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# Cost optimal nZEBs in future climate scenarios

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## Abstract

The key-concepts of nearly Zero Energy Building (nZEB) and cost optimality have driven many research activities across Europe in recent years. Considering the ongoing global changes, it is necessary to study and guarantee the resilience of the nZEB design to the variations of the boundary conditions in which the cost optimal calculation is performed.
We present the analysis of the variation of the cost-optimal design of a single-family house in a continental climate (Paris) in different climate change scenarios in the short-medium term (2026-2045). The main finding from the results analysis is that the higher the energy performance, the higher is the resilience to the variation of weather conditions.

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*Keywords:* climate change; cost optimality; optimization; future scenarios; weather data

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## 1. Introduction

The European Directive on the Energy Performance of Building (EPBD – 2010/31/EU) introduced the key-concept of nearly Zero Energy Building (nZEB), of which the energy performance level has to be set according to cost optimality criteria. This has driven many research activities across Europe [1-2] and results have demonstrated that cost optimal nZEB design rarely corresponds to net zero energy design.

Moreover, it has been recognized that this optimal nZEB design is strictly related to the local scale and depends on

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the interaction between the many design variables and the boundary conditions, such as weather data trends, available technologies and materials, market trends, etc. Since these boundary conditions are under constant evolution, the ZEB design can be seen as a complex optimization problem that has to deal with uncertain future scenarios. The cost-optimal methodology framework for the nearly Zero Energy Building design, as defined by the European Commission [3], includes a sensitivity analysis of the financial parameters, but the analysis of the possible variations of climate conditions is not included. However, many studies have been carried out on the creation of future weather data for building dynamic simulation [4-5], based on the latest predictions of the Intergovernmental Panel of Climate Change [6]. Early applications show that they may lead to significant variability of the building energy need [7].

Since the recast of EPBD, the nZEB cost-optimal levels have been identified using the current weather conditions, but there it is necessary to study the possible range of variability of such levels due to projected climate change. This should be done in order to define the design strategies that are able to guarantee the resilience of building design to the variations of such boundary conditions.

In this work, these future weather scenarios are implemented within a cost-optimal analysis in order to investigate the variations in the resulting design solutions and the robustness of the results.

**Nomenclature**

| | |
|---|---|
| Bm | width of the mezzanine window on the South facade |
| Blr | width of the ground floor windows on the South facade |
| ELE | traditional all-electric energy system |
| HP | reversible heat pump energy system |
| ResO | thermal resistance of the insulation of external vertical walls |
| ResR | thermal resistance of the roof insulation |
| ResS | thermal resistance of the roof insulation |
| RW | reference weather scenario |
| WT | window type in North, West and East orientation |
| WTS | window type in South orientation |
| WTR | roof window type |

## 2. Methodology

### *2.1. The case study building and the optimization variables*

The case study building is a reference single-family house in France. The building has two floors for a conditioned floor area of 155 $m^2$. The massive envelope is made of bricks and has insulation on the indoor side. Refer to [8] for additional details about the building layout. In this study, the calculation is performed for the reference building located in Paris, France.

Concerning the building envelope, the insulation thickness in vertical walls (ResO), slab (ResS), roof (ResR), the window dimension (Bm and Blr) and the type of window in the different wall orientations (WT, WTS, WTS) were set as optimization variables. Refer to Tables A.1-2 in Appendix A for details.

Regarding the energy systems, two alternatives were considered. One (HP) is a highly performing reversible heat pump [9] for providing heating and cooling (if needed), the other (ELE) is composed of electric radiators for heating and a multi-split system for cooling that is included only in case the annual cooling energy demand is higher than 4 kWh/$m^2$). The setpoint temperatures to be maintained in the space were set to 19°C in winter and 26°C in summer. The French conversion factor of 2.58 was applied for computing the electricity primary energy consumptions.

