sustainability

MDPI

Article

Energy Retrofit of Social Housing with Cultural Value in Spain: Analysis of Strategies Conserving the Original Image vs. Coordinating Its Modification

Belinda López-Mesa *, Marta Monzón-Chavarrías * and Almudena Espinosa-Fernández *

Department of Architecture, University of Zaragoza, c/María de Luna 3, 50018 Zaragoza, Spain
* Correspondence: belinda@unizar.es (B.L.-M.); monzonch@unizar.es (M.M.-C.); almudenaef@unizar.es (A.E.-F.)

Received: 2 June 2020; Accepted: 7 July 2020; Published: 10 July 2020

Abstract: Two renovation strategies were considered and compared in this paper for the energy renovation of social housing in condo buildings built in 1945–1969, situated in residential estates that have been declared urban areas of interest. One of the strategies, named here the image conservation approach, consists of renovating the building with very efficient solutions, except for the brick-facing walls, which will only have insulation in the existing cavities. The other strategy, the image coordination approach, consists of renovating the whole building with efficient solutions, including external insulation for existing brick-facing walls, and drawing up coordination plans for each of the residential estates in order to guarantee a coordinated new image of the residential estates. By means of three case studies in the city of Zaragoza and four scenarios of improvement, the two strategies are compared regarding the regulation compliance, the energy use, the emissions reduction, the thermal comfort, and the cost-effectiveness of the measures. The results show that the image coordination approach is the best strategy in regard to the studied aspects, achieving a 69%–79% reduction of CO_2 emissions and a 75%–97% reduction of heating use, as well as being the only one capable of transforming these buildings into nearly zero energy buildings (nZEBs).

Keywords: social housing; major renovation; nZEB renovation; cultural value; condominium

1. Introduction

The European Union (EU) has set targets for reducing its greenhouse gas emissions progressively up to 2050 by means of the 2020 climate and energy package, the 2030 climate and energy framework, and the 2050 long-term strategy [1]. Sustainable construction is expected to play a big part in meeting the European Union's climate and energy goals since the built environment is estimated to account for approximately 40% of energy consumption and 36% of CO_2 emissions in the EU [2]. Sustainable, climate-proofed buildings are needed on a massive scale to meet the objectives for 2020 and 2030, and to achieve a climate-neutral Europe by 2050 [2]. Now, the EU is urging countries to bring the building renovation wave into postpandemic recovery plans.

The majority of the building floor area in Spain is composed of residential buildings (82.67% in 2013) [3]. Since the existing residential buildings at present will represent the major part of the housing stocks of Spanish cities in 2050 [4,5], energy retrofit has become one of the most important strategies for the decarbonization of the residential sector. The European Directive 2010/31/EU on Energy Efficiency in Buildings introduced the need to transform buildings into nearly zero energy (nZEB) by 2050, and the European Directive 2018/844/EU amended the existing Directive 2010/31/EU in order to accelerate the decarbonization of the parks in the EU.

The energy retrofit of multifamily residential buildings built in 1945–1969 is of great importance in Spain because it is one of the countries in Europe with the highest share of multifamily dwellings (70.78%

in 2010) and due to the fact that this is the interval of years with the highest share of dwellings (18.62% in 2014) in Spain among the thermally significant periods identified by the European Commission [3]. This stock of buildings was built after the wars and before the first thermal standard was introduced in Spain in 1979, and therefore it is highly energy inefficient. In this period, the share of social housing in Spain (understood as that which has been built with the support of the State) was significantly higher than the mean value for the country (26.6% for the years 1952–2016 [6]). Specifically, the share of social housing was 30%–50% between 1945–1958, 70%–90% between 1959–1965, and 30%–40% between 1966–1969 [6], i.e., 50% as mean value for the period 1945–1969.

The public administrations in Spain started to promote an energy retrofit of social housing estates built in the mentioned period about fifteen years ago. This is the case, for example, of the city of Zaragoza, where 19 multifamily social housing estates (including 7981 dwellings [7]) started being studied in 2004 (together with another two residential estates of single-family houses) [8] and demonstrative building renovation projects were developed in four of these estates in 2008–2011 [9]. These estates were designed in the period of 1942–1964 and built in the period of 1945–1965, except for one of them (Balsas de Ebro Viejo), whose construction took place between 1964 and 1975. They had been declared urban areas of interest (UAI, *Conjuntos Urbanos de Interés* in Spanish) in the General Plan of Urban Planning of Zaragoza (PGOUZ) of 2001 and 2007 due to their character of unity, bringing together representative environmental values of types of residential building and urban areas characteristic of its time (Figure 1). These estates are characterized by buildings of poor quality in the regimes of condominiums with walk-up free-market private apartments, public places with poor quality environments, and selective population loss. It must be noted that social rental housing parks are virtually nonexistent in Spain (1.5%) [6] and social private housing parks are freed from 10 to 30 years after their construction, depending on the autonomous community. For this reason, the interventions on the common areas of the property in multifamily houses must be agreed by the community of neighbors of each condominium. The pilot interventions included the improvement of the envelope and systems, the installation of elevators, and, in given cases, the improvement of the surrounding areas.

These pilot building renovation projects in the residential estates had important qualitative effects for Zaragoza in terms of capacity building and visualization of the model. This positively contributed to reach a deep renovation rate in the whole city of about 0.1% (300 dwellings per year [10] out of a total of 277,411 main regular dwellings [11]) during the subsequent years, which the Zaragoza Municipal Housing Company (ZMHC) aims to increase up to 1% by 2030.

At this moment, the ZMHC, with whom one of the authors has a close contact by means of a collaboration agreement that has been running for eight years [12], is facing an important challenge regarding its renovation strategies in the UAI, which has to do with the loss of character of unity of these residential estates as a consequence of the major renovations. No specific restrictions had been defined in the PGOUZ for the building renovations in UAI, and since the dwellings' usable floor areas are notably small (more of the 70% of dwellings have usable floor areas ranging between 34 m^2 to 56 m^2), the façades have been externally insulated in the interventions conducted so far, changing the external appearance of the buildings (Figure 2). This can bring loss of the character of unity (Figure 2a) when different interventions propose different visual solutions. In other occasions, the visual solution has been carefully designed to remain very close to the original image (Figure 2b), and it is even difficult to appreciate which buildings are externally renovated and which are original from a certain distance (Figure 2(b2)). The character of unity loss is more likely to affect those renovated buildings whose façades are composed of load-bearing walls of facing bricks. Sixteen out of the nineteen residential estates have buildings with facing brick façades. The share of facing brick façades is about 74% for the whole of the UAI [13].

Figure 1. Example of social housing estate declared as urban area of interest (UAI) in Zaragoza: San Jorge.

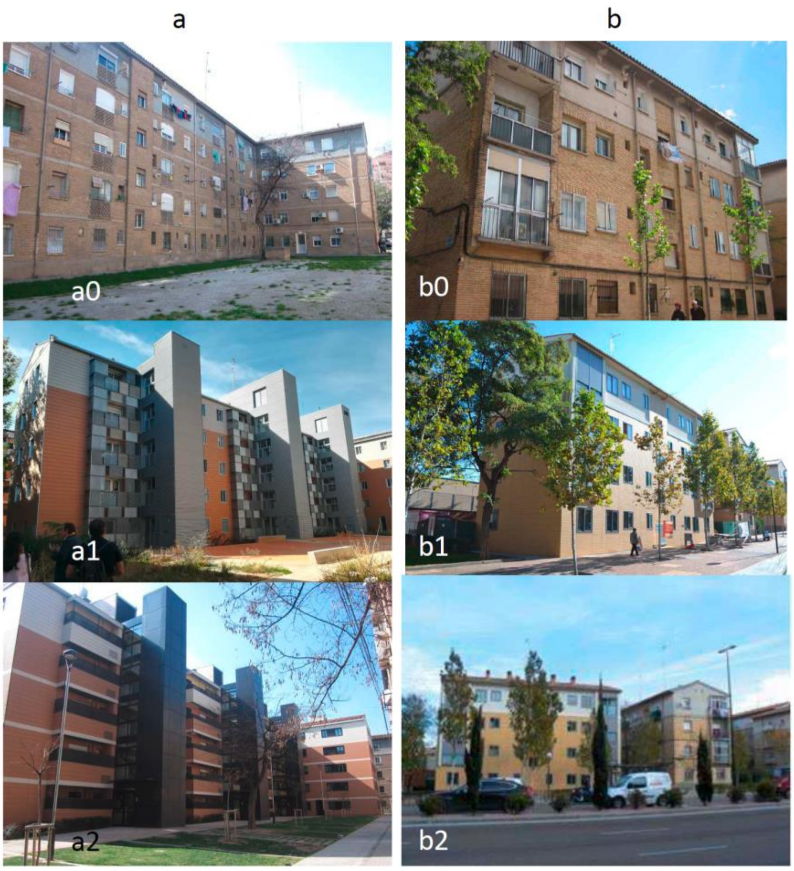

Figure 2. (**a**) Example of unity character loss after renovation with external insulation in *Girón* residential estate: (**a0**) original building image, (**a1**) example 1 of renovated building, (**a2**) example 2 of renovated building; (**b**) example of unity character continuation after renovation with external insulation in *Alférez Rojas* residential estate: (**b0**) original building image, (**b1**) example of renovated building, (**b2**) renovated building in context.

