed and applied to a reference dwelling in a case-study.

The paper is structured as follows: in Section 2, the main problem characteristics are presented and the implementation of Directive 2010/31/EU among the Member States countries is analysed. In Section 3, relevant literature on optimization for creating nZEB buildings is reviewed. Then, the mathematical model is presented in Section 4. In Section 5, the model is applied to a case-study and the results are compared. A sensitivity analysis is conducted in order to improve the current optimization model. Finally, in section 6 some conclusions are drawn.

2. Problem contextualization

2.1 Nearly Zero-energy Buildings

Voss *et al.* (2012) explicit how the energy balance is defined through the chart of Figure 1. In this graph, the so-called reference building is a new building, built in order to meet the minimum requirements of the respective legislation. This building is the starting point for achieving the NZEB goal. In the x-axis of the graph the current building energy demand is represented. This is first minimized by applying energy efficiency measures such as the improvement of thermal insulation of windows or facades, or substitution of appliances by others with increased efficiency. On the other hand, the generation of renewable energy - the y-axis - compensates the energy needs of the building. Consequently, when the power generation fully makes up the energy needs, the building has a net-zero energy balance (NZEB). Contrarily, if it only partially compensates the building's energy needs, then it means a nearly-zero balance (nearly zero-energy building - nZEB). Finally, if it generates more energy than it consumes, it is a plus energy building.

In detail, for the EPBD Recast, a nearly zero-energy building means "a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby". So, it defines the building as a boundary for the energy balance calculation.

2.2 EPBD Recast implementation

According to the information provided by the European Commission through publications on the progress of the implementation of Directive 2010/31/EU, from the twenty-eight countries of

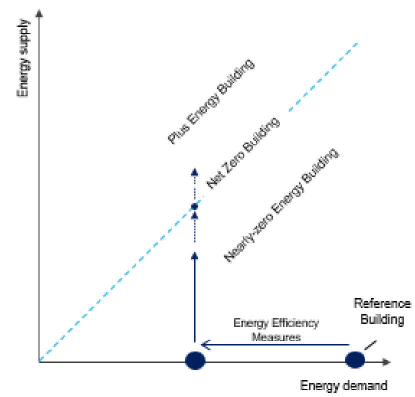

Figure 1 - Graph depicting the concept of NZEB, adapted from: Voss *et al.*, 2012.

the EU, slightly more than half of them (fifteen countries and two of the three regions in which Belgium is divided) already have a description of the application of buildings with nearly zero-energy requirements for new buildings (BPIE, 2015).

Regarding the numerical indicator for the use of primary energy, from the Member States which have it established, this value varies between 20 kWh/(m^2.year) and 270 kWh/(m^2.year) However, as can be seen in Table 1, not all the Member States have defined this indicator directly on kWh/(m^2.year) units. Moreover, it is important to mention that this indicator refers different kinds of energy demand. Some include electric devices and auxiliary systems besides the energy needs for space and water heating, space cooling, lighting and ventilation as required by the EPBD recast. Also, in some cases, this numerical indicator is not clearly defined.

Regarding the requirements for the share of renewable energy, again, there is no uniformity. According to BPIE (2015), there are both qualitative and quantitative definitions relating to buildings classified as nZEB.

Finally, the EPBD recast requires Member States to promote policies and trigger financial measures to foster the creation of nearly zero-energy buildings. The chart of Figure 2 shows the

Table 1 – Summary of the numerical indicator definition for the use of primary energy in nZEB buildings by the various Member States – Sources: BPIE (2015); COM (2013); Ecofyz (2014); Kurnitski *et al.* (2014).

