

# Passive designs and renewable energy systems optimization of a net zero energy building in Embrun/France

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**Abstract.** Buildings' optimization is a smart method to inspect the available design choices starting from passive strategies, to energy efficient systems and finally towards the adequate renewable energy system to be implemented. This paper outlines the methodology and the cost-effectiveness potential for optimizing the design of net-zero energy building in a French city; Embrun. The non-dominated sorting genetic algorithm is chosen in order to minimize thermal, electrical demands and life cycle cost while reaching the net zero energy balance; and thus getting the Pareto-front. Elimination and Choice Expressing the Reality decision making method is applied to the Pareto-front so as to obtain one optimal solution. A wide range of energy efficiency measures are investigated, besides solar energy systems are employed to produce required electricity and hot water for domestic purposes. The results indicate that the appropriate selection of the passive parameters is very important and critical in reducing the building energy consumption. The optimum design parameters yield to a decrease of building's thermal loads and life cycle cost by 32.96% and 14.47% respectively.

## 1. Introduction

Worldwide, buildings' energy demands are expected to increase in the following years. By the end of 2014, buildings (residential, commercial and public) consumed around 49% of the world's electricity consumption, where the residential sector consumed about 27% of the global electrical usage [1].

Net Zero Energy Building (NZEB) is a recent approach suggested to limit energy consumption and pollution emissions in buildings [2]. Building optimization is an effective method to evaluate design choices and to get the perfect solution for a specific purpose expressed as objective functions under several constraints [3]. Multi-objective optimization (MOO) results are sets of non-dominated solutions represented as a Pareto front [4]. After obtaining the Pareto front, the multi-criterion decision-making (MCDM) process is applied in order to select the final optimal solution among all offered possibilities. MCDM is capable to review the problem in accordance with the significance of different criteria and the preferences of the decision maker (DM).

In this paper, cost-effective design options for a residential NZEB in Embrun, a commune in the Hautes-Alpes department in the Provence-Alpes-Côte d'Azur region in South-eastern France, is inspected. Initially, the base case design options, RE systems, and simulation results are defined. Afterward, optimization problem of an extensive variety of design options is offered; including wall



and roof insulation levels, windows glazing type, window to wall ratio (WWR) in eastern and western facades, cooling and heating set points, Photovoltaic (PV) and Solar domestic hot water system (SDHW) sizing. The optimization is carried out using “MOBO”, a Multi-Objective Building Optimization tool presented by Palonen et al. (2013) [5]. Furthermore, in order to obtain a single solution, the ELECTRE III (Elimination and Choice Expressing the Reality) MCDM method, developed by Roy [6] is employed. Finally, a set of recommendations is outlined in order to ameliorate the performance design of NZEB in Embrun.

## 2. Base case building characterization

The investigated building is located in Embrun, characterized by an inland mountain climate. The monthly average dry bulb temperature is represented in ‘Figure 1’ according to the data from meteorological stations [7].

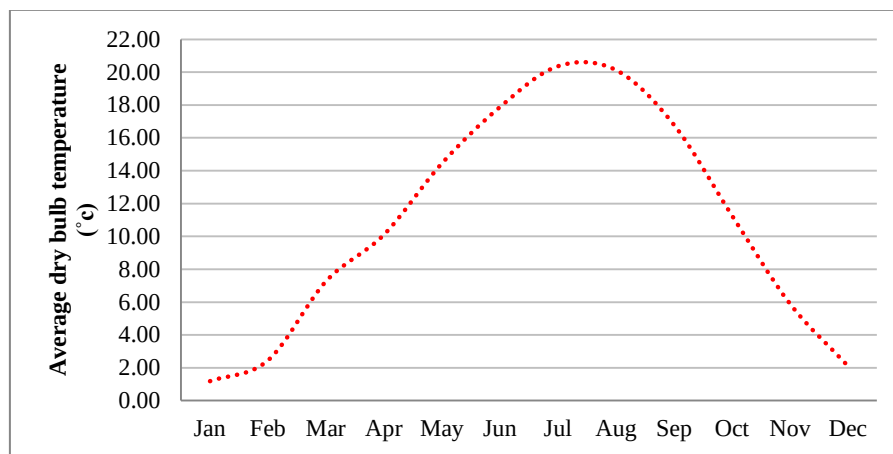


**Figure 1.** Monthly average dry bulb temperature for Embrun (Data Source: [7])

Besides, the building is composed of three stories, each of 205 m<sup>2</sup>. Windows are distributed on Eastern and western facades, shaded with opaque blinds. Heating loads are covered by a natural gas condensing boiler (Efficiency=98.3%). Cooling loads are covered by air source heat pumps, with a coefficient of performance (COP) equal to 2.9. Systems set points are fixed respectively at 24°C for cooling and 20°C for heating during occupied hours. Though, during uninhabited times, cooling and heating systems are switched off. The design relative humidity is fixed at 50 %. The building is considered as tight, so the infiltration rate is equal to 0.38 ACH [8].