The tensions and conflicts between the sustainability goals and the preservation of the modern built heritage have broadly been addressed in the literature [14–21]. Some authors took a stand against the demolition of old housing buildings, arguing that important synergies can be found between sustainability and conservation, e.g., [4,5,18,21]. Other authors focused on the design challenge of finding an architectural balance between existing and newly added qualities when designing the renovation of housing blocks with specific architectural heritage values, e.g., [14,15,19,20]. Oorschot et al. [20] considered the careful analysis of the architectural and cultural value of the original building by recording which characteristics must be preserved and which could be modified to be of great importance. In Amsterdam, buildings with historic and visual values were observed to offer fewer possibilities for interventions on the outside, especially the façades and the roofs, whereas inside insulation creates more inconvenience, especially if tenants stay in their homes during the intervention [14]. Dowson et al. [16] estimated that in UK there are restrictions on external wall insulation for a further 1.2 million dwellings in conservation areas and 300,000 listed dwellings [22] because of the change of appearance. Ben and Steemers [17] argued that some measures are generally not considered appropriate for listed buildings in UK, such as external wall insulation and double (or triple) glazing, and proposed several viable improvement strategies, including cavity wall insulation, roof insulation, secondary glazing, and draughtproofing, for the Brunswick Centre in London.

In the case of the UAI of Zaragoza, the main cons of inside insulation strategies discussed by the technicians of the municipality and the researchers were the following:

- It reduces the already small usable floor areas. This disadvantage is very difficult to avoid by merging different dwellings in one, as in the case of Amsterdam [14] because of the condominium regime of the buildings, or by expanding the area of the dwellings because the floor additions would affect the image as much as, or even more than, the insulation.
- It obliges occupants to temporarily leave their homes during the intervention. This is an inconvenience that could be partially mitigated by carefully planning the stages with more impact on the occupants' daily life and reducing their duration as much as possible.

For these reasons, the internal insulation strategies were discarded in Zaragoza and this position was accepted in this paper as a starting point. The disadvantage of external insulation is, as already mentioned, the potential loss of the residential estates' character of unity, and two possible options were considered in this study and have been discussed with the ZMHC to overcome the problem:

- One of the options is to use image conservation-oriented energy retrofit strategies that do not compromise the façades image, as in the case of the Brunswick Centre in London [17], but without using inside insulation so that the usable floor area remains equal after the intervention. This implies energy improvement of roofs, windows, plastered walls, and existing wall cavities. Plastered walls are externally insulated, and brick-facing walls are improved by pumping insulation into the existing wall cavities, which are 3 cm thick [13].
- The other option is to assume the preponderance of environmental matters and mitigate their negative impact on cultural aspects as much as possible by drawing up coordination plans for each of these areas in order that the individual interventions in each of the buildings follow some common rules that ensure a final image of unity. This implies that the whole envelope is deeply renovated. All façades, including brick-facing walls, are externally insulated.

This paper focused on comparing different energy retrofit strategies for the case of the UAI in Zaragoza that do not reduce the usable floor area, with the aim to know if the image conservation approach and the image coordination one can ensure comparable levels of performance regarding the regulation compliance, the energy use, the emissions reduction, the thermal comfort, and the cost-effectiveness of the measures, in order to support with data the decisions of the local administration. The scientific contribution of this paper is in the field of design research [23,24], and focuses on the improvement of the observed phenomenon in architectural design of dealing with the tensions between the sustainability goals and the preservation of the modern built heritage.

2. Materials and Methods

In order to compare the different energy retrofit strategies, three case studies were used of real social housing buildings located in three of the 19 multifamily UAI of Zaragoza. The research methodology is composed of the next steps, which we develop in the following sections:

1. Selection of cases studies
2. Scenarios definition
3. Definition of comparison criteria and simulation methods
4. Results analysis and discussion
5. Conclusions.

2.1. Selection of Cases Studies

In previous research works, we had cataloged the 19 multifamily residential estates of Zaragoza declared as UAI [25], identified the construction characteristics of the buildings [13,26], done an energy and acoustic characterization of their envelopes [27,28], and simulated the buildings energy use through a simplified methodology [7,26,27]. Important conclusions from these previous studies have been useful to define the criteria to select our case studies.

On the one hand, we tried to select cases studies representative of the most common energy efficiency performances found among the buildings of the 19 residential estates. The energy performance rating for the indicator of nonrenewable primary energy was found to be an E for 88.5% of the buildings, F for 5.2%, and G for 3.1%, with the remaining 3.2% being renovated buildings in 2016 [29]. Regarding the energy performance rating for the indicator CO_2 emissions, the share was 80.9% of E and 15.9% of D [29]. As can be seen, by far the majority of buildings had a rating of E for nonrenewable primary energy and a rating of E for CO_2 emissions. Our three case studies had an E estimation for nonrenewable primary energy rating and an E estimation for CO_2 emissions rating, except for one of them (the *Alférez Rojas* case), which had an F estimation for nonrenewable primary energy rating (Table 1).

Table 1. Construction characteristics of the case studies (the façade coding is the same as in [13]).

Case Study	Social Housing Block in Residential Estate *Girón*	Social Housing Block in Residential Estate *Alférez Rojas*	Social Housing Block in Residential Estate *Balsas de Ebro Viejo*
Year of Construction	1957	1960	1969
Nonrenewable Primary Energy Rating [29]	E	F	E
CO_2 Emissions Rating [29]	E	E	E
Ground Floor Façade	Façade type F1: 36 cm facing solid brick + 1 cm mortar cement coating + 3 cm nonventilated air space + 4 cm hollow brick + 1.5 cm plastering		Main solution (façade type F9): 12 cm facing solid brick + 1 cm mortar cement coating + 3 cm air space + 4 cm hollow brick + 1.5 cm plastering Solution below windows (façade type F10): 1.5 cm mortar cement exterior coating + 9 cm hollow brick + 1 cm mortar cement coating + 3 cm nonventilated air space + 4 cm hollow brick + 1.5 cm plastering
1st to 3rd Floor Façade	Façade type F2: 24 cm facing solid brick + 1 cm mortar cement coating + 3 cm nonventilated air space + 4 cm hollow brick + 1.5 cm plastering		
4th Floor Façade	Façade type F3: 1.5 cm mortar cement exterior coating + 24 cm hollow brick + 1 cm mortar cement coating + 3 cm nonventilated air space + 4 cm hollow brick + 1.5 cm plastering		
Roof	Pitched roof with ventilated chamber		
Ground	Concrete slab-on-ground	Suspended concrete floor	Slab in contact with uninhabitable room
Windows	Wood frame with single glass 3 mm. Dark shutter		

On the other hand, we selected cases studies with different construction solutions observed in the 19 residential estates in order to check whether these different solutions can make an important difference or not regarding the energy performance of the renovated building:

- Most of the buildings presented façades with thick brick-bearing walls without thermal insulation, and only some of the buildings, built at the end of the studied period, presented structures of pillars with the corresponding thinning of the façade without thermal insulation [13]. Two of our case studies (the *Alférez Rojas* and *Girón* cases) presented thick brick-bearing walls, and one of them presented thinner walls (the *Balsas de Ebro Viejo* case), as can be seen in Table 1.

- With regard to the grounds, most of the buildings (65% of them) presented concrete slab-on-grounds, some of them (26%) had suspended reinforced concrete one-way floors, and the remaining part (9%) had reinforced concrete one-way slabs in contact with uninhabitable rooms, such as storage rooms [13]. Each of our case studies presented one of these three solutions (Table 1).

