CODE 372

ENERGY RENOVATION OF THE BUILT HERITAGE HOUSING BASED ON THE LIVING BUILDING CHALLENGE CERTIFICATION. CASE STUDY IN BRESCA (SPAIN)

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ABSTRACT

In light of increasing sustainability requirements, one of the challenges related to the heritage building stock consists in finding a balance between preserving the existing architectural character and improving energy efficiency. The project presented in this article has been carried out through a collaborative design process, involving experts from different disciplines (e.g. construction, energy, low-carbon materials, etc.), through a simulation-driven approach integrating both architectural and energy-performance evaluation aspects from the early-design phases of the project. In order to go as far as possible in terms of sustainability, the Living Building Challenge (LBC) label has been taken as a guide, providing a design framework to create regenerative spaces where people connect to daylighting, air, food, nature and community. It aims to obtain self-sufficient buildings from a holistic point of view (e.g. positive-energy building approach, treatment of the used-water onsite, prioritizing low-impact materials to obtain healthy living spaces).

The project consists of the complete renovation of a rural home located in the medieval urban fabric of a small village called Bresca in the north of Spain. The initial construction date is unknown, but the house underwent a first basic renovation in 2007. The building consists of a typical farmhouse, well oriented regarding solar exposure, with poorly insulated massive walls and no heating system. The renovation project includes both passive and active strategies, improving thermal insulation of the building envelope and integrating a sunspace that helps to reduce heating and lighting demand, in addition to a photovoltaics (PV) installation with storage system that feeds a high-performance heat pump. This paper focuses on the energy aspects, comparing design results and post-occupancy evaluation in terms of energy consumption/production (energy performance gap). We highlight the high energy performance achieved while surmounting the architectural challenges related to the heritage constraints of the existing building. Results show that between February and March 2019, the house produced 858 and consumed 508 kWh, demonstrating that it is possible to achieve high levels of annual PV coverage ratio while respecting and valuing traditional architecture.

KEYWORDS: heritage; retrofit; sustainable architecture; energy simulation; living building challenge certification

1. INTRODUCTION

The energy renovation of buildings is one of the main strategies that countries of the European Union put in evidence in order to reach the objectives of 2050 [1,2], and thus mitigate the consequences of climate change by reducing the consumption of energy resources and associated CO_2 emissions, while improving comfort of interior spaces. The renovation of buildings, in addition to significantly contributing to reducing the environmental impact of the built environment, also allows the conservation of the architectural heritage of cities and towns, thus avoiding the risk of obsolescence and demolition of buildings. The current regulation on energy efficiency – the "HE-energy saving" document of the Spanish construction technical code (CTE) [3] – requires a high efficiency of the building envelope and the HVAC system to provide heating/cooling and domestic hot water (DHW), taking into account the climate zone in which the building is located. Since 2013, existing buildings that are renovated must also follow the CTE [3] and obtain the energy performance certificate (EPC) [4,5] that allows to verify the compliance of the performance values through a comparison with a typical building that meets the minimum legal requirements. Although this regulatory framework is well defined and based on the 2012 European directives [6], the requirements are still far from the targets set for 2050 [2]. In this context, the voluntary imposition of a certification system such as the LBC [7], allows not only to achieve higher levels of energy efficiency, but also to implement a holistic vision to the renovation project. Indeed, it covers a series of aspects that are not contemplated in current regulations, such as human-scaled living, responsible water use, a healthy interior environment, a responsible use of materials, social inclusion, beauty and biophilia.

2. OBJECTIVES AND METHOD

This paper presents a real project consisting of the complete renovation of a rural home located in Bresca (Spain) following the LBC certification procedure [7]. The objective is to highlight the high energy performance that can be achieved while surmounting the architectural challenges related to the heritage constraints of the existing building. To do so, an iterative design process involving hourly-step energy performance simulation using EnergyPlus [8] is conducted in order to evaluate the effect of the different passive and active renovation strategies. The evaluation includes three main groups of indicators: 1) the photovoltaic performance, including the energy consumed directly on-site, expressed by self-consumption rate, and the level of energy independence, represented by the self-sufficiency rate; 2) the final energy balance; and 3) life cycle cost of the whole renovation.

3. DESCRIPTION OF THE PROJECT

3.1. Original status of the building

The initial construction date is unknown, but the house, composed by two main volumes with three stories each, underwent a first basic renovation in 2007. Figure 1a shows the house prior to this basic renovation, which was conducted mainly on volume 2. The construction work consisted of renovating the floors and adding a building envelope to finish the building and make it inhabitable.