Member State	Maximum value for primary energy [kWh/(m^2.year)]				This indicator refers to:							
	New buildings		Buildings undergoing major renovation									
	Residencial	Non-residencial	Residencial	Non-residencial	Heating	Cooling	HW	Ventilation	Lighting	Eletric devices	Auxiliar systems	ND
Austria	160	170	200	250								x
Belgium (Brussels)	45	~90 [1]	54	~108 [1]	x	x [2]	x		x [2]	x		
Belgium (Flanders)	30% PEref [3]	40% PEref [3]	ND	ND	x	x	x	x			x	
Croatia	33-41 [4]	Being developed	ND	ND	x	x	x	x	x			
Cyprus	100	125	100	125	x	x	x		x			
Czech Republic	75%-80% [1,3]	90% [3]	75%-80% [1,3]	90% [3]								x
Denmark	20	25	20	25	x	x	x	x	x [2]			
Estonia	50-100 [1]	90-270 [1]	ND	ND	x	x	x	x	x	x	x	
France	40-65 [1,4]	70-110 [1,4]	80[4]	60% PEref [1]	x	x	x		x		x	
Ireland	45	~60% PEref	75-150	ND	x		x	x	x			
Latvia	95	95	95	95	x	x	x	x	x			
Lithuania	Included in the calculation method; The building has to fulfill the requirements for A++ levels.		Included in the calculation method; The building has to fulfill the requirements for A++ levels.		x							
Luxembourg	Included in the calculation method; The building has to fulfill the requirements for A-A-A levels.		ND	ND								x
Netherlands	Included in the calculation method; The building has to achieve na energy performance coefficient of 0.		ND	ND	x	x	x	x	x			
Romania	93-217 [1,4]	50-192 [1,4]	ND	ND								x
Slovakia	32-54 [1]	34-96 [1]	SD	SD	x	**x [2]**	x	**x [2]**	**x [2]**			
United Kingdom	~44 [1]	ND	ND	ND								x
	Included in the calculation method; The building has to fulfill the requirements for carbon emissions levels ~0.											

Notes:

[1] – It depends on reference building

[2] – Only for non-residential buildings

[3] – It depends on location

[4] – This requirement depends on the renewable energy measures adopted

PEref – Primary energy consumption of the corresponding reference building

ND – No data

main policies and measures taken by Member States. In addition, it should be noted that several countries have not taken any step in this direction (Ecofys, 2014).

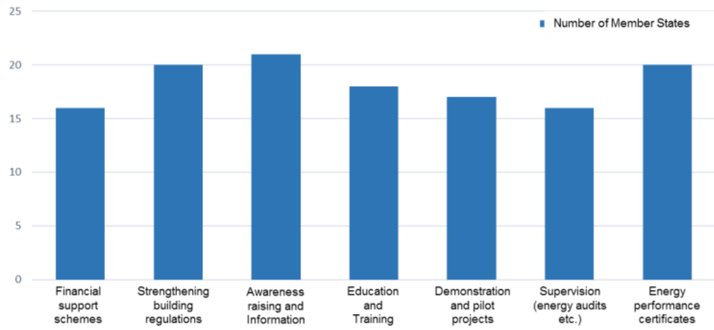

Figure 2 - Main policies and measures in support of nZEBs in Member States – Source: Ecofys (2014).

3. Literature review

When planning and design of buildings NZEB, the decision-making process requires the evaluation of several conflicting objectives: costs minimization; energy savings maximization; comfort maximization, among others. In this context, it becomes relevant the application of multi-objective optimization.

Thus, the main multi-objective optimization function is finding efficient solutions which can be considered while the construction or renovation of a building is planned in order to meet the NZEB goal.

Being so, the literature concerning the application of multi-objective optimization models to the design and renovation of buildings in order to improve the energetic performance was analysed. Table 2 summarizes the literature review.

From the state of the art, it can be concluded that the metaheuristics approach is preferred for the resolution of such problems. This is justified by the fact that this approach is less computationally intensive, revealing a higher efficiency than the exact approach, achieving good solutions to the problem. Nonetheless, optimal solutions are not guaranteed to be achieved.

In particular, from this approach, NSGA-II was the most common method used. This method consists in a genetic algorithm in which the chromosomes are classified and, consequently, the non-dominated solutions are easily obtained.

Finally, the majority of the case studies was applied in European countries and takes into account objective functions aimed at determining cost-efficient solutions that are energetic efficient too. This can be justified by the launch of the EPBD recast.

4. Optimization model

First of all, it is worth mentioning that Directive 2010/31/EU focuses on energy needs for space heating and cooling; water heating; ventilation and lighting. However, for the development of the optimization model described in this section, only the space heating and cooling and water heating needs will be considered.