The general image and urban layout of each of these case studies can be observed in Figure 3. The specific *U*-value of the different construction solutions for the envelope can be found in Appendix A. Since the thermal mass is important in the energy retrofit of buildings from this period [30], the internal areal heat capacity and periodic thermal transmittance for the different façades and grounds are provided in Appendix A to evaluate their thermal inertia, as suggested by [31,32]. The calculations were made according to EN ISO 13786:2017 [33].

Figure 3. General image and urban layout of the three case studies (plans legend: highlighted black are the buildings selected as case studies, highlighted dark grey are the buildings of the same residential estate, highlighted light grey are other buildings in the surroundings).

2.2. Scenarios Definition

Five scenarios were considered for each of the three case studies (Figure 4):

- Scenario 0: original state. The envelope is the original one, described in Table 1 and thermally characterized in Appendix A. With regard to the heating and domestic hot water (DHW) systems, all of them are individual, and so are the cooling systems when they exist. For the sake of comparison, we considered, for the heating and DHW systems, an individual regular gas boiler in each of the dwellings, since it is the most extensive system in Spain [34]. For the cooling system, an electrical single zone system with a seasonal energy efficiency of 2.52 was considered, as recommended by the user guide for the official tool for energy rating in Spain when the system is not known or nonexistent [35].

- Scenario 1: the envelope is improved, avoiding the external insulation of the façades made out of facing bricks. Efficient solutions are considered for the rest of elements of the envelope, even when installing very thick insulations is technically difficult, such as in the case of the external insulation of plastered façades and grounds, in order to compensate the thin insulation of brick facing walls. This scenario follows the image conservation approach. Specifically, the energy improvement of the envelope is made by means of:
    - Insulation of roofs by means of 25 cm thick mineral wool blankets installed in the air chamber. According to the literature, efficient solutions for roofs have a *U*-value between 0.09 and 0.2 W/m^2·K [36,37]. As can be observed in Appendix A, the *U*-value of our renovated roofs is 0.12 W/m^2·K.
    - Secondary glazing. Since in Spain the original windows are aligned with the inside surface of the façade, the additional glazing is external. For the calculations, the inside glazing was considered not to contribute to insulation, since many of them present serious problems of permeability. According to the literature, very efficient solutions for windows have a *U*-value between 0.80 and 1.26 W/m^2·K [36,37]. Our windows have a *U*-value of 1.04 W/m^2·K (Appendix A). The permeability of the new window is 3 m^3/h·m^2 at 100 Pa (class 4, according to EN 12207:2016).
    - Grounds are improved for the case of suspended floors with 20 cm thick external Polyurethane (PUR) insulation, and for the case of slabs in contact with uninhabitable rooms with 20 cm thick external PUR insulation. According to the literature, efficient solutions for grounds have a *U*-value between 0.2 and 0.25 W/m^2·K [37,38]. In our case studies, the *U*-value of these two types of renovated grounds are considerably lower, specifically 0.16 and 0.15 W/m^2·K, respectively (Appendix A). For the case of the slab-on-ground, perimeter insulation is installed because insulating the whole slab would imply important interferences with occupants.
    - External insulation of 16 cm thick for plastered walls. According to the literature, efficient solutions for façades have a *U*-value between 0.15 and 0.3 W/m^2·K [36–38]. As can be observed in Appendix A, the *U*-value of our renovated plastered façades is quite low, specifically 0.15 W/m^2·K.
    - Cavity wall insulation of 3 cm thick for the brick facing walls. These walls have a *U*-value that ranges from 0.60 to 0.73 W/m^2·K (Appendix A).
- Scenario 2: the envelope is improved, insulating externally the whole façade. Efficient solutions are used for the elements of the envelope that they are technically easy to install (roofs and windows), whereas for more problematic elements of the envelope (grounds and external insulation of walls) more technically feasible solutions are considered. This scenario is thought to follow the image coordination approach. Specifically, the improvement is made by means of:
    - Same solutions for roofs and windows as in scenario 1.
    - Grounds are improved for the case of suspended floors with 10 cm thick external PUR insulation, and for the case of slabs in contact with uninhabitable rooms with 10 cm thick external PUR insulation. The *U*-value of these two types of renovated grounds is 0.28 W/m^2·K (Appendix A). For the slab-on-ground, perimeter insulation is used.
    - External insulation of 10 cm thick for façades. The *U*-values of our renovated façades in this scenario range from 0.21 to 0.23 W/m^2·K (Appendix A).
- Scenario 3: the envelope improvement is the same as in scenario 1, and additionally:
    - The heating and DHW system is substituted by gas condensing boilers.
    - Solar panels are installed in order to guarantee that at least 60% of the energy for DHW is solar, as prescribed in the Spanish Technical Code for this location if the system is changed.

- Scenario 4: the envelope improvement is the same as in scenario 2, and as in scenario 3 the heating system is substituted by gas condensing boilers and 60% of the energy for DHW is solar.

The values for the parameters of the envelope and the heating, cooling, and DHW systems that define their contribution to the buildings energy efficiency can be found in Appendix A.

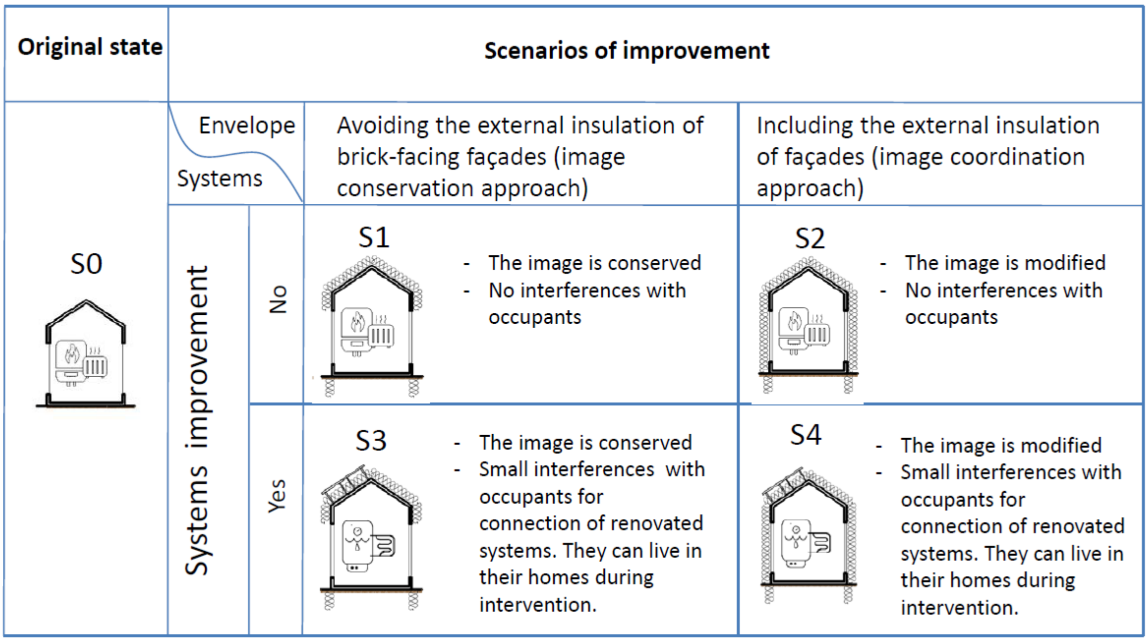

Figure 4. Studied scenarios for each of the three case studies.

2.3. *Definition of Comparison Criteria and Simulation Methods*

The five scenarios of the three case studies were compared in terms of: energy regulation compliance; energy use, CO_2 emissions, and thermal comfort performance; and cost-effectiveness of the measures.

2.3.1. Methodology to Check the Energy Regulation Compliance

In December 2019, a royal decree modifying the Basic Document on Energy Saving (DB-HE) of the Buildings Technical Code was approved in Spain. This recently updated regulation sets, on the one hand, more restrictive requirements for major renovations—which are compulsory when more than 25% of the envelope is improved, as is our case— and, on the other hand, defines for the first time specific requirements for the transformation of existing buildings into nZEBs—which are not mandatory, but must be met if an nZEB renovation is aimed for.

In this paper, we checked the compliance or not of the five scenarios with the two set of requirements: the compulsory major renovation requirements and the optional nZEB renovation requirements.