## 3. Renewable energy (RE) systems characteristics and simulation

### 3.1. Solar domestic hot water system characteristics

The hot water demands are covered by means of a flat plate direct active SDHW system with auxiliary electric heater. The SDHW system is composed of 5 solar collectors (SC) connected in series of total area equal to 31.35 m<sup>2</sup>, south oriented, located at building rooftop and sloped to Embrun local latitude. The employed system characteristics are represented in ‘Table 1’.

**Table 1.** SDHW system characteristics (Data source: [9])

| Characteristics                   | Value | Characteristics                                       | Value  |
|-----------------------------------|-------|-------------------------------------------------------|--------|
| Collector area, m <sup>2</sup>    | 2.09  | Collector flow rate, Kg/hr                            | 70     |
| Storage tank area, m <sup>3</sup> | 2.271 | Intercept efficiency                                  | 0.79   |
| Hot water set point, °C           | 60    | Efficiency slope, W/m <sup>2</sup> .K                 | 3.48   |
| Hot water supply temperature, °C  | 45    | Efficiency curvature, W/m <sup>2</sup> K <sup>2</sup> | 0.0056 |

### 3.2. Base case demands

The software TRNSYS is adopted to simulate buildings' electrical, thermal and hot water demands. The resulting buildings' total annual electrical demands are 64.03 KWh/y.m<sup>2</sup>. Whereas, heating and cooling demands are 107.59 KWh/y.m<sup>2</sup> and 10.45 KWh/y.m<sup>2</sup> respectively. The monthly space heating and cooling demands are represented consecutively in 'Figure 2' and 'Figure 3'.