### *2.2. The cost-optimal methodology*

The objective of the cost-optimal analysis is the minimization of the global cost (defined in the Standard EN 15459), which takes into account both the investment and the operational costs related to the implementation of energy efficiency measures over the building economic lifecycle. The global cost calculation leads to evaluate the net present value of the costs paid over a period of time (usually 30 years) taking into account the residual value of equipment having longer lifetime than the calculation period. The equation of Global Cost $C_g$ can be written as

$$Cg = CI + \left(\Sigma_j \left(\Sigma_i \left(C_{a,i}(j) \cdot R_d(i)\right) - V_f(j)\right)\right) \tag{1}$$

where *CI* denotes the sum of the initial investment cost for each component; $C_{a,i}(j)$ is the annual cost for component *j* at the year *i*; $R_d(i)$ is the discount rate for year *i* (set at 4.5%); $V_f(j)$ is the final value of component *j* at the end of the calculation period (set at 30 years).

For each component *j*, included in the previously defined set of optimization variables, the cost functions representing the related investment, maintenance, and replacement costs were created. Each value that is assigned to an optimization variable is a so-called energy efficiency measure, while a set of values assigned to the different variables becomes a package of energy efficiency measures. For the cost functions related to the building envelope, refer to Tables A.1 and A.2.

The investment cost of the HP system is 14000€, according to the manufacturer price lists, while the investment cost of the ELE system is set to 300€ for each 0.5 kW of heating loads and to 1500€ for each 2.5 kW of cooling loads. The electricity cost was set to 0.9 6 €/kWh for daytime and 0.0567 €/kWh for nighttime, plus 0.0228 €/kWh for contract and taxes. Refer to [7] for details about costs related to replacement and maintenance.

### *2.3. Simulation-based optimization*

The resulting cost-optimization problem, defined within the cost-optimal methodology framework, has been solved through an automated simulation-based optimization methodology that involves the coupling of the TRNSYS building dynamic energy simulation software with the GenOpt optimization program. The binary version of the Particle Swarm Optimization algorithm was used, for its ability to deal with discrete variables and to effectively minimize the global cost function in this kind of problems [9].

In an iterative process, the optimization algorithm in GenOpt selects the set of values to be inputed to the optimization variables and TRNSYS allows the global cost function to be calculated, as a function of the simulated heating and cooling energy needs of the building. Based on the previous objective function value, the algorithm selects another set of values to assign to the optimization variables and the process is iteratively repeated until the termination criterion (150 generations) is reached.

### *2.4. Future climate scenarios*

The Paris weather file (Paris Orly 071490 - IWEC) was used for calculation in the current conditions (reference weather – RW). Based on climate projections run for the recent IPCC Fifth Assessment, the WeatherShift® tool [10] was used for generating future climate scenarios. The tool is based on the morphing method [4] and takes into account different greenhouse gas emission scenarios (Representative Concentration Pathways, RCP) and various warming percentile (WP). As an example, because the projections are made following many different climate change models, a 50% percentile indicates that the half of the models lead to a temperature offset that is minor or equal to the offset considered in the scenario.. The four resulting scenarios refer to the 2026-2045 period, combining two RCP scenarios (4.5-moderately aggressive mitigation and 8.5-business as usual, which refer to additional radiative forcing in 2100 of 4.5 W/m$^2$ and 8.5 W/m$^2$, respectively) and two WP scenarios (50% and 95%) [6].

The different weather scenarios were compared in Fig. 1a according to the heating degree days (the sum of the differences between the reference temperature, fixed to 18°C in France, and the average daily temperature, as in Equation (1)) and to the cooling hours (the number of hours in which the outside temperature is above the reference temperature, which is set to 26°C as in Equation (2)). Moreover, Fig. 1b and Fig. 1c show that, in the warmest scenarios, the coldest temperature increases by 3 °C, while the summer maximum temperature increases by 5.5 °C.