For both levels of renovation (major renovation and nZEB), the main parameters that are regulated are:

- The envelope global heat transfer coefficient *K*-value (W/m^2·K) must be less than a limit value Klimit. The *K*-value depends on the *U*-values of the envelope elements and thermal bridges and it is the heat transfer coefficient of ISO 14683:2017, divided by the exchange area [39]. The maximum allowable Klimit depends on the climate zone and the compactness of the building and is the same for major renovation and nZEB renovation.
- The value of the solar control of windows will be lower than 2 kW·h/m^2·month for the month of July for households, for both major renovation and nZEB renovation. The solar control is the

ratio between the solar gains in July of all windows of the envelope with their solar protections activated and the useful floor area of the building.

- Nonrenewable primary energy (kW·h/m^2·year) and total primary energy (kW·h/m^2·year) use are limited by a fixed value depending on the climate zone. The values for nZEB renovation are more restrictive than for major renovation. Specifically, for our climate zone D, the limit values for nonrenewable primary energy are 70 kW·h/m^2·year for major renovation and 38 kW·h/m^2·year for nZEB renovation, and the limit values for total primary energy are 105 kW·h/m^2·year for major renovation and 76 kW·h/m^2·year for nZEB renovation.

Additionally, the regulation sets other requirements, such as:

- A maximum *U*-value is set for each element of the envelope that is added, replaced, or modified (Table 2). Our four scenarios of improvement fulfill these values except for the brick facing walls in scenarios 1 and 3.

Table 2. Maximum *U*-value according to the Spanish Buildings Technical Code for climate zone D.

Part of the Envelope	*U*-value lim (W/m^2·K)
Façade—Exterior Wall	0.41
Roof	0.35
Ground	0.65
Windows	1.80

- In our climate zone, at least 60% of the energy demand for DHW has to be obtained from renewable sources, with local origin or nearby the building. This is applicable to those renovations that change the building installations. We made scenarios 3 and 4 fulfil this requirement.
- The accepted permeability of the windows depends on the climate zone. In our location, class 3 or higher, as defined in EN 12207:2017, is demanded. We chose class 4 with lower permeability and therefore better energy performance.

We made our four scenarios of improvement fulfil the additional requirements (except for the *U*-value of the brick-facing walls in scenarios 1 and 3), and afterwards we checked whether the main requirements were met or not for major renovation and nZEB renovation. To check the compliance of these main requirements, the official tool for energy certification of buildings in Spain was used, named HULC version 2.0.1960.1156 [39].

2.3.2. Methodology to Estimate Energy Use, CO_2 Emissions, and Thermal Comfort

To estimate energy use and CO_2 emissions, we used the HULC version 2.0.1960.1156 software [37], and to characterize the thermal comfort the Design Builder version 6 software [40]. This implies a total of 30 simulations.

The same building models were introduced in the two software tools regarding the shapes and orientations of the buildings, their construction solutions (Table 1 and Appendix A), and thermal bridges (Appendix B). The linear thermal transmittances of thermal bridges were calculated using the catalogue of thermal bridges of the HULC version 2.0.1960.1156 software [39], and the same values were used in the Design Builder model. The use and climate conditions established by default in the HULC software were used in the Design Builder software and can be found in Appendix C. The renewal air flow was estimated according to the calculation method proposed in the Spanish Technical Code. The result, 33 L/s, was the same for the five scenarios (scenarios 0–4), since it depends on the household layout, which was kept the same in the improved scenarios. It includes the infiltrations plus the ventilation through the use of the windows. Additionally, we considered the following values for the infiltration air flow rate per internal volume through the envelope (n50), both in HULC and Design

Builder: 5.72 h^{-1} for scenario 0 (original building), as reported by Fernández-Agüera et al. [41] for multifamily social housing in Mediterranean Europe, and 4.91 h^{-1} for the improved scenarios (1 to 4), since according to Almeida et al. [42], the average window contribution for the room permeability is 15% and we changed windows with air permeability of 50 $m^3/h{\cdot}m^2$ to 3 $m^3/h{\cdot}m^2$ (a reduction of 94%). Night ventilation of four renovations per hour during summer was considered in the two software tools, since all the studied buildings allow for crossed ventilation.

With regard to the solar control of windows, we defined two parameters:

- The total transmittance of solar energy of windows when all the solar devices are activated: according to the support document of the Spanish Technical Code for calculation of envelope parameters [43], it is of 0.15 for scenario 0 (characterized by a dark exterior shutter with single glass) and 0.05 for the improved scenarios 1 to 4 (characterized by a light shutter and a window with triple glass).
- The activation of the solar protection: the activation values by default in HULC, for 30% for the summer period, were considered in both software tools. The way this parameter is introduced in Design Builder can be seen in Appendix C.

To estimate the thermal comfort, we used the adaptative comfort approach according to the ASHRAE55-2017 standard included in the Design Builder software for naturally ventilated buildings. This method has been proven to be useful for mixed-mode buildings such as ours (i.e., a combination of operable windows and mechanical conditioning) [44]. An annual simulation was run at intervals of one hour. Once the simulation was done, the data (air temperature, mean radiant temperature, operative temperature, exterior air temperature, renovations per hour by means of mechanical ventilation, natural ventilation, and infiltrations) in csv format were exported to the software CONFADAPT-ASH55 version 1.0 [45], which allowed us to obtain the hours inside and outside the 80% and 90% acceptability limits, indicating the percentage of occupants expected to be comfortable at the indicated indoor. We used the 90% acceptability limit to do the estimations with a higher standard of thermal of comfort.

2.3.3. Methodology to Estimate the Cost-Effectiveness of the Scenarios

We first estimated the total investment renovation costs of the measures for each of the four improvement scenarios of the three case studies by means of the CYPE software and database [46], and afterwards we divided it by the total surface to obtain the renovation investment per m^2 for each case. To estimate the cost-effectiveness of each scenario of improvement, the costs-to-effectiveness ratio [47] that we established divided the total investment costs by the saved kW·h of nonrenewable primary energy for the five scenarios of the three case studies.

3. Discussion and Results

3.1. Energy Regulation Compliance

Only one of the scenarios complied with the nZEB renovation requirements, scenario 4, and two of the scenarios, scenarios 2 and 4, complied with the major renovation requirements (Table 3). For the case study of Balsas de Ebro Viejo, it was necessary to increase the percentage of solar energy for domestic hot water (DHW) up to 65% in order to make it comply with the nZEB renovation requirements (we name this scenario 4* in Tables 3 and 4 and Tables A1–A3). This building presented a worse energy performance in all the scenarios (with 27%–59% more nonrenewable primary energy and total primary energy use), which could be explained by the fact that it is the only one with thinner façades and a corresponding lower thermal mass, as shown by the values of the periodic thermal transmittance in Appendix A.

This implies that if social housing in Zaragoza is renovated following the image conservation approach (scenarios 1 and 3), the energy regulation for major renovation, which is compulsory, could not be fulfilled, unless additional measures were taken on the top of those that we have studied here. Only the image coordination approach provides solutions that would comply with current regulations (scenarios 2 and 4) and could even transform existing social housing buildings into nZEBs when improving both the envelope and the systems (scenario 4). This was the case for the two case studies with massive load-bearing façades (*Girón* and *Alférez Rojas*). For the case of the building with thinner façades and a structure of pillars (*Balsas de Ebro Viejo*), the only scenario fulfilling the major renovation requirements was scenario 4. In order for the image conservation approach (scenarios 1 and 3) to fulfil the major renovation requirements, it would be necessary to reduce the K-value (Table 3). This would require, for example, adding internal insulation, but as already discussed this is not considered a feasible solution due to the small size of households.

Table 3. Results of compliance with the Spanish Buildings Technical Code.