Specifically, for the formulation of the optimization model, it is necessary to define the decision variables, constraints and objective functions. So, these aspects are described in the following subsections.

4.1 Decision variables

When defining the decision variables, it was considered the optimization models developed by Monteiro et al. (2016) e Eilhauer (2015).

The sets of decision variables considered in the current model are shown in Table 3.

Table 3 – Decision variables set for the multi-objective optimization model.

Set of decision variables	Nomenclature
Device for water heating	x_j^W
Device for space heating	x_j^S
Device for space cooling	u_j
Windows type	y_j
Shading type	v_j
External insulation material	w_j
Supply Option	p_j

4.2 Constraints

To find the set of optimal solutions, the model resolution considers five main constraints, explained below.

Meeting energy needs for space heating

It is required that the devices used for space heating are able to, at least, meet the corresponding energy needs. Thus, in this constraint the decision variables for space heating (combined with the respective performance characteristics) are included. Also, on the other side of the inequality, it considers the variables that have an impact on the structure of the building - which, consequently, will determine the energy. Among these last variables, it is included: the windows type, the shading device and the external insulation material.

Table 2 – Summary of the literature review.

Research work	Application	Location	Objective Function	Approach	Method
Antipova *et al.* (2014)	Twin building	Portugal (Center)	1. Minimize total cost; 2. Minimize environmental impact.	Exact	MILP
Asadi *et al.* (2014)	School	Coimbra, Portugal	1. Minimize energy consumption (total); 2. Minimize investment costs; 3. Minimize thermal disconfort.	Metaheuristic	GA and ANN
Ascione *et al.* (2015)	Residential Building	Naples, Italy	1. Minimize thermal disconfort; 2. Minimize primary energy consumption by ar conditioning system.	Metaheuristic	Controled elitist GA
Ascione et al. (2016)	Hospital	Italy (South)	1. Minimize investment costs; 2. Minimize variation on primary energy consumption; 3. Minimize difference on global cost.	Metaheuristic	Controled elitist GA
Azari *et al.* (2016)	Office building	Seatle, USA	Mimize the impact troughout the life cycle	Metaheuristic	NSGA-II and ANN
Carluccia *et al.* (2015	House	Italy (South)	1. Minimize thermal disconfort felt during winter; 2. Minimize thermal disconfort felt during summer; 3. Minimize visual disconfort due to intense brightness; 4. Minimize visual disconfort due to an inappropriate quantity of daylight.	Metaheuristic	NSGA-II
Delgarm *et al.* (2016)	Room in a building with several floors	Iran (several climate zones)	1. Minimize annual consumption of eletricity for lighting; 2. Minimize annual consumption of eletricity for space cooling; 3. Minimize annual consumption of eletricity for space heating.	Metaheuristic	PSO
Eilhauer (2015)	Apartment and house	Lisbon, Portugal	1. Minimize LCOT; 2. Minimizar energy consumption (space and water heating and space cooling).	Metaheuristic	NSGA-II
Gossard *et al.* (2013)	House	Nancy and Nice, France	1. Minimize annual energy consumption; 2. Minimize thermal disconfort felt during summer.	Metaheuristic	NSGA-II and ANN
Hamdy *et al.* (2013)	House	Finland	1. Minimize LCC; 2. Minimize primary energy consumption.	Metaheuristic	PR-GA
Hasan (2011)	House	Finland	1. Minimize investment costs; 2. Minimize energy consumption for space heating.	Metaheuristic	Combines simulation and GA
Magnier & Haghighat (2010)	Twin building	Canada	1. Minimize thermal disconfort; 2. Minimize energy consumption from HVAC systems.	Metaheuristic	NSGA-II and ANN
Malatji *et al.* (2013)	Building with 25 facilities to be intervened	South Africa	1. Maximize energetic savings; 2. Minimize payback period.	Metaheuristic	GA with penalty function
Monteiro *et al.* (2016)	School	Lisbon, Portugal	1. Minimize investment costs; 2. Minimize energy needs (heating and cooling).	Metaheuristic	NSGA-II
Murray *et al.* (2014)	University building	Ireland	1. Minimize energy costs; 2. Minimize payback period; 3. Minimize carbon emissions.	Metaheuristic	GA
Penna *et al.* (2015)	Several buildings	Italy	1. Minimize NPV; 2. Minimize thermal disconfort; 2. Maximize energetic performance for heating.	Metaheuristic	GA
Shao *et al.* (2014)	Office building	Germany	1. Minimize investments costs; 2. Minimize energy consumed annually; 3. Minimize greenhouse gases emissions.	Metaheuristic	NSGA-II
Son e Kim (2016)	University building	South Corea	1. Minimize energy consumption; 2. Minimize CO2 emissions; 3. Minimize investment costs; 4. Maximize thermal confort.	Metaheuristic	NSGA-III
Tadeu *et al.* (2016)	T2	Amarante, Portugal	1. Minimize global costs; 2. Minimize primary energy consumption.	Metaheuristic	NSGA-II
Wang *et al.* (2005)	Office building with one floor	Montreal, Canada	1. Minimize LCC; 2. Minimize environmental impact on the building's life cycle .	Metaheuristic	Structered GA
Wang et al. (2014)	Building with 25 facilities to be intervened	South Africa	1. Maximize energy savings; 2. Minimize payback period.	Metaheuristic	DE
Wang *et al.* (2015)	University Campus	Stockholm, Sweden	1. Minimize LCC; 2. Minimize greenhouse gases emissions.	Metaheuristic	NSGA-II

