Effects of energy efficiency measures on building performance: an analysis in seven European cities

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Abstract. This work presents the energy performance analysis of an autarkic residential building, located in the suburb of L'Aquila, in central Italy. The analysis is performed via a calibrated dynamic thermal model, carried out with EnergyPlusTM engine coupled with DesignBuilder. The aim of this study is the further understanding of the optimization margins of the energy self-sufficient building by considering different Energy Efficiency Measures and the effects obtainable in different climatic conditions. Four Italian cities and three European capitals are considered, in addition to different scenarios, characterized by various technological plants. In fact, a significant difference between the high efficiency of the envelope, and the poor performance of the heating system was observed. The results highlighted the remarkable energy performance optimization of the analyzed building, although the effects of the Energy Efficiency Measures showed notable differences between colder and warmer climates.

1. Introduction
The research of low energy buildings represents one of the main actions within the energy efficiency strategy, in order to reduce energy consumption and, at the same time, increase the occupants’ thermal comfort. All over the world, the experiences aimed at realizing buildings with high energy performance are many and each proposes different coded design theories, such as for example the Passivhaus (Germany) and the Zero Energy Home (United States) [1]. Furthermore, new approaches to energy savings lead to the realization of advanced systems making buildings increasingly more efficient [2,3]. Therefore, to date, there are many high efficiency building definitions around the world and an international universal zero energy standard would be necessary [4]. In a recent paper [5], the possible optimization margins of a self-sufficient buildings, in terms of energy efficiency, were considered. After a detailed literature analysis, an interesting case study was selected. The reference building, located in central Italy, represents a novelty for its being completely self-sufficient, according to the energy requirements, and for the particular materials employed for the envelope. The analysis, based on a mix of calibrated simulation and experimental measures, showed that, indeed, also such a building can have optimization margins. The present work further extends the previous paper [5] by considering different scenarios (with different technological plants) and different climatic conditions, both in Italy and Europe. The proposed procedure, described in detail in [5], will be very briefly outlined in the following.

2. Materials and methods
The analyzed building (Fig. 1) is a two-storey residential single-house, full time inhabited by two people, characterized by energy self-sufficiency and complete independence from the utilities [5, 6]. The heated ground floor of the building includes all the occupied rooms, while the attic is devoid of heating system. The natural ventilation guarantees the air changes.
Figure 1. South façade of the self-sufficient building located in L’Aquila (Central Italy).

The building envelope is made of prefabricated wood-cement blocks with high thermal performance (U-value equal to 0.12 W/m²K), thanks to the EPS insulation [7]. The thermal needs are satisfied by a hydronic system with biomass boiler manually switched and tubular steel radiations. As shown in [5], the selected building can be considered a Zero Energy Building (ZEB) [8] and, being off-grid and independent of third parties regarding energy consumption, an “autarkic house” [9, 10].

The methodology employed in this work is shown in Fig. 2.

Figure 2. Flowchart of the employed methodology.

After the document acquisition, a detailed knowledge of the building was gained through the analyses of the technical plants, the materials used in the construction and so on. Then monitoring campaigns were performed to obtain information about the actual features of the building envelope. Experimental results were obtained by infrared thermography and heat flow meter method. Moreover, also temperature values (indoor and outdoor) and the thermal energy supplied by the heat generator were measured. Simulations were carried out via EnergyPlus™ and Design Builder. For further details and a complete description, the reader is referred to [5, 11]. The EnergyPlus™ virtual model was calibrated following the M&V Guidelines of ASHRAE [12], hourly calibration type, by comparing the simulated thermal energy consumption of the heat generator with the value measured by means of a heat meter installed downstream of the biomass boiler. The experimental campaign had a duration of two months (March 15th - March 15th, 2016), and it was conducted by installing a heat meter (model Conteca 755405 provided by Caleffi) downstream of the biomass boiler, since the building is completely independent from the utilities and no bills were available. The two main statistical indices analyzed were the mean bias error (MBE) (Eq. (1)) and the coefficient of variation of the root mean square error (CV(RMSE)) (Eq. (2)), respectively equal to 5.31% and 6.95%, that resulted less than the limit values equal to ± 10% and 30%.