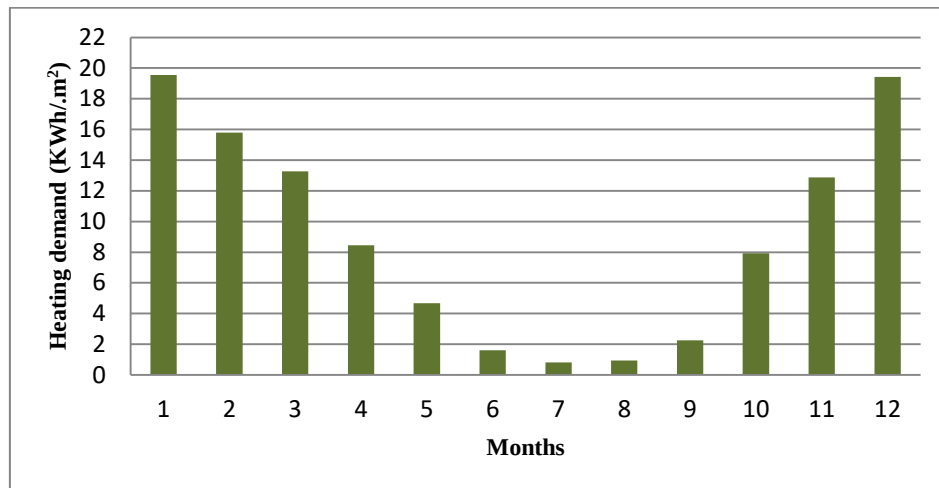


**Figure 2.** Monthly space heating load (KWh/m<sup>2</sup> of heated area)

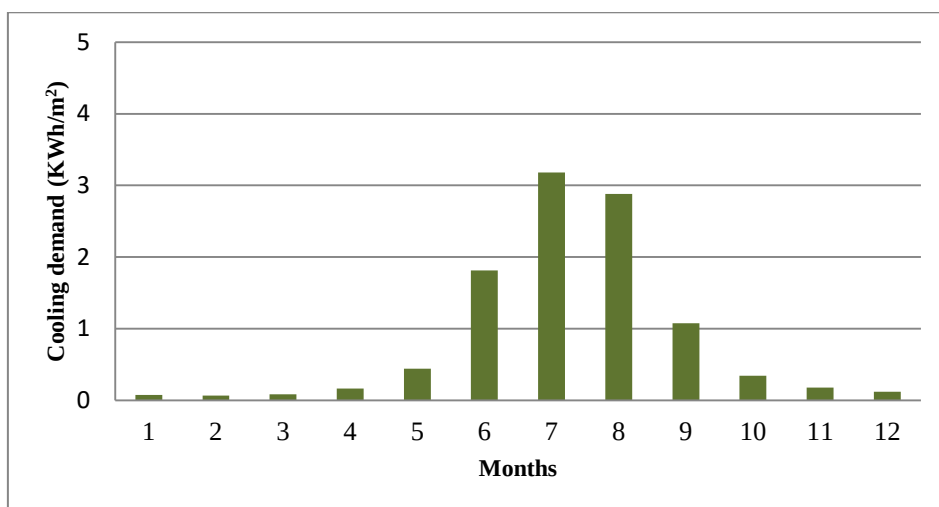


**Figure 3.** Monthly space cooling load (KWh/m<sup>2</sup> of cooled area)

### 3.3. Photovoltaic system characteristics

In order to generate buildings required electricity, a PV system is used. The PV array is south oriented and sloped at Embrun local latitude. The analytical calculation [9], yield to 90 PV modules (15 in series, and 6 in parallel). The technical data of each module are represented in 'Table 2'. The building uses the utility power grid for storage, it delivers energy to the grid when the PV system produces more energy than the building needs and draws from the grid when the PV system produces less energy than the building needs.

### 3.4. Base case electrical and economic simulation results

The annual electric balances, are summarized in 'Table 3'.

Besides, the simulated LCC for a life period of 20 years and an annual discount rate of 5% is 169,300 \$ (275 \$/m<sup>2</sup>). It can be observed that about 38% of building loads are covered by the PV

system. The zero energy balance is reached however with a great “Gains” that represents a loss in terms of investment cost. Also it is worth to mention the building’s high heating load.

**Table 2.** Parameters of PV module (Data source:[10])

| Panel characteristics                               | Value  | Panel characteristics      | Value |
|-----------------------------------------------------|--------|----------------------------|-------|
| Short circuit current, A                            | 9.32   | Open circuit voltage, V    | 45.92 |
| Current at maximum power, A                         | 8.85   | Number of cells in series  | 72    |
| Voltage at maximum power, V                         | 37.38  | Panel area, m <sup>2</sup> | 1.94  |
| Temperature coefficient/ open circuit voltage, V/K  | -0.318 | Module efficiency, %       | 17    |
| Temperature coefficient/ short circuit current, A/K | 0.042  | Nominal output, Wp         | 295.3 |

**Table 3.** Summary of electrical balances

| Description | PV system output | From PV to building | From PV to grid | Building demand | From grid to building | Gains “Load-generated by PV” |
|-------------|------------------|---------------------|-----------------|-----------------|-----------------------|------------------------------|
| Value (MWh) | 68.15            | 15.3                | 37.68           | 39.38           | 24.08                 | -27.14                       |

Optimization problem and decision making process

### 3.5. Objective functions and decision variables

The electric consumption is due to thermal loads, lights, appliances and consumption of SDHW system auxiliary heater and circulating pump. The consumption from cooling and heating are minimized when minimizing the thermal demands. Besides, energy star appliances and fluorescent lights are used to reduce consumption. Therefore, in this study there are four objective functions to be minimized:

f1=min (“Auxiliary electric heater + Pump” consumptions)

f2=min (Thermal demand)

f3=min (Difference between load and generation)

f4=min (LCC)

‘Table 4’ provides the list of building passive and RE systems decision variables. The optimization problem is constrained by the occupant’s thermal comfort, which is given by the following condition: the average predicted mean vote (PMV) of the whole building must remain between its acceptable bounds  $|PMV| \leq 0.5$ .