Meeting energy needs for space cooling

Similarly to the previous constraint, it is required that the devices used for space cooling are able to, at least, meet the corresponding energy needs. So that, in this constraint enter the decision variables for space cooling (combined with the respective performance characteristics). Also, on the other side of the inequality, there are the variables that have an impact on the structure of the building (as referred for the before).

Meeting energy needs for water heating

Also, it is required the meeting of the energy needs for water heating. However, in this case, this constraint only depends on the available devices for water heating and on their corresponding performance characteristics.

Number of options that can be put in practice

This constraint comprises several others due to the existing limitations for the simultaneous implementation of decision variables with the same function. For instance, just one option for the windows type must be choosen.

Additionally, the occupied area with solar panels should be limited to the available roof area.

4.3 Objective functions

This model considers two objective functions: the energy balance minimization and the life-cycle costs minimization. These two objectives will allow to evaluate several energetic effiency measures as asked by the EPBD recast. So, specifically, this is a bi-objective model.

Energy balance minimization

In other words, this objective function refers to the minimization of the difference between the amount of energy consumed and energy produced. Furthermore, this will be calculated on an annual basis and converted to primary energy values. Thus, when referring to the energy consumption amount, this is given by the sum of the energy consumption resulting from the application of the space heating and cooling appliances and water heating devices. On the other hand, the portion corresponding to the energy production is given by the sum of the energy produced by the solar thermal and photovoltaic panels, where the first is considered as options for the water heating.

Life-cycle cost minimization

The life-cycles cost includes the investment costs incurred to install the various decision variables, the operating cost due to the energy consumption and the replacement costs of the devices.

5. Case-study

5.1 Reference Building

For the application of the developed model, it was established a reference building, located in Lisbon, built between 1960-1990 and representative of residential buildings with the same localization. Therefore, the data from the Portuguese Census of 2011 was analysed and it was determined the average characteristics of the buildings.

In particular, this model was applied to a dwelling of the defined reference building. Afterwards, it is possible to extrapolate the results for the entire building.

Table 4 – Characteristics of the reference dwelling.

Model parameter	Value
Floor area	98,1 m^2
Exterior windows area	21,9 m^2
Exterior walls area	50,9 m^2
Roof area	0 m^2
Roof area available for solar panels	16,4 m^2
Conventional number of occupants	3 people

It is important to mention that the reference dwelling is situated on the middle of a building with three floors. So, that is the reason for the value of the roof area. Moreover, it will be ignored the heat exchanges between the floors of the building. It will only be consired the heat exchanges with the exterior.