$$\mathrm{Heating\_DD}=\sum_{d=1}^{365}(T_{ref}-T_{mean})=\sum_{d=1}^{365}(18-T_{mean}) \tag{2}$$

$$\mathrm{Cooling\_H}=\sum_{T_{out}\geq T_{ref}}(T_{out}-T_{ref})=\sum_{T_{out}\geq 26}(T_{out}-26) \tag{3}$$

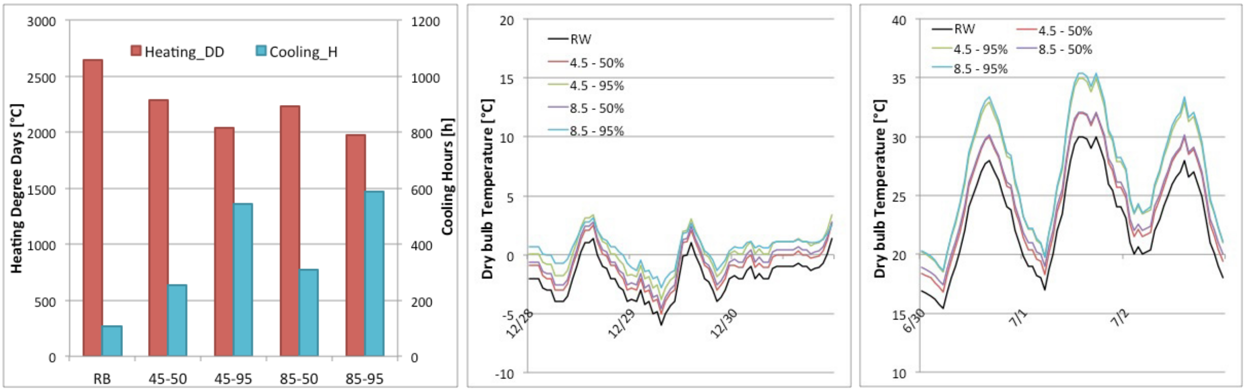

Fig. 1. Future scenarios comparison.(a) Heating degree days and cooling hours; (b) winter coldest days; (c) summer warmest days.

## 3. Results and discussion

The resulting cost optimal solutions in the reference current climate scenario (RW) refer to global cost and primary energy consumption values of 440 €/m$^2$ and 140.4 kWh/m$^2$ for the ELE system and 485.5 €/m$^2$ and 46.2 kWh/m$^2$ for the more performing HP system. The set of optimal values of variables are reported in the RW scenario rows in Table 1. The position of these solutions in the cost optimal graph (global cost on the vertical axis, annual primary energy on the horizontal axis) is reported with blue round points in Fig. 2. As expected, the HP system leads to higher global costs, but the primary energy consumption is much lower than in case of ELE system.

Fig. 2 also reports the positions of the same optimal building configurations in the other climate scenarios. It is interesting to note that, for the HP system, future climate will slightly increase both the global cost and the energy need. Instead, for the ELE system, the different weather scenarios could lead to decrease the energy needs by 14%, because of the reduction of heating needs. However, the higher cooling needs may lead to increase the investment, maintenance and replacement costs of the cooling system, causing the higher position in the graph of the cost optimal point (in Fig.2, green and purple arrows indicate the variation in global cost caused by the installation of a cooling system due to cooling needs higher than 4 kWh/m$^2$ in both RCP scenarios with 95% warming percentile).

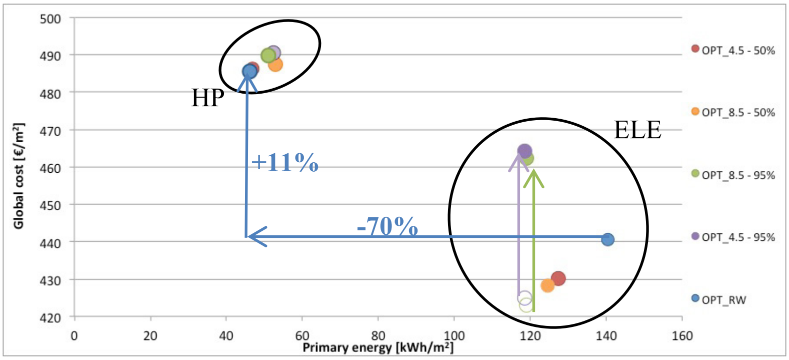

Fig. 2. Cost-optimal point resulting from the optimization in RW scenario and position of the same building design with other scenarios

The optimal set of variable values resulting from each scenario is reported in Table 1. As shown, the optimal building design is the same for all scenarios with HP. Such design is proven to be resilient to climate variation.