\[
MBE(\%) = \frac{\sum_{\text{Period}} (S - M)_{\text{Interval}}}{\sum_{\text{Period}} M_{\text{Interval}}} \times 100 \tag{1}
\]

where (M) is the measured indoor air temperature and (S) is the simulated one.
\[ CV(RMSE_{\text{period}}) = \frac{RMSE_{\text{period}}}{A_{\text{period}}} \times 100 = \sqrt{\frac{1}{N_{\text{interval}}} \sum (S - M)^2_{\text{interval}}} \times \frac{1}{A_{\text{period}}} \times 100 \]  

where \((A_{\text{period}})\) is the mean of the measured data for the period, and \((N_{\text{interval}})\) is the number of time intervals in the monitoring period, equal to 4500. The calibrated model provided the energy performance in winter season of the use case in its actual location, that resulted equal to 29.9 kWh/(m²·yr) and 2964.4 kWh/yr.

In this work, a multi-scenario analysis, was performed considering the same building equipped with different utilities, as summarized in Table 1.

**Table 1. Different technological solutions hypothesized.**

| Scenarios | Biomass boiler | Condensing gas boiler | Air-to-water heat pump | Air handling unit |
|-----------|----------------|-----------------------|-----------------------|-------------------|
| OS-1      |               |                        |                       |                   |
| OS-2      |               |                        |                       |                   |
| OS-3      |               |                        |                       |                   |
| OS-4      |               |                        |                       |                   |
| OS-5      |               |                        |                       |                   |

Furthermore, as proposed in several studies [13, 14], also different climatic zones were considered to understand how climate conditions influence the energy performance of the case study. The cities have been selected on the basis of the climatic conditions. In fact, according to the Italian climate classification [15] the three selected cities are: Palermo, climate zone “B”; Rome, climate zone “D”; Milan and L’Aquila, climate zone “E”. For the selected European cities (Madrid, Paris and London), the Köppen-Geiger classification was used [16]. According to this classification, Europe has a dominant cold climate D (44.4%), followed by arid B (36.3%), temperate C (17.0%) and polar E (2.3%) climates. Spain has a rather variable climate, mainly BSk, Csa, Csb and Cfb, i.e. mainly arid-steppe and temperate-mild. Madrid, in particular, is characterized by temperate climate with dry summer (Csa, Csb). France (i.e. Paris) has a mainly temperate climate and warm summer (Cfb), with some exceptions for the Alpine areas (Dfc), while the United Kingdom (i.e. London) has a very uniform and temperate climate with warm summer (Cfb). Mean climatic conditions of the selected cities during the heating season are reported in Table 2. A uniform heating season, 15th October – 15th April, has been assumed for all the cities for ease of comparison. For each parameter (mean temperature, mean solar radiation and mean wind speed) the percentage difference, with respect to L’Aquila, is also given.

**Table 2. Climatic conditions for the selected cities.**

|                  | Mean temperature \[°C\] \(^a\) | Mean solar radiation [kWh] | Mean wind speed [m/s] |
|------------------|---------------------------------|-----------------------------|-----------------------|
|                  | Δ% \(^b\)                       | Δ% \(^b\)                   | Δ% \(^b\)             |
| L’Aquila (Ref. Case) | 8.1                             | 0.0%                        | 84.6                  | 0.0%                 | 0.0%                       |
| Milan            | 6.8                             | -16.6%                      | 64.3                  | -24.0%               | 1.1                        | 75.8%                       |
| Rome             | 10.8                            | 32.7%                       | 85.7                  | 1.3%                 | 3.1                        | 376.8%                      |
| Palermo          | 15.0                            | 84.4%                       | 109.1                 | 29.0%                | 5.3                        | 733.4%                      |
| London           | 6.7                             | -17.6%                      | 70.9                  | -16.1%               | 3.3                        | 417.4%                      |
| Paris            | 6.8                             | -17.1%                      | 69.7                  | -17.6%               | 4.3                        | 573.6%                      |
| Madrid           | 9.1                             | 11.6%                       | 140.6                 | 66.3%                | 2.3                        | 267.1%                      |

\(^a\) Average values during the heating season.