5.2 Model Application

For the application of the model, it was used the MATLAB software. Despite being a model multi-objective, given the function limitations "gamultiobj ()" MATLAB (which, among other limitations, does not allow the definition of decision variables as integers) was necessary to transform the model for a single objective function in order to be able to run using the tool "ga ()". Thus, the transformation of the two objective functions, resulted in the function represented by the expression [1], where λ is a coefficient by which each function is evaluated.

$$[1]\ f = \min(\boldsymbol{\lambda}.f_1(x) + \boldsymbol{\lambda}.f_2(x))$$

As a result, to obtain the Pareto Curve, it was needed to run the model several times, changing the coefficient at each time.

5.3 Results

After the model application, it was obtained the solutions shown on Figure 3 and Tables 5 and 6.

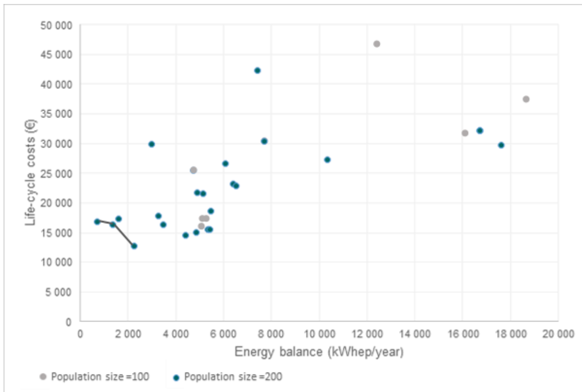

Figure 3 – Obtained results from the model resolution.

However, since the only available device for space cooling was the air conditioner and as it can also be used for space heating, to run the model the constraint "meeting energy needs for space cooling" was not considered in order to allow a higher degree of freedom in the results.

From Figure 3 and Table 5, with an initial analysis of the three non-dominated solutions (the Pareto Curve as represented by the grey lines), it is noted that the solution that minimizes the energy balance ("Point 1") can reach such a low amount of energy balance due to energy savings on energy consumption for space cooling.

In contrast, the solution of "Point 3" (the point with the lower y-axis value), it is highlighted that the non-investment on shading is one of the reasons why the LCC is lower.

Table 6 – Non-dominated solutions: characteristics (continuation).

Point	Energy Balance $\left(\frac{kWh_{ep}}{year.m^2}\right)$	LCC $(€/m^2)$	N_w $\left(\frac{kWh}{m^2.year}\right)$		N_s $\left(\frac{kWh}{m^2.year}\right)$		U_{wind} $\left(\frac{W}{m^2.°C}\right)$		U_w $\left(\frac{W}{m^2.°C}\right)$		$F_o.F_f$	%REN[1]
1	7,6	172,01	17,21	-61%[4]	34,00	+4%[5]	2,64	-34%[6]	0,34	-80%[7]	0,86	78,6%
2	14,2	166,91	25,64	-42%[4]	30,40	-7%[5]	2,99	-25%[6]	0,77	-55%[7]	0,8	68,0%
3	23,2	131,04	20,97	-52%[2]	34,11	+4%[3]	3,6	-10%[4]	0,36	-79%[5]	0,9	54,5%

Both solutions show a reasonable reduction on energy needs for space heating (N_w), when compared to the reference dwelling. This is justified by the investment on new windows and insulation material. Moreover, to better understand these values, it was calculated the limit value for N_w as imposed by the legislation (Portaria N.º 349-B/2013). This calculation results on the maximum allowed value for N_w: N_{wmax} =25,38 $kWh/(m^2.year)$, for all new buildings. Thus, both, "Point 1" and "Point 3" comply with the law requirements. However, the same was performed to the space cooling energy needs (N_s), $N_{smax} = 20,74\ kWh/(m^2.year)$, and it was concluded that none of the solutions are in compliance with the requirements.

5.4 Sensitivity analysis

From the results, it became relevant to investigate how they would be affected if the energy balance was measured in final energy instead of primary energy and, also, what will be the solutions if they were obliged to comply with the requirements for the maximum space heating and cooling needs. As so, it was performed a sensitivity analysis, making some alterations to the initial model.

5.4.1 Energy balance measured in final energy

The results from this sensitivity analysis are presented by Figure 4.