	K-Value ($W/m^2 \cdot K$)		Qsol, jul ($kW \cdot h/m^2 \cdot month$)		Nonrenewable Primary Energy ($kW \cdot h/m^2 \cdot year$)			Total Primary Energy ($kW \cdot h/m^2 \cdot year$)			Compliance with Requirements	
Scenario	**Calculated**	**Limit**	**Calculated**	**Limit**	**Calculated**	**MR Limit**	**n ZEB Limit**	**calculated**	**MR Limit**	**n ZEB Limit**	**MR**	**nZEB**
						***Girón* case study**						
0	1.59	0.65	1.59	2	103.5	70	38	105.5	105	76	NO	NO
1	0.94	0.65	0.35	2	80.0	70	38	82.0	105	76	NO	NO
2	0.53	0.65	0.35	2	64.1	70	38	66.1	105	76	YES	NO
3	0.94	0.65	0.35	2	46.9	70	38	69.3	105	76	NO	NO
4	0.53	0.65	0.35	2	33.7	70	38	56.0	105	76	YES	YES
						***Alférez Rojas* case study**						
0	1.93	0.65	1.93	2	113.0	70	38	115.8	105	76	NO	NO
1	1.01	0.65	0.48	2	83.9	70	38	86.9	105	76	NO	NO
2	0.33	0.65	0.48	2	51.6	70	38	54.8	105	76	YES	NO
3	1.01	0.65	0.48	2	54.2	70	38	73.9	105	76	NO	NO
4	0.33	0.65	0.48	2	27.6	70	38	47.5	105	76	YES	YES
						***Balsas de Ebro Viejo*case study**						
0	1.83	0.66	1.79	2	165.0	70	38	168.3	105	76	NO	NO
1	0.96	0.66	0.66	2	101.5	70	38	105.3	105	76	NO	NO
2	0.36	0.66	0.66	2	72.3	70	38	76.2	105	76	NO	NO
3	0.96	0.66	0.66	2	61.2	70	38	87.9	105	76	NO	NO
4	0.36	0.66	0.66	2	38.9	70	38	65.8	105	76	YES	NO
4 *	0.36	0.66	0.66	2	37.2	70	38	65.8	105	76	YES	YES

Note: MR: major renovation; nZEB: nearly zero energy buildings; highlighted grey are the unfulfilled limits; * Additional 5% of DHW (in total 65%).

Table 4. CO_2 emissions of the three case studies for the five studied scenarios.

Case Study	***Girón***	***Alférez Rojas***	***Balsas de Ebro Viejo***
Scenario	**CO_2 Emissions ($kg\ CO_2/m^2 \cdot year$)**	**CO_2 Emissions ($kg\ CO_2/m^2 \cdot year$)**	**CO_2 Emissions ($kg\ CO_2/m^2 \cdot year$)**
0	21.6	23.46	34.4
1	16.6	17.25	20.82
2	13.23	10.35	14.52
3	9.59	10.95	12.28
4	6.78	5.26	7.49
4*	-	-	7.14

Note: *Additional 5% of DHW (in total 65%).

3.2. Energy Use, CO_2 Emissions, and Thermal Comfort

When looking at the CO_2 emissions of the three case studies for the five scenarios considered (Table 4), we observed that:

- The energy retrofit of the envelope following the image conservation approach (scenario 1) could be responsible for the reduction of 23%–39% of CO_2 emissions, depending on the case study, whereas the improvement of the envelope following the image coordination approach (scenario 2) could entail a reduction of 39%–58% of CO_2 emissions, according to simulations.
- If, additionally, the systems are improved, the total reduction of CO_2 emissions following the image conservation approach (scenario 3) could be up to 53%–64%, whereas following the image conservation approach (scenario 4) it could be up to 69%–79%, according to simulations.

Therefore, the image coordination approach could bring about an additional 13%–24% reduction of CO_2 emissions, as compared to the image conservation approach, which is quite a significant figure considering the objectives of the EU to reduce emissions by 80%–95% for 2050.

When the CO_2 emissions are broken down into heating, cooling, and DHW emissions for the three case studies and five scenarios (Figures 5–7), we observed that:

- The envelope energy retrofit would significantly contribute to the reduction of emissions caused by the use of heating systems: a 45%–64% reduction in heating CO_2 emissions with the image conservation approach, and 75%–96% with the image coordination approach. On the other hand, it would increase the emissions caused by the use of cooling systems: a 9%–27% increase in cooling CO_2 emissions with the image conservation approach and 13%–39% with the image coordination approach. However, these increases are not so significant because CO_2 emissions due to cooling only represent a 6%–8% of total emissions in the original buildings (scenario 0) for this city and these case studies. The reason for this low need of cooling systems may be due to the combination of high internal thermal inertia, night ventilation, and solar protection, which together would significantly reduce the cooling demand in the five scenarios [48].
- The proposed systems improvement would reduce 5%–20% of CO_2 emissions of heating systems and 69% of DWH systems.

Therefore, the most significant CO_2 emissions reductions would be caused by the deep energy retrofit of the envelope in the image coordination approach and the improvement of the DHW production systems.

When analyzing the energy use (broken down into heating, cooling, and DHW, as well as into renewable and nonrenewable) and thermal comfort for the three case studies and five scenarios (Figures 8–10), we observed that:

- The reason why the emissions get so significantly reduced by the deep renovation of the envelope is the significant saving in heating energy use: a 45%–64% saving with the image conservation approach (scenario 1) and 75%–97% for the image coordination one (scenario 2), according to simulations. This reduction in heating energy use could be achieved without compromising the comfort. In fact, it would actually increase the percentage of hours of 90% acceptability, with an additional 48%–54% of hours for the image conservation approach (scenario 1) and 45%–55% for the image coordination approach (scenario 2). The comfort achieved would be quite similar for both approaches.
- The reason why the emissions get so significantly reduced by the improvement of the DHW production systems is mainly the installation of renewable sources. As can be seen in Figures 8–10, the energy use for DHW would only be reduced by 21% in all the cases, and the rest of the emissions reduction (48%) would be achieved by the use of sun as energy source.

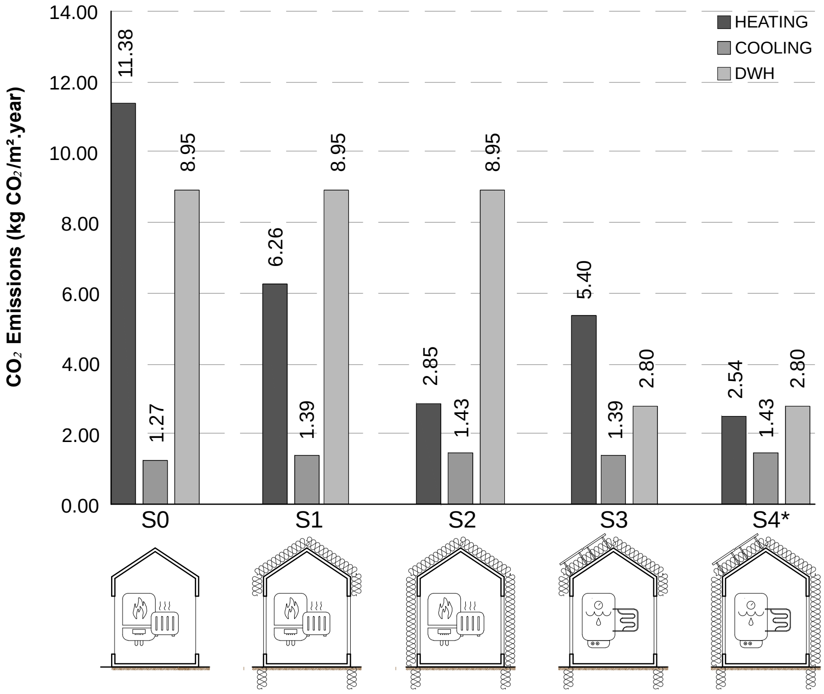

Figure 5. CO_2 emissions for the case study of *Girón* (S#: scenario #).

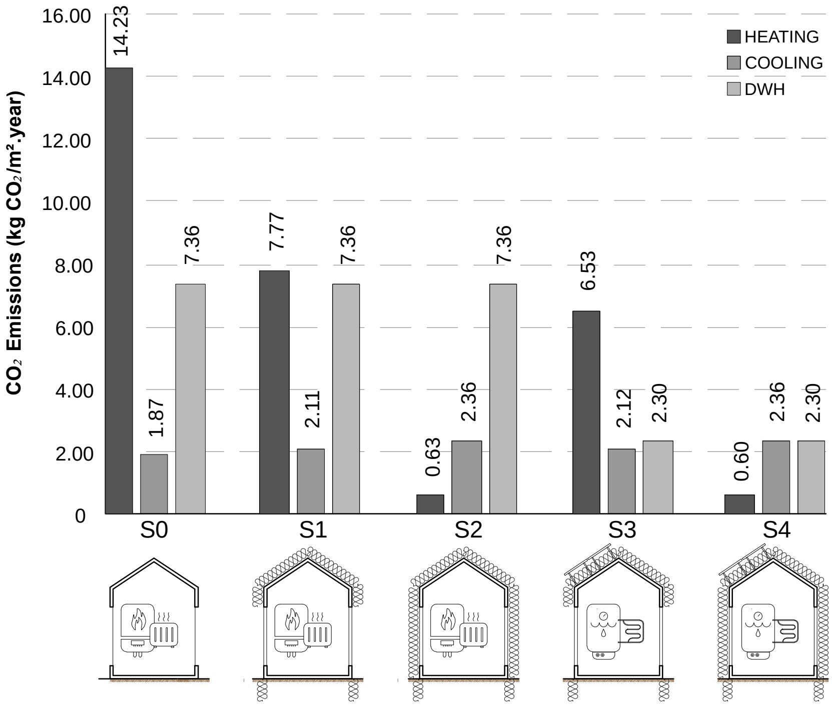

Figure 6. CO_2 emissions for the case study of *Alférez Rojas* (S#: scenario #).