Pictures in Figure 1b and 1c, taken during this first renovation process in 2007, show the type of construction of this building. It is possible to intuit that the improvement of the airtightness as well as the insulation of the building envelope were not part of the scope of this basic renovation.

At the time, taking into account the good orientation and solar exposure of the building, the owners considered that they did not need to improve the performance of the envelope. As such, a thermal mass wood stove was installed for the winter months, but the thermal comfort achieved was far from the optimal conditions.

(a)

(b)

(c)

(d)

(e)

Figure 1: Images during the first renovation conducted in 2007 (a, b and c) and the current status (d and e).

Main characteristics of the building prior to the energy renovation.

- Total floor area: 250 m^2.
- Sloped roof (uninsulated), wood structure and terracotta colour ceramic tiles.
- Monolithic walls in rubble masonry walls without insulation.
- Wooden frame windows with single glazing.
- Wooden structure balcony. Metal railings.

- The floors are built with wooden beams embedded in the façades with ceramic hollow slabs.
- The original HVAC system consists in an old gas-boiler to supply domestic hot water (DHW) at high temperature and a high thermal mass wood stove for heating.

Table 1 shows the estimated U-values of the different parts of the building envelope before the renovation project; the original envelope has high U-values between 1.82 and 3.19. The result of a blower test door revealed that the infiltration rate of the envelope was around 20 air-changes per hour (ACH), representing the biggest problem to be solved.

Table 1: Estimated U-values of the different parts of the building envelope in the **original status** of the building.

Roof	**Façade**	**Floor**	**Openings**	**Infiltration rate**
U-value [W/m^2.K]				*ACH*
1.82	1.89	3.87	3.19	20

3.2. Renovation strategies

The project includes both passive and active strategies, improving thermal insulation of the building envelope and integrating a greenhouse (referred to as sunspace) that helps reduce heating and lighting demand, in addition to a photovoltaics installation with storage system that feeds a high-performance heat pump. The choice of materials was based on a number of criteria:
- Absence of toxic components as defined in the LBC Red List [7];
- Low embodied carbon;
- Short distance between manufacturing site and construction site.

Passives strategies
The main passive strategies, which aim to reduce as much as possible the energy demand regarding heating and cooling, consist of:
- Interior insulation of the façades using between 20 and 25 cm of wood fibre panels;
- External insulation of roof with 35 cm of wood fibre panels;
- Radiant adobe interior walls to increase the thermal inertia and reduce the peak power needed from the heating system (Figure 2d);
- Retrofitting of existing fenestration with wooden frame windows and replacing the single glass for double-glazing 6-10(argon)-6 mm (Figure 2a and 2b).
- Creation of a double-height glazed greenhouse as a preheater of the indoor air and for facilitating cross-ventilation within the house (Figure 2a, 2b and 2c). This sunspace is located on the two façades with the greatest solar irradiation (south and west), and functions as a passive solar heat accumulator. It presents a series of openings towards the interior spaces (e.g. living room), allowing the heat distribution to the spaces with worse orientation.

The resulting U-value of the different parts of the building envelope after renovation are presented in Table 2, showing an important improvement on the building envelope performance. Although the infiltration rate has been reduced from 20 to 7 ACH, representing a significant improvement, the value is not definitive because additional work will be conducted during the coming months to reduce the infiltration caused by the wooden beams that pass through the façade wall for creating the balcony slab.

Table 2: Final U-value of the different parts of the building envelope **after the renovation** of the building.

Roof	**Façade**	**Floor**	**Openings**	**Infiltration rate**
U-value [W/m^2.K]				*ACH*
0.13	0.18	0.18	1.1 glazing 1.4 window frame	7 (measured value) 3 (simulation value)

Actives strategies
The main active strategies, which aim to reduce as much as possible the energy consumption regarding heating and cooling, consist of (Figure 3):

- A new ventilation system without heat recovery;
- A high efficiency air to water heat pump to produce DHW as well as hot water for the radiant floor and walls (35°C).


(a)


(b)


(c)


(d)

Figure 2: Sample of images to illustrate the passive strategies implemented in the project.


(a)


(b)

Figure 3: Sample of images to illustrate the active strategies implemented in the project.