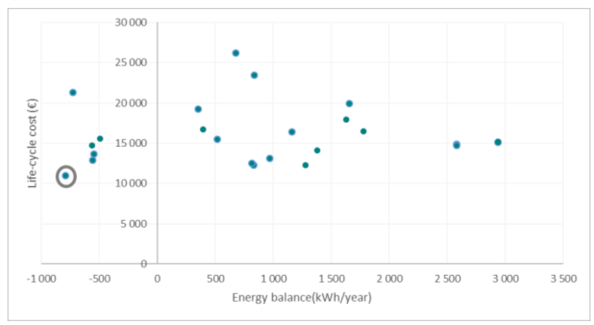

Figure 4 – Obtained results when energy balance is measured in final energy.

Figure 4 shows that when the energy balance is measured in final energy, it is possible to achieve negative balances. It means that the building supplies more energy than it demands ("plus energy building" as referred in 2.1). Therefore, it can be concluded that it is easily to achieve the NZEB goal when energy balance is evaluated by final energy. Still, these results reinforce the relevance of the placement of solar panels in residential buildings for their self-consumption.

5.4.2 Compliance with the limit values for the energy needs

Since Portaria nº 349/B-2013 requires $\frac{N_w}{N_{wmax}} < 1,25$ and $\frac{N_s}{N_{smax}} < 1,25$ for buildings built in the period 1960-1990, a penalty was added to the model when the solutions did not comply with the legislation. In addition, this model resolution considers the restriction "meeting the space cooling needs".

Therefore, Figure 5 and Table 6 shows the results for this model application.

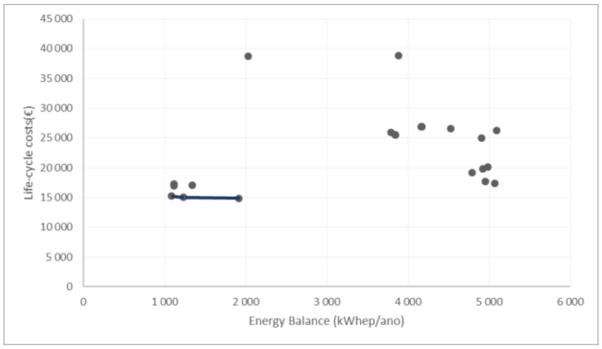

Figure 5 – Obtained results when it is mandatory the compliance with legislation.

The solutions in the Pareto Curve (represented by the blue line in Figure 5) were analysed in detail, being noticed the existence of a photovoltaic panel oversized for the self-needs. Consequently, the obtained results presented by Table 6 were recalculated in order to resize of the photovoltaic panel. The new results are described in Table 7.

Table 7 – Recalculated values for the non-dominated solutions previously obtained.

Point	Energy Balance* ($kWh_{ep}/year$)	LCC* (€)	Energy Balance* ($kWh_{ep}/(year.m^2)$)	LCC* (€/m^2)	%Photovoltaics[6]	%REN[7]	New photovoltaics panel dimension
1	2.902,00	11.888	29,58	121,19	48,5%	62,1%	5 m^2
2	2.823,40	12.120	28,78	123,55	56,8%	84,0%	6 m^2
3	2.597,80	13.584	26,48	138,48	100%	100%	8 m^2

The solutions presented in Table 7 show an energy balance from $26{,}48\, kWh_{ep}/(m^2.year)$ to $29{,}58\, kWh_{ep}/(m^2.year)$. Thus, with an increment of 12,5% in LCC, it is possible to move from the solution where LCC presents its minimum value (but with a higher energy balance) for the energy balance minimization.

In addition to this, the value of produced energy by the photovoltaic panel that covers the final energy demand varies from 48,5% to 100%. When considering the energy from solar thermal panel as a supply instead of a reduction in demand, the value of renewable energy that covers the energy demand varies from 84% till 100%. This last value indicates that it is possible to get a self-sustainable house through the use of solar energy.

In brief, it is important to further analyse how the results would be affected if the energy produced by the photovoltaic panel was limited to the electricity consumed. Nonetheless, it is expected that the solutions which minimize energy balance would be replaced by ones with only electric devices.