\(^b\) Percentage variations with respect to the reference case, i.e. L’Aquila.
From Table 2, Milan has the worst climatic condition, because of a low mean temperature and a low mean solar radiation. London and Paris have similar mean temperatures but slightly higher mean solar radiation. Palermo is, among all, the city with the highest average temperature, followed by Rome and Madrid, which, however, boasts the highest average solar radiation value. L’Aquila is in an intermediate position between the cities with the coldest climate (Milan, London and Paris) and the mildest climate cities (Palermo, Rome and Madrid).

3. Results and discussion
The main results of the multi-scenario analysis for the seven different cities are shown in Fig. 3.

Figure 3. Main results of the multi-scenario analysis in different climatic conditions. (a) Original or reference state. (b)-(f) Different scenarios (please ref. to Table 1).
Numerical results are summarized in Table 3.

Table 3. Energy consumption in the winter season (kWh/yr) and percentage variation.

| Ref. state | ∆%<sup>a</sup> | OS-1 | ∆%<sup>b</sup> | OS-2 | ∆%<sup>b</sup> | OS-3 | ∆%<sup>b</sup> | OS-4 | ∆%<sup>b</sup> | OS-5 | ∆%<sup>b</sup> |
|------------|----------------|------|----------------|------|----------------|------|----------------|------|----------------|------|----------------|
| L’Aquila   | 2964.5         | 0.0  | 1392.1         | -53.0| 2084.4         | -29.7| 974.7          | -67.1| 4401.4        | 48.5 | 1767.49        | -40.4|
| Milan      | 3224.5         | 8.8  | 1966.6         | -39.0| 2263.2         | -29.8| 1385.2         | -57.0| 5375.4        | 66.7 | 2375.58        | -26.3|
| Rome       | 2891.2         | -2.5 | 1064.1         | -63.2| 2029.8         | -29.8| 746.4          | -74.2| 3211.8        | 11.1 | 1262.34        | -56.3|
| Palermo    | 1807.4         | -39.0| 413.2          | -77.1| 1252.5         | -30.7| 295.0          | -83.7| 1424.8        | -21.2| 450.79         | -75.1|
| London     | 3455.1         | 16.5 | 1856.2         | -46.3| 2433.2         | -29.6| 1300.1         | -62.4| 5008.5        | 45.0 | 2128.85        | -38.4|
| Paris      | 3356.0         | 13.2 | 1814.9         | -45.9| 2360.9         | -29.7| 1272.7         | -62.1| 5032.8        | 50.0 | 2186.87        | -34.8|
| Madrid     | 2651.2         | -10.6| 865.1          | -67.4| 1862.6         | -29.7| 608.4          | -77.1| 3471.8        | 31.0 | 1306.26        | -50.7|

<sup>a</sup> Percentage variation with respect to reference state in original location (L’Aquila).

<sup>b</sup> Percentage variation with respect to reference state in each city.

Scenarios with reduced energy consumption are shown in bold.

The results analysis allows to observe a significant reduction of the energy consumption when mechanical ventilation system with heat recovery is installed (OS-1). The solution that determines the best result is the OS-3 (i.e. condensing gas boiler and air handling unit), while the hypothesis of installing an air-to-water heat pump (AWHP) (OS-4) provides negative effects, maybe due to the simultaneous low external temperature and high relative humidity. The AWHP installation becomes feasible only if a mechanical ventilation system is considered (OS-5). The hypothesis of considering the building in different climatic zones shows that the high thermal performance of the envelope diminish the external thermal stress in cities with more rigid climate (Milan, London and Paris), while the cities characterized by a warmer climate have lower benefits deriving from the envelope thermal performance. The positive effects gathered by the mechanical ventilation system installation are observable for all the considered cities. The scenario in which the simple replacement of the biomass heat generator with a more efficient condensing gas boiler is hypothesized (OS-2) determined energy savings almost equal, for all the climate zones considered, and approximately equal to 30.0%, while the AWHP hypothesis has negative effects with respect to the “original case”, with the exception of Palermo, where energy savings amounted to 21.2%.