**Table 4.** Description and different options of decision variables used in the optimization problem

| Description                                                             | Type       | Values     | Step |
|-------------------------------------------------------------------------|------------|------------|------|
| External walls, Roof insulation thickness (cm)                          | Discrete   | 1,3,5,7,10 | -    |
| Type of double glazing: Krypton or Argon, U-value (W/m <sup>2</sup> .K) | Discrete   | 0.86, 1.4  | -    |
| Cooling set point (°C)                                                  | Discrete   | 24, 25, 26 | -    |
| Heating set point (°C)                                                  | Discrete   | 19, 20     | -    |
| Number of solar collectors in series                                    | Continuous | 1 to 20    | 1    |
| SDHW pump flow rate (Kg/h)                                              | Continuous | 50 to 120  | 5    |
| Number of solar panels in series                                        | Continuous | 1 to 20    | 1    |
| Number of solar panels in parallel                                      | Continuous | 1 to 40    | 1    |
| Width window bedrooms, kitchen (m)                                      | Continuous | 1 to 2     | 0.25 |
| Width window Living and dining (m)                                      | Continuous | 1 to 3     | 0.25 |
| Width window Living and dining (m)                                      | Continuous | 1 to 3.7   | 0.25 |

### 3.6. Building optimization tool, algorithm and Pareto front

In this study, the optimization tool MOBO is coupled with TRNSYS. The non-dominated sorting genetic algorithm (NSGA-II), developed by Deb et al. [11], is adopted. The parameters’ of NSGA are set as follows: Population size = 40, Generation number = 25, Crossover probability= 70%, and Mutation probability= 2%. These parameters are selected based on the preliminary researches to get

the best compromise between the Pareto-front accuracy and the optimization computational time [4]. Note that the four-objective optimization generates a four-dimensional (4D) problem. The projection of the 4D problem in a bi-dimensional (2D) graph, gives the Pareto front represented in 'Figure 4'.