6. Conclusions

From the model application to a reference dwelling and the analysis of its results, it was concluded that a numerical indicator for the energy balance of 29,58 $kWh_{ep}/(m^2.year)$ is suitable for a residential building located in Lisbon and subject to major intervention works. Still, for the same building, the share of renewables should be at least equal to 48.5%.

For future work development, it is relevant to establish if the renewable energy production options may or not be fitted to the self-consumption values, when performing the energy balance.

Furthermore, for more robust conclusions, several scenarios must be tested considering: different building locations and types. Also, it would be interesting to study parameters variations such as discount and evolution factors of energy prices and to include other devices options that manage renewable energy and that satisfy the energy needs. Also, it would be important to perform a research on options installation costs, since this value has a higher impact than the investment costs that is associated to the equipment purchase.

Finally, for better conclusions and recommendations to be drawn, in order to support the nZEB goal definition for Portugal, it is important that the model to be adapted for new commercial and services buildings. However, it should be highlighted that further modifications to the model structure increase its complexity and hence, its computational solution.

7. References

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Table 5 – Non-dominated solutions: characteristics.

Point	Energy Balance $(kWh_{ep}/year)$	LCC (€)	Device for water heating	Device for space heating	Device for space cooling	Windows type	Shading type	External insulation material	Photovoltaics panel dimension
1	741,01	16.874	Natural gas boiler and Solar Thermal panel: Thermosyphon (4 m^2)	Natural gas boiler	-	Metal (TB), Double glazing, Argon (6mm+10mm+6mm)	Metal - vertical fix - 45º	Expanded Cork Board 0,1m	12 m^2
2	1.390,50	16.374	Biomass boiler and Solar Thermal panel: Thermosyphon (3 m^2)	Air conditioner	Air conditioner	Metal (TB), Double glazing, Argon (6mm+6mm+6mm)	PVC – horizontal fix 30º	EPS 0,03m	13 m^2
3	2.277,20	12.855	Heat pump and Solar Thermal panel: Thermosyphon (4 m^2)	Air conditioner	Air conditioner	Metal (no TB), Double glazing, Argon (6mm+10mm+6mm)	No shading	EPS 0,08m	12 m^2

Table 6 – Non-dominated solutions when it is mandatory the compliance with legislation: characteristics.

Point	Energy Balance $(kWh_{ep}/year)$	LCC (€)	Device for water heating	Device for space heating	Device for space cooling	Windows type	Shading type	External insulation material	Photovoltaics panel dimension
1	1.086,00	15.172	Biomass boiler and Solar Thermal panel: Thermosyphon (3 m^2)	Air conditioner	Air conditioner	Metal (no TB), Double glazing, Argon (6mm+10mm+6mm)	Metal - *overhang* fix - 45º	Expanded Cork Board 0,08m	13 m^2
2	1.234,40	14.993	Biomass boiler and Solar Thermal panel: Thermosyphon (3 m^2)	Air conditioner	Air conditioner	Metal (no TB), Double glazing, Argon (6mm+10mm+6mm)	Metal - horizontal fix - 45º	XPS 0,05m	13 m^2
3	1.916,80	14.816	Heat pump and Solar Thermal panel: Thermosyphon (5 m^2)	Air conditioner	Air conditioner	Metal (no TB), Double glazing, Air (4mm+6mm+4mm)	Metal - horizontal fix - 45º	Rockwool 0,08m	11 m^2

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[1]This value is equal to the energy produced by photovoltaic solar panel divided by the primary energy consumed by the various appliances.

[2]Compared with the nominal value for the annual needs of useful energy for space heating of the reference housing.

[3]Compared with the nominal value for the annual needs of useful energy for space cooling of the reference housing.

[4]Compared to the value of the thermal transmission coefficient of the reference housing windows.

[5]Compared to the value of the thermal transmission coefficient of the reference housing walls insulation material.

[6]This value is equal to the energy produced by photovoltaic panel divided by the final energy consumed by the various appliances.

[7]This value is equal to the energy produced by photovoltaic panel and solar thermal panel divided by the final energy consumed by the various appliances.