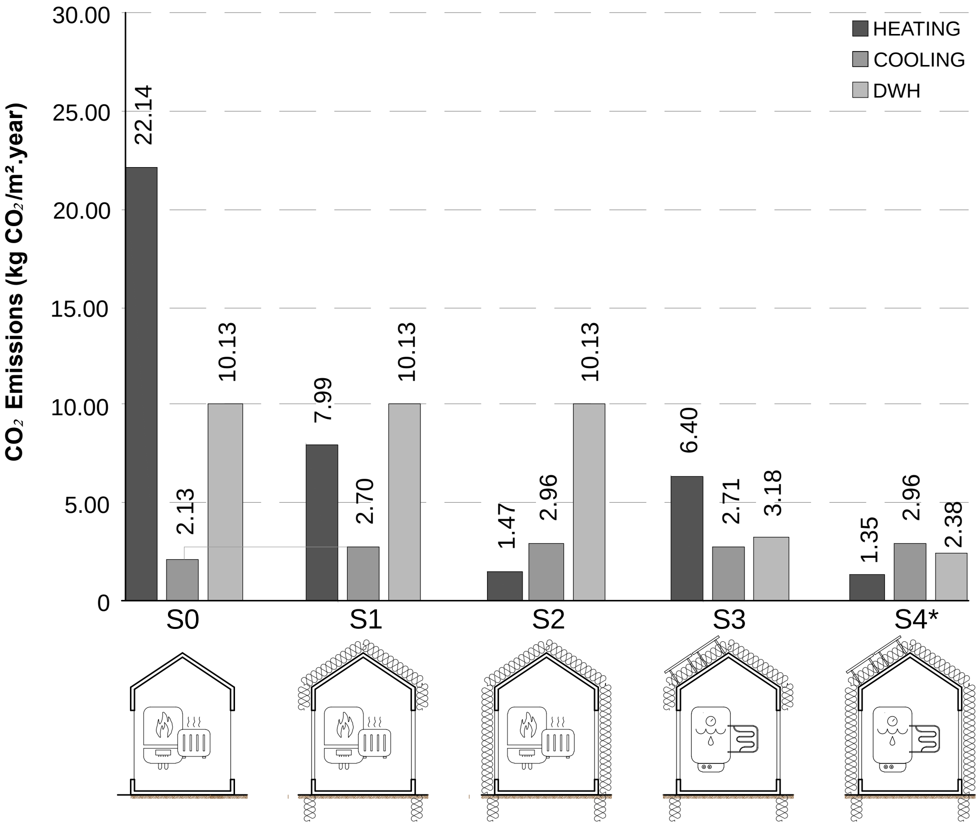

Figure 7. CO_2 emissions for the case study of *Balsas de Ebro Viejo* (S#: scenario #).

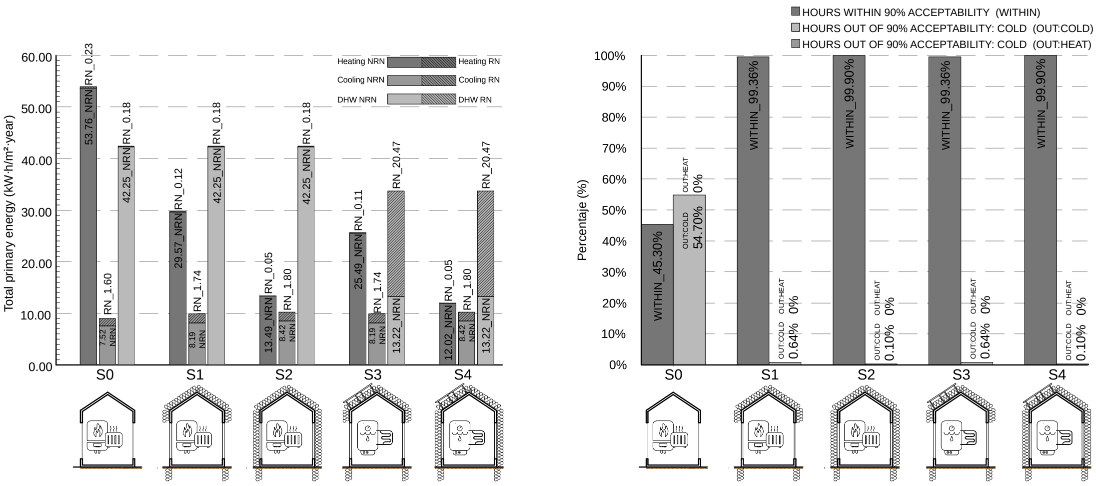

Figure 8. Primary energy use (**left**) and percentage of hours within the 90% of acceptability comfort range (**right**) in *Girón* case study (S#: scenario #; NRN: nonrenewable; RN: renewable).

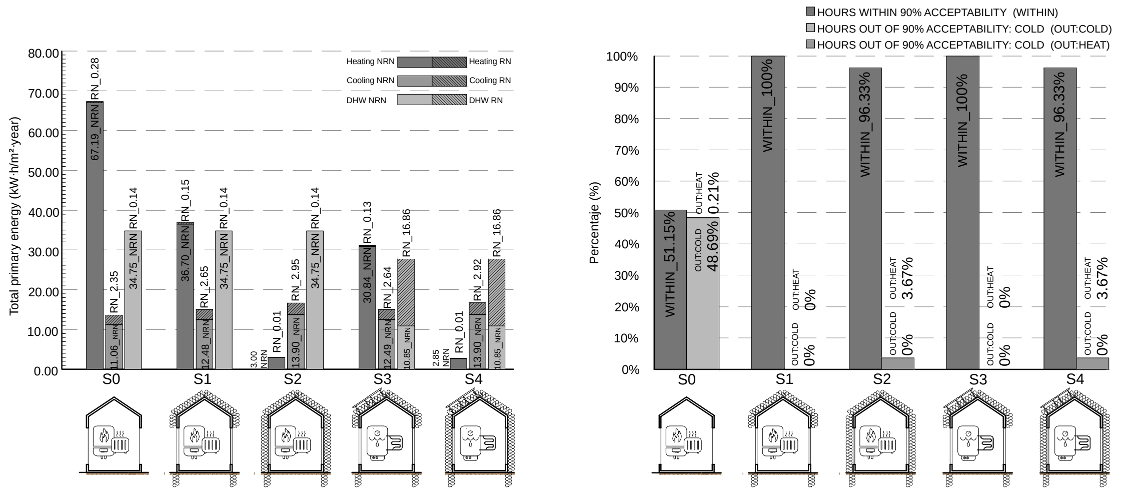

Figure 9. Primary energy use (**left**) and percentage of hours within the 90% of acceptability comfort range (**right**) in *Alférez Rojas* case study (S#: scenario #; NRN: nonrenewable; RN: renewable).

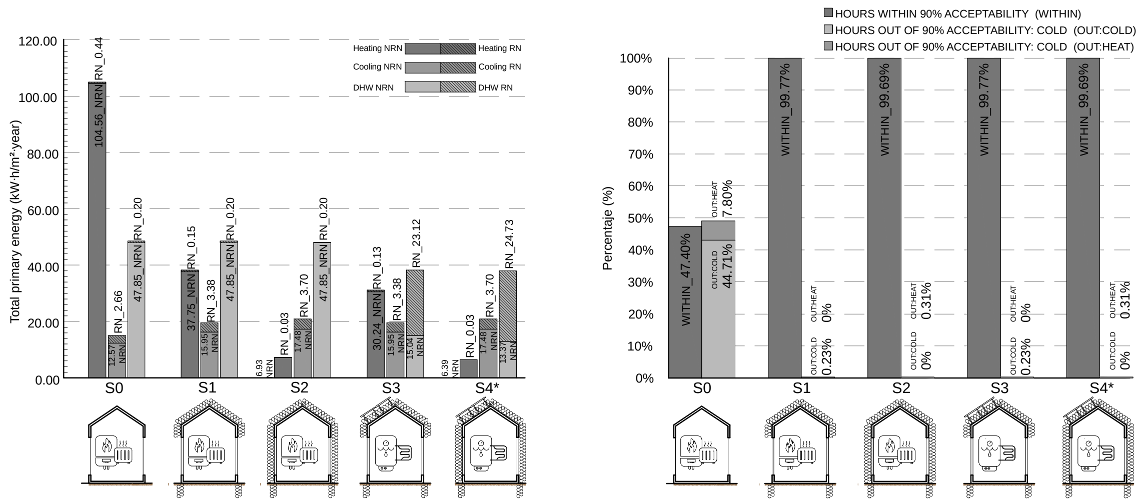

Figure 10. Primary energy use (**left**) and percentage of hours within the 90% of acceptability comfort range (**right**) in *Balsas de Ebro Viejo* case study (S#: scenario #; NRN: nonrenewable; RN: renewable).