On-site production strategies

The main on-site production strategy consists of a photovoltaic installation on the roof of a total installed power of 4,95 kWp, in combination with a 5,12 kWh capacity battery storage system. The system allows to self-consume 52% of the total produced energy on-site, while the overproduction is injected into the grid. Figure 4a shows the installation of the 15 PV panels with 330 Wp each on the roof and Figure 4b shows the inverter with 5 kW [9], the charger-inverter regulator [10] and the battery block with 5,12 kWh of capacity, but with the space available to upgrade to 10,24 kWh [11].

Figure 4: Sample of images to illustrate the on-site production strategy implemented in the project.

3.3. Monitoring of the building

The proposed monitoring system to control and verify the performance of the building comprises a series of temperature and humidity sensors on the different living spaces and energy meters to know the electricity produced, stored in the batteries and imported from/exported into the grid. Figure 5 shows the location of the different temperature and humidity sensors located across spaces of the house.

Figure 5: Situation of the monitoring sensors.

4. RESULTS

This section shows the comparison between the simulated values and the real values regarding the photovoltaic installation, the final energy balance, and the life-cycle cost of the whole renovation.

4.1. Passive strategies performance - sunspace

Figure 6 shows the comparison of the evolution of the temperature in the sunspace during a typical day in February between the simulated and the measured values. During the period between 12h and 19h, the sunspace can supply heat to the interior spaces through the interior windows. The sunspace therefore appears to fulfil its intended purpose of a passive solar heat accumulator as described in section 3.2.

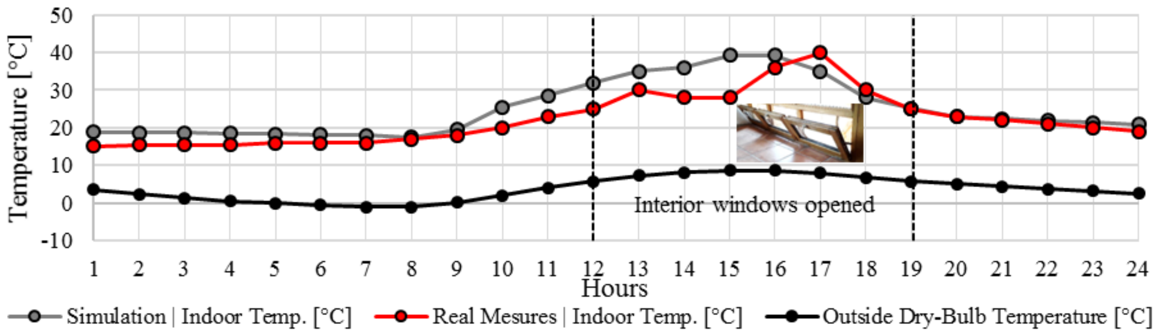

Figure 6: Temperature evolution in the sunspace (real vs simulation values) for a typical February day.

4.2. Photovoltaic performance

Table 4 presents the results for the different indicators regarding the photovoltaic performance. We can observe an average of 20% of overestimation of the values from the simulation, mainly due to differences in the input data of the energy model and weather conditions (in weather file) compared to the real weather. The building achieves high self-consumption and self-sufficiency rates [12,13].

Table 4: Photovoltaic performance indicators (regarding only the BIPV installation)

Indicator [units]	**Value**		
PV and battery installation cost [€]	19.000 €		
	Simulated value	**Real value**	***Difference***
PV electricity production [kWh/year]	12’700	10’300	*-2’400*
PV electricity self-consumed by building [$kWh_{e\text{-}pv}/m^2\cdot year$]	6’600	5’800	*-800*
PV electricity injected into grid [$kWh_{e\text{-}pv}/m^2\cdot year$]	6’100	4’500	*-1’600*
Self-consumption rate [%]	52%	56%	*+4%*
Self-sufficiency rate [%]	30%	35%	*+5%*
Levelized Cost of Energy (25 years horizon) [$€/kWh_{e\text{-}pv}$]	0.060	0.073	*+0.013*

4.3. Final electricity balance

Table 5 presents the results of the final energy balance, considering that the real occupation of the building over the last 6 months was around 41% of the time. We can observe that, in the simulation, the energy balance is negative, meaning that the building produces more energy that it needs. However, in reality, mainly due to the overconsumption caused by the uncontrolled infiltrations, the energy consumption for heating is higher than expected. The energy performance gap (EPG) is calculated as the difference between the actual final energy consumption (for all applications combined) and the estimated value from simulations according to [14]. The EPG in our case is estimated to be of 48%.