On the other hand, for the ELE system, the cost-optimized building design varies from one to the other climate scenarios. As expected, the insulation thickness decreases with the increase of projected global warming. Some scenarios lead to a more performing window type, while the window dimensions are the same in all scenarios.

Moreover, the shape of the clouds related to the ELE system reveals the impact of climate change if a cooling system becomes necessary in a climate where, in the current climate conditions, it may be avoided. This demonstrates that, for the traditional and low-performance ELE system, the cost-optimal solution resulting from calculation under the current climate scenario is not resilient to future scenarios and may lead to higher global cost values, closer to the cost of high performance technologies (such as HP).

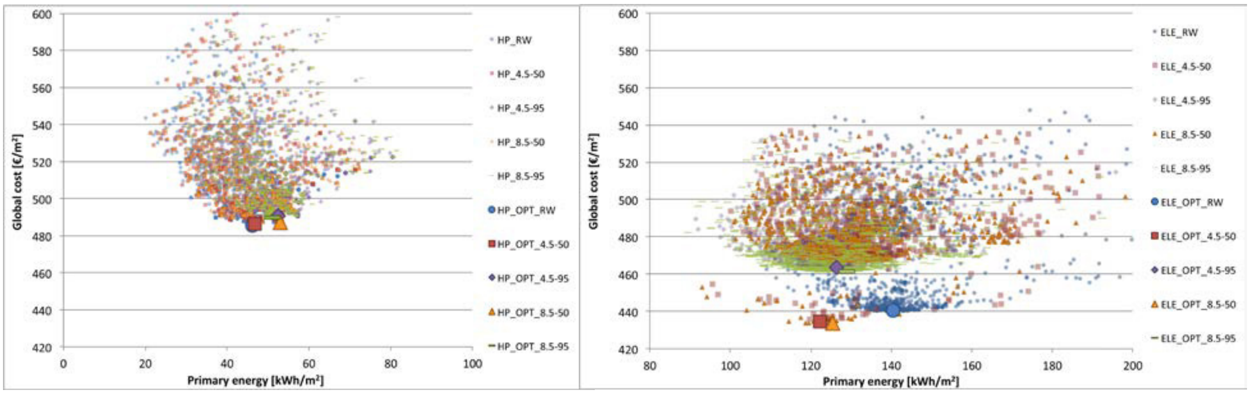

Fig. 3. (a) cost-optimal cloud for the HP system; (b) cost optimal clouds for the ELE system

Table 1. Optimal set of variables values and the related global cost and energy needs for all the analysed scenarios.

| Scenario | | ResO | ResR | ResS | Blr | Bm | Hr | WT | WTS | WTR | Cg $€/m^2$ | PEtot $kWh/m^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ELE OPT | RW | 1.25 | 1.75 | 2.5 | 2.2 | 0 | 0 | 1 | 1 | n/a | 440.6 | 140.4 |
| | 4.5 – 50% | 1.25 | 1.5 | 2.5 | | | | 1 | 1 | n/a | 434.7 | 122.2 |
| | 4.5 – 95% | 1 | 1.5 | 2.25 | | | | 3 | 1 | n/a | 463.7 | 126.4 |
| | 8.5 – 50% | 1 | 1.5 | 2.25 | | | | 1 | 1 | n/a | 433.7 | 125.5 |
| | 8.5 – 95% | 1 | 1.5 | 1.75 | | | | 3 | 1 | n/a | 461.6 | 128.9 |
| HP OPT | RW | 0.25 | 0.5 | 0.5 | 2.2 | 0 | 0 | 1 | 1 | n/a | 485.5 | 46.2 |
| | 4.5 – 50% | | | | | | | | | | 486.3 | 46.8 |
| | 4.5 – 95% | | | | | | | | | | 490.6 | 52.4 |
| | 8.5 – 50% | | | | | | | | | | 487.4 | 52.9 |
| | 8.5 – 95% | | | | | | | | | | 489.7 | 51.1 |