3.3. Cost-Effectiveness of the Scenarios

To complete the analysis, we performed a cost-effectiveness analysis of the scenarios for the three case studies. As can be seen in Table 5, the most cost-effective scenario is number 2, corresponding to the deep renovation of the envelope following the image coordination approach, with a cost of 0.69€–2.02€ per nonrenewable kW·h saved, depending on the case study. The next most cost-effective scenario is the one improving the envelope following the image conservation approach (scenario 1), followed by the scenarios that also improve systems (scenarios 4 and 3). Again, the image coordination approach was proven to be more advantageous from the sustainability point of view than the image conservation one.

Table 5. Costs analysis (TC: total renovation investment costs; RC/S: renovation investment costs per usable surface; C-E: cost-effectiveness: NRN: nonrenewable).

	Girón Case Study			*Alférez Rojas* Case Study			*Balsas de Ebro Viejo* Case Study		
Scenario	**TRC (€)**	**RC/S (€/m²)**	**C-E (€/NRN kW·h Saved)**	**TRC (€)**	**RC/S (€/m²)**	**C-E (€/NRN kW·h Saved)**	**TRC (€)**	**RC/S (€/m²)**	**C-E (€/NRN kW·h Saved)**
1	139,402	70.07	2.97	89,850	57.16	1.96	51,221	55.08	0.87
2	158,975	79.90	2.02	96,411	61.33	0.99	59,350	63.82	0.69
3	289,299	145.41	5.26	210,805	134.10	3.84	141,590	152.25	2.15
4	308,872	155.25	3.80	217,367	138.27	2.25	148,700	159.89	1.71

4. Conclusions

How to conduct the energy renovation of social housing of the period 1945–1969 in Spain, without compromising the character of unity of the residential estates to which they belong, is a challenge that some city councils are facing.

In Spain, the energy retrofit of social housing with cultural value presents different challenges from those identified in other countries, such as England or the Netherlands [14–22], since inside insulation is not considered a feasible option because of the small size of the households and the difficulty of merging dwellings in condo buildings.

Two possible approaches were considered in this paper to deal with the tensions between the sustainability goals and the preservation of the modern built heritage. One of them, named here the image conservation approach, consists of renovating the building with very efficient solutions, except for the brick-facing walls, which will only have insulation in their existing 3 cm thick cavities. The other strategy, the image coordination approach, consists of renovating the whole building with efficient solutions, including external insulation for existing brick-facing walls, and drawing up coordination plans for each of the residential estates in order to guarantee a coordinated new image of the residential estates.

By means of three case studies in the city of Zaragoza and four scenarios of improvement, the two strategies were compared regarding the regulation compliance, the energy use, the emissions reduction, the thermal comfort, and the cost-effectiveness of the measures.

The results show that from the points of view of environment (energy use and emissions) and cost-effectiveness, the image coordination approach is the best strategy because:

- It would bring about an additional 13%–24% reduction of CO_2 emissions as compared to the image conservation approach. In total, it could contribute to up to 69%–79% reduction of CO_2 emissions in comparison with the original buildings, which is quite close to the objectives of the EU for 2050 to reduce emissions in the building sector by 80%–95%.
- It implies an additional reduction of heating energy use of 29%–51% as compared to the image conservation approach. The heating energy use can be reduced in total up to 75%–97% in comparison with the original buildings with this approach, according to simulations.
- Even if it implies an additional increase of the cooling energy use of 4%–13% as compared to the image conservation approach and a total increase of 13%–39% with regard to the original buildings (scenario 0), this is not so significant when looking at the whole picture because cooling only represents a 6%–8% of total emissions in scenario 0 thanks to the high thermal inertia, night ventilation, and solar protection of these types of buildings, which are maintained or improved in the subsequent scenarios.

Regarding thermal comfort, both strategies provide high levels of comfort, reaching 96%–100% of hours within the 90% acceptability.

The analysis also shows that the image coordination strategy is the only one that can ensure the fulfilment of the compulsory major renovation requirements recently modified in Spain, and can even transform existing social housing buildings into nZEBs by improving both the envelope and the systems.

For these reasons, the image coordination approach is the only strategy recommended in this paper, unless the boundary conditions were changed, for example by defining innovative solutions to facilitate merging households in condo buildings and using inside insulation solutions.

The buildings from this period with thick brick-bearing walls show a better energy performance before and after renovation than buildings with structures of pillars and the corresponding thinning of the façade, due to the higher thermal inertia of their façades making it easier and cheaper (up to 14%–62%) to achieve the major renovation and nZEB standards.

Author Contributions: Conceptualization, B.L.-M.; data curation, M.M.-C. and A.E.-F.; formal analysis, B.L.-M., M.M.-C. and A.E.-F.; funding acquisition, B.L.-M.; investigation, B.L.-M., M.M.-C. and A.E.-F.; methodology, B.L.-M., M.M.-C. and A.E.-F.; project administration, B.L.-M.; resources, B.L.-M.; software, M.M.-C. and A.E.-F.; validation, B.L.-M., M.M.-C. and A.E.-F.; visualization, A.E.-F.; writing—original draft, B.L.-M.; writing—review and editing, B.L.-M., M.M.-C. and A.E.-F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Economy and Competitiveness of Spain, project "BIA2013-44001-R Integrated design protocol for social housing retrofit and urban regeneration"; and by FEDER 2014–2020, project "Construyendo Europa desde Aragón", research group T37_17R "Grupo de Investigación en Arquitectura".

Acknowledgments: The authors would like to express their gratitude to "Sociedad Municipal Zaragoza Vivienda" and to Juan Rubio del Val (director of the Observatory *Ciudad 3-R*) for providing information about the case studies and the exchange of ideas.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Thermal characterization of the elements of the envelope and systems of the simulation models (Y_{12}: periodic thermal transmittance; k_1: internal areal thermal capacity).

Scenarios and Cases		Façade	Roof	Ground	Windows	Systems
Scenario 0	*G irón*	F1*U*-value = 1.05 W/m^2·K Y_{12} = 0.11 W/m^2·K K_1 = 41 kJ/m^2·K	*U*-value = 2.25 W/m^2·K	*U*-value = 3.81 W/m^2·K	Old wood frame *U*-value = 2.0 W/m^2·K; Single glass *U*-value = 5.6 W/m^2·K; g = 0.85; Dark shutter Window *U*-value = 5.08 W/m^2·K [13]	Regular gas boiler Performance 81% [34]
	Alférez Rojas	F2 *U*-value = 1.23 W/m^2·K Y_{12} = 0.30 W/m^2·K K_1 = 45 kJ/m^2·K F3 *U*-value = 0.78 W/m^2·K Y_{12} = 0.13 W/m^2·K K_1 = 43 kJ/m^2·K		*U*-value = 2.21 W/m^2·K		
	Balsas de Ebro Viejo	F9*U*-value = 1.49 W/m^2·K Y_{12} = 0.89 W/m^2·K K_1 = 48 kJ/m^2·K F10 *U*-value = 1.20 W/m^2·K Y_{12} = 0.75 W/m^2·K K_1 = 49 kJ/m^2·K	*U*-value = 2.31 W/m^2·K	*U*-value = 1.92 W/m^2·K		
Scenario 1	*Girón*	F1*U*-value = 0.60 W/m^2·K Y_{12} = 0.04 W/m^2·K K_1 = 41 kJ/m^2·K	*U*-value = 0.12 W/m^2·K	*U*-value = 3.81 W/m^2·K; Perimeter insulation: 1 m, R = 3.0 m^2·K/W;	PVC frame *U*-value = 1.80 W/m^2·K Triple glass *U*-value = 0.85 W/m^2·K; g = 0.70 Light shutter Window *U*-value = 1.04 W/m^2·K	Regular gas boiler Performance 81% [34]
	Alférez Rojas	F2 *U*-value = 0.66 W/m^2·K Y_{12} = 0.11 W/m^2·K K_1 = 42 kJ/m^2·K F3 *U*-value = 0.15 W/m^2·K Y_{12} = 0.00 W/m^2·K K_1 = 41 kJ/m^2·K		*U*-value = 0.16 W/m^2·K		
	Balsas de Ebro Viejo	F9*U*-value = 0.73 W/m^2·K Y_{12} = 0.33 W/m^2·K K_1 = 45 kJ/m^2·K F10 *U*-value = 0.15 W/m^2·K Y_{12} = 0.03 W/m^2·K K_1 = 42 kJ/m^2·K	*U*-value = 0.12 W/m^2·K	*U*-value = 0.15 W/m^2·K		