Table 5: Final electricity balance (operational phase)

Indicator [units]	**Simulated value**	**Real value**	***Difference***
Final electricity balance (Cons. – Prod.) [$kWh/m^2\cdot year$]	-1.10	52.30	*53.40*

4.4. Life-cycle cost

This section shows the results of the life-cycle cost assessment to give an overview of the cost-effectiveness of the renovation project. Results for all economic indicators are presented in Table 6, including the global investment cost and the payback time (PBT) using a discounted rate of 3%.

Table 6: Life cycle cost indicators

Indicator [units]	**Value**		
Envelope investment | insulation + windows [€]	75’000		
HVAC system | heating and DHW and PV installation [€]	37’000		
Total investment [€]	**112’000**		
	Simulated value	**Real value**	***Difference***
Annual energy bill | before renovation [€/year]	10’803	9’722	*-1’081*
Annual energy bill | after renovation [€/year]	-1’262	2’400	*+3’662*
PBT [years]	9	15	*6*

5. CONCLUSIONS

This paper focuses on the energy performance improvement of a heritage building renovation project. In terms of energy consumption, the difference between the expected airtightness of 3 ACH and the actual measurement of 7 ACH make the actual consumption of the building higher than estimated in the simulations. The sealing of beams that form the balcony should solve the problem of airtightness and bring down the energy performance gap to less than 30%. Despite this, the energy consumption has been reduced by 75% compared to the initial state. The building needs 11'139 kWh of electricity per year, while the PV production is of 10'300 kWh/year. Therefore, in terms of consumption and total PV production, the building produces almost as much as it consumes. However, if we take into account that the self-consumption rate is of 56%, as the building needs to import 5'371 kWh from the grid and that it exports (injects) 4'532 kWh, the self- sufficiency is of 35%. Although there is still some work to be done to reach the desired efficiency values and reduce the observed performance gap, this project demonstrates that it is possible to achieve high levels of self-sufficiency while respecting and valuing traditional architecture.

6. BIBLIOGRAPHY

[1] Aguacil Moreno S. Energy rehabilitation of residential buildings in Spain and European objective 2050. Proposal and validation of a multicriteria tool, oriented to strategic decision-making and based on cost-optimal methodology and life-cycle analysis at territorial scale. Universitat Politècnica de Catalunya, 2017. http://futur.upc.edu/21221174 (accessed: September 2019).
[2] EU. Directive 2018/844/EU Energy performance of buildings, Official Journal of the European Union. 2018; 75–91. https://eur-lex.europa.eu/ (accessed: August 2019).
[3] Ministerio de Fomento. Documento básico HE ahorro de energía. Código Técnico de La Edificación (CTE). 2017; 1–68. https://www.codigotecnico.org/ (accessed: September 2019).
[4] Spanish government. Real Decreto 235 / 2013 (5 de abril) Procedimiento básico para la certificación de la eficiencia energética. 2013; 1–14.
[5] Spanish government. Real Decreto 47/2007. Boletin oficial del estado. 27 (2007) 4499–4507.
[6] European Parliament. Directive 2012/27/EU (25 October 2012), Eenergy efficiency. Official Journal of the European Union. (2012) 1–56. https://doi:10.3000/19770677.L_2012.315.eng
[7] International Living Future Institut. Living Building Challenge 4.0. 2019. https://living-future.org/lbc4/ (accessed: September 2019).
[8] US Department of Energy. EnergyPlus. 2018. https://energyplus.net/ (accessed: April 2018).
[9] Fronius. Primo Inverters. 2019. https://www.fronius.com/ (accessed: September 2019).
[10] Victron Energy. 2019. https://www.victronenergy.com.es/ (accessed: September 2019).
[11] BYD. PV Batteries. 2019. https://www.byd.com/ (accessed: September 2019).
[12] Aguacil S, Lufkin S, Rey E. Active surfaces selection method for building-integrated photovoltaics (BIPV) in renovation projects based on self-consumption and self-sufficiency. *Energy and Buildings*. 2019; 193(15-28). https://doi.org/10.1016/j.enbuild.2019.03.035.
[13] Aguacil Moreno S. Architectural Design Strategies for Building Integrated Photovoltaics (BIPV) in Residential Building Renovation (Thesis N°9332), École polytechnique fédérale de Lausanne. 2019.
[14] Galvin R. Making the “rebound effect” more useful for performance evaluation of thermal retrofits of existing homes: Defining the “energy savings deficit” and the “energy performance gap,” Energy and Buildings. 2014; 69(515–524). https://doi:10.1016/j.enbuild.2013.11.004.