4. Conclusions

The energy assessment of the analyzed building, performed through a calibrated EnergyPlus™ virtual model, has allowed to obtain some interesting results:

- the energy self-sufficient condition of the residential house does not guarantee high energy performance: the low efficiency of the heating system, in fact, entails considerable margins for energy improvement;
- the performance of the envelope and of the heating system should be evaluated together for achieving an overall energy efficiency: the high thermal resistance of the envelope and the low efficiency of the heating system do not allow satisfying energy results;
- the mechanical ventilation system with heat recovery system is fundamental for the energy saving goal;
- the diagnosis phase, realized with a combination of infrared inspection, heat flow meter measurements and temperature monitoring, is essential for achieving a complete and detailed knowledge of the building;
- the different climatic conditions that characterize Europe are such as to require very different energy standards: based on the results obtained in this work, it can be stated that the energy policies taken by the European directives are moving into the right direction.
References

[1] Filippi M, Fabrizio E. Il Concetto di Zero Energy Building (in Italian), Conference Paper: Verso gli edifici a energia quasi-zero: Le tecnologie disponibili. 2011 SAIE - Piazza Costituzione 2 - Fiera di Bologna – Bologna.

[2] de Rubeis T, Mutillo M, Pantoli L, Nardi I, Leone I, Stornelli V, Ambrosini D. A first approach to universal daylight and occupancy control system for any lamps: Simulated case in an academic classroom. 2017 Energ. Buildings 152 24-39.

[3] de Rubeis T, Nardi I, Mutillo M, Ranieri S, Ambrosini D. Room and window geometry influence for daylight harvesting maximization – Effects on energy savings in an academic classroom. 2018 Energy Procedia 148 1090-1097.

[4] Williams J, Mitchell R, Raicic V, Vellei M, Mustard G, Wismayer A, et al. Less is more: a review of low energy standards and the urgent need for an international universal zero energy standard. 2016 J. Build. Eng. 6 65–74.

[5] de Rubeis T, Nardi I, Ambrosini D, Paoletti D. Is a self-sufficient building energy efficient? Lesson learned from a case study in Mediterranean climate. 2018 Appl. Energ. 218 131-145.

[6] de Rubeis T, Nardi I, Pasqualoni G, Ambrosini D, Paoletti D. Energy assessment of an autarkic building in Mediterranean climate. Eighth International Symposium on Energy, 6-9 August 2018, Aberdeen, Scotland (Poster).

[7] Nardi I, de Rubeis T, Buzzi E, Sfarra S, Ambrosini D, Paoletti D. Modeling and optimization of the thermal performance of a wood-cement block in a low-energy house construction. 2016 Energies 9 677–94.

[8] Torcellini P, Pless S, Deru M, Crawley D. Zero energy buildings: a critical look at the definition. In: Conference paper, national renewable Energy Laboratory, Pacific grove, California, august 14-18, 2006.

[9] Pan W. System boundaries of zero carbon buildings. 2014 Renew. Sust. Energ. Rev. 37 424-434.

[10] Erhorn H, Erhorn-Klutting H. Terms and definitions for high performance buildings. Concerted action – Energy performance of buildings. Detailed report; 2011.

[11] Smarra F, Jain A, de Rubeis T, Ambrosini D, D’Innocenzo A, Mangharam R. Data-driven model predictive control using random forests for building energy optimization and climate control. 2018 Appl. Energ. 226 1252-1272.

[12] U.S. Department of Energy – Federal Energy Management Program, M&V Guidelines: Measurements and verification for Performance-Based Contacts Version 4.0, 2015.

[13] Eicker U, Colmenar-Santos A, Teran L, Cotrado M, Borge-Diez D. Economic evaluation of solar thermal and photovoltaic cooling systems through simulation in different climatic conditions: An analysis in three different cities in Europe. 2014 Energ. Buildings 70 207-223.

[14] Jazaeri J, Gordon R L, Alpcan T. Influence of building envelopes, climates, and occupancy patterns on residential HVAC demand. 2019 J. Build. Eng. 22 33-47.

[15] Decreto del Presidente della Repubblica 26 Agosto 1993, n. 412, Allegato A – Tabella dei gradi giorno per i comuni italiani raccolti dalle Regione e dalle Province.

[16] Peel M.C., Finlayson B.L., McMahon T.A., Updated world map of the Köppen-Geiger climate classification, 2018 Hydrol. Earth Syst. Sci. Discuss. 4(2) 439–473.