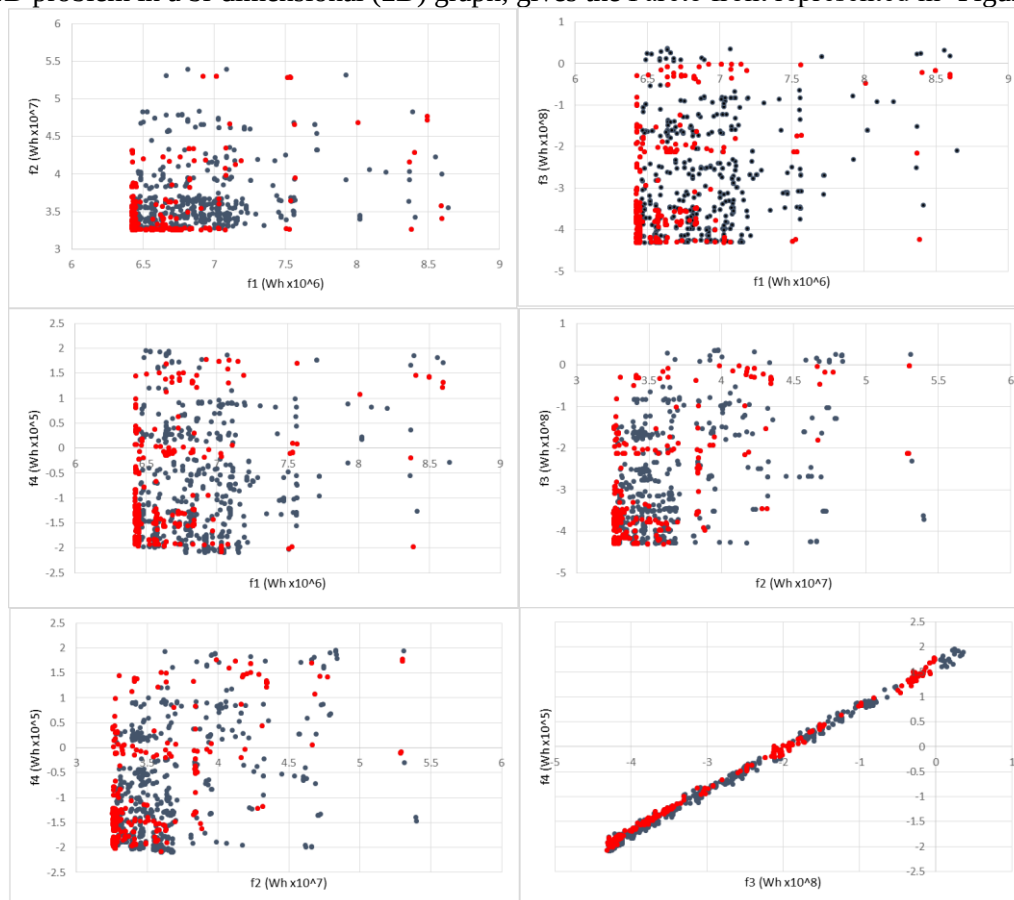


**Figure 4.** Bi-dimensional projections of the analyzed 4D-problem space (Blue: Building variants, Red: Pareto-front)

### 3.7. Decision making and sensitivity analysis

In order to classify the Pareto front solutions and to choose the most suitable one, the ELECTRE III method is adopted. Indifference, preference and veto thresholds of ELECTRE III are assigned respectively as follows: 5%, 10% and 30% relative to the average of each objective function's value for the Pareto front points. The Analytical Hierarchy Process (AHP), proposed by Saaty [12], is implemented to assign the relative weight of each objective. The best solutions resultant of ELECTRE III ranking are summarized in 'Table 5', together with the difference between the best case and the base case.

**Table 5.** Difference between best solution and the base case

|                        | f1 (MWh) | f2 (MWh) | f3 (MWh) | f4 (1000\$) |
|------------------------|----------|----------|----------|-------------|
| <b>Best solution</b>   | 6.73     | 34.12    | -13.6    | 197.94      |
| <b>Base case value</b> | 6.98     | 50.90    | -27.14   | 169.30      |
| <b>% difference</b>    | 3.58     | 32.96    | -49.92   | 14.47       |

### 3.8. Results and discussion

'Table 6' lists NZEBs parameters results of the decision making process. The results obviously show that there is a significant potential to improve the energy performance of residential buildings in Embrun, by implementing proven passive strategies. It can be noticed that building's envelop

insulation is a key parameter, walls and roof insulation thicknesses are increased up to 7 cm and 10cm instead of 5 cm and 1cm respectively. Windows U-value of 0.86 W/m<sup>2</sup>.K is found to be more suitable than 1.4W/m<sup>2</sup>.K so as to lessen heat thermal flows from inside to outside the building. Moreover, the optimal WWR in eastern and western façades must ensure the essential heat gains from day time's solar radiation. WWR in eastern and western façades are decreased to 17.18% and 32.92% respectively. Optimal cooling and heating set points are modified to 25°C and 19°C respectively, with the intention of decreasing the thermal loads; the occupants comfort is untouched since the PMV is considered as a constraint.

**Table 6.** Summary of the optimal building design options

| Variable         | Insulation |      | Windows<br>U-value    | Set points |         | WWR   |       | PV  | SDHW         |    |
|------------------|------------|------|-----------------------|------------|---------|-------|-------|-----|--------------|----|
|                  | Walls      | Roof |                       | Cooling    | Heating | East  | West  |     | Pump<br>flow | SC |
| Unit             | (cm)       | (cm) | (W/m <sup>2</sup> .K) | (°C)       | (°C)    | (%)   | (%)   | -   | (Kg/h)       | -  |
| <b>Base case</b> | 5          | 1    | 1.4                   | 24         | 20      | 23.43 | 59.5  | 108 | 70           | 15 |
| <b>Optimal</b>   | 7          | 10   | 0.86                  | 25         | 19      | 17.18 | 32.92 | 90  | 95           | 16 |

#### 4. Conclusion

The challenge in ZEB design is to find the best combination of design strategies that would face the energy performance problems of a particular building.

In this study, an energy simulation and optimization programs (TRNSYS and MOBO) coupled with a ranking decision making technique (ELECTRE III) are employed to assess the most cost-effective passive strategies and RE systems sizes that should be implemented to achieve a NZE design for a residential building in Embrun. In the optimization analysis, an extensive variety of design and operating choices are considered including wall and roof insulation levels, windows glazing type, WWR in eastern and western facades, cooling and heating set points, PV and SC systems sizing.

The optimum design parameters and their corresponding objective functions shows that the annual thermal load and LCC can be decreased by 32.96% and 14.47% respectively, compared to the baseline model. Envelop high level of insulation is an essential step to decrease the high heating demands. Besides, WWR of about 17.18% and 32.92% respectively on eastern and western facades are sufficient to collect the necessary solar radiation and to avoid heat losses due to the excessive outside low temperature.

Future studies may be extended to other passive design parameters, energy efficient systems, and RE systems as well as other objective functions such as the life cycle assessment impact.

#### 5. Acknowledgments

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