## 4. Conclusions

The cost-optimization of a reference single-family house in Paris, France, was performed considering different future climate scenarios for the period 2026-2045, based on the most recent IPCC climate projections.

Results show that, especially for low-performance technologies (ELE), these scenarios may affect the optimality of the current cost-optimal solution throughout the calculation period. The high-performance system (HP), combined with the most cost-effective envelope design, results as the most robust solution to be implemented in order that the selected cost-optimal nZEB design becomes resilient to possible future climate change.

Further work should be done to compare different methods for predicting future climate conditions and integrate different future financial scenarios. Future works will lead to define possible policies and measures for bridging the gap between cost optimality and ZEB while ensuring resilience to the variation of boundary conditions.

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[10] WatherShift$^{TM}$ toot http://www.weather-shift.com

## Appendix A. Optimization variables and cost functions

Table A.1. Optimization variables, adapted from [8]

| Parameter name and description | Unit | Min | Max | Step | Related cost function [€] |
|---|---|---|---|---|---|
| ResO- Thermal resistance of wall internal insulation | [m$^2$Kh/kJ] | 0.25 | 5.00 | 0.25 | $CI_{outwall1} = (37.639 \cdot ResO^{0.351} + 92.25) \cdot A_{outwall}$ |
| ResR - Thermal resistance of roof insulation layer | [m$^2$Kh/kJ] | 0.50 | 5.00 | 0.25 | $CI_{roof1} = (43.478 \cdot ResR^{0.309} + 105.30) \cdot A_{roof}$ |
| ResS - Thermal resistance of slab insulation layer | [m$^2$Kh/kJ] | 0.25 | 3.00 | 0.25 | $CI_{slab1} = 38.115 \cdot ResS^{0.186} \cdot A_{slab}$ |
| Blr - Ground floor south window width (h= 2.15 m) | [m] | 2.20 | 7.80 | 0.20 | All the opaque envelope cost functions depends on these parameters, since $A_{outwall}$, $A_{roof}$ and $A_{slab}$ results from the difference between the entire envelope area and the wall area. |
| Bm - First floor south window width (h= 0.80 m) | [m] | 0.00 | 7.80 | 0.20 | |
| Hr - Roof window height (w= 2.28 m) | [m] | 0.00 | 4.72 | 0.59 | Also the window cost functions (see Table A2) depend on the window area, which is related to these parameters. |
| WT, WTS, WTR- Window Type of North-East-West /South walls/Roof | - | 1 | 4 | 1 | |

Table A.2. Window types, adapted from [8]

| **Name** | **Description** | **U-value [W/(m$^2$K)]** | **g-value** | **Related cost function [€]** |
|---|---|---|---|---|
| 1 | 4/16/4 - Double glazing | 2.00 | 0.70 | $CI_{W1} = 349 \cdot A_{w1} + 28$ |
| 2 | 4/16/4 - Double glazing, low-e with Argon | 1.43 | 0.58 | $CI_{W2} = 390 \cdot A_{w2} + 29$ |
| 3 | 4/16/4/16/4 - Triple glazing | 0.70 | 0.50 | $CI_{W3} = 454 \cdot A_{w3} + 36$ |
| 4 | 4/16/4/16/4 - Triple glazing, with Argon | 0.50 | 0.40 | $CI_{W4} = 470 \cdot A_{w4} + 36$ |