Table A1. *Cont.*

Scenarios and Cases		Façade	Roof	Ground	Windows	Systems
Scenario 2	*Girón*	F1 *U*-value = 0.23 W/m^2·K Y_{12} = 0.00 W/m^2·K K_1 = 41 kJ/m^2·K	*U*-value =0.12 W/m^2·K	*U*-value = 3.81 W/m^2·K; Perimeter insulation: 1 m, R = 3.0 m^2·K/W;	PVC frame *U*-value = 1.80 W/m^2·K Triple glass *U*-value = 0.85 W/m^2·K; g = 0.70 Light shutter Window *U*-value = 1.04 W/m^2·K	Regular gas boiler Performance 81% [34]
	Alférez Rojas	F2 *U*-value = 0.23 W/m^2·K Y_{12} = 0.01 W/m^2·K K_1 = 41 kJ/m^2·K F3 *U*-value = 0.21 W/m^2·K Y_{12} = 0.01 W/m^2·K K_1 = 41 kJ/m^2·K		*U*-value = 0.28 W/m^2·K		
	Balsas de Ebro Viejo	F9 *U*-value = 0.22 W/m^2·K Y_{12} = 0.04 W/m^2·K K_1 = 42 kJ/m^2·K F10 *U*-value = 0.23 W/m^2·K Y_{12} = 0.05 W/m^2·K K_1 = 43 kJ/m^2·K	*U*-value = 0.12 W/m^2·K	*U*-value = 0.28 W/m^2·K		
Scenario 3	*G irón*	F1 *U*-value = 0.60 W/m^2·K Y_{12} = 0.04 W/m^2·K K_1 = 41 kJ/m^2·K	*U*-value = 0.12 W/m^2·K	*U*-value = 3.81 W/m^2·K; Perimeter insulation: 1 m, R = 3.0 m^2·K/W;	PVC frame *U*-value = 1.80 W/m^2·K Triple glazing *U*-value = 0.85 W/m^2·K; g = 0.70 Light shutter *U*-value window = 1.04 W/m^2·K	Gas condensing boiler Performance 100% 60% solar energy DHW
	Alférez Rojas	F2 *U*-value = 0.66 W/m^2·K Y_{12} = 0.11 W/m^2·K K_1 = 42 kJ/m^2·K F3 *U*-value = 0.15 W/m^2·K Y_{12} = 0.00 W/m^2·K K_1 = 41 kJ/m^2·K		*U*-value = 0.16 W/m^2·K		
	Balsas de Ebro Viejo	F9 *U*-value = 0.73 W/m^2·K Y_{12} = 0.33 W/m^2·K K_1 = 45 kJ/m^2·K F10 *U*-value = 0.15 W/m^2·K Y_{12} = 0.03 W/m^2·K K_1 = 42 kJ/m^2·K	*U*-value = 0.12 W/m^2·K	*U*-value = 0.15 W/m^2·K		

Table A1. *Cont.*

Scenarios and Cases		Façade	Roof	Ground	Windows	Systems
Scenarios 4 and 4*	*Girón*	F1 U-value = 0.23 W/m^2·K Y_{12} = 0.00 W/m^2·K K_1 = 41 kJ/m^2·K F2 U-value = 0.23 W/m^2·K Y_{12} = 0.01 W/m^2·K K_1 = 41 kJ/m^2·K F3 U-value = 0.21 W/m^2·K Y_{12} = 0.01 W/m^2·K K_1 = 41 kJ/m^2·K	U-value = 0.12 W/m^2·K	U-value = 3.81 W/m^2·K; Perimeter insulation: 1 m, R = 3.0 m^2·K/W;	PVC frame U-value = 1.80 W/m^2·K Triple glass U-value = 0.85 W/m^2·K; g = 0.70 Light shutter U-value window =1.04 W/m^2·K	Gas condensing boiler Performance 100% 60% solar energy DHW (scenario 4) 65% solar energy DHW (scenario 4*)
	Alférez Rojas			U-value = 0.28 W/m^2·K		
	Balsas de Ebro Viejo	F9 U-value = 0.22 W/m^2·K Y_{12} = 0.04 W/m^2·K K_1 = 42 kJ/m^2·K F10 U-value = 0.23 W/m^2·K Y_{12} = 0.05 W/m^2·K K_1 = 43 kJ/m^2·K	U-value = 0.12 W/m^2·K	U-value = 0.28 W/m^2·K		

Note: * Additional 5% of DHW (in total 65%)

Appendix B

Table A2. Linear thermal transmittance of thermal bridges (W/mK).

Scenario	Floor-To-Wall Junctions	Wall-To-Wall Junctions: Exterior Corners	Wall-To-Wall Junctions: Interior Corners	Window-To-Wall Junctions: Ledge	Window-To-Wall Junctions: Lintel	Window-To-Wall Junctions: Jambs	Slab-On-Ground	Suspended Concrete Floors and Slabs in Contact with Uninhabitable Rooms
				***Girón* case study**				
0	0.99	0.15	−0.22	0.10	0.58	0.37	3.51	-
1, 3	0.67	0.08	−0.12	0.12	0.55	0.34	3.76	-
2, 4	0.07	0.04	−0.06	0.08	0.09	0.03	3.88	-
				***Alférez Rojas* case study**				
0	0.98	0.15	−0.22	0.11	0.59	0.37	-	−2.67
1, 3	0.18	0.08	−0.19	0.15	0.70	0.43	-	0.94
2, 4	0.08	0.05	−0.07	0.08	0.09	0.04	-	0.19
				***Balsas de Ebro Viejo* case study**				
0	1.06	0.19	-	0.10	0.56	0.36	-	−6.11
1, 3	0.61	0.09	-	0.12	0.51	0.32	-	0.9
2, 4, 4 *	0.06	0.04		0.08	0.09	0.04	-	0.81

Note: * Additional 5% of DHW (in total 65%).

Appendix C

Table A3. Use and climate conditions in the simulation models.

Parameters	Values
Occupancy density (3 people)	0.05 people/m^2
Hours of operation and occupancy: Monday to Friday: 7 am to 3 pm	25% occupation
Hours of operation and occupancy: Monday to Friday: 3 pm to 8 pm	50% occupation
Hours of operation and occupancy: Monday to Friday: 8 pm to 7 am	100% occupation
Hours of operation, activity and occupancy: Saturday and Sunday	100% occupation
Climate equipment operating hours (heating)	7 a.m. to 10 p.m.
Climate equipment operating hours (cooling)	9 a.m. to 8 p.m.
Running of the air conditioning system from Monday to Sunday	7 days/week
Summer period	1st June–30th September
Winter period	1st October–31st May
Metabolic factor: "Standing/walking" option	1
Clothing values (CLO)	Summer 0.5 Clo; winter: 1.0 Clo
Load due to general lighting	4.4 W/m^2–100lux (10% (0–7 h, 30% (7–18 h), 50% (18–19 h), 100% (19–23 h), 50% (23-24 h)
High set point temperature (June-September)	27 °C (0:00–7:00, 23:00–23:59) 25 °C (15:00–22:59)
Low set point temperature (January-May, October-December)	17 °C (0:00–7:00, 23:00–23:59) 20 °C (7:00–22:59)
Relative humidity of the indoor air	50%
Infiltration air flow rate per internal volume through the envelope (n50)	5.72 h^{-1} for scenario 0 [41], and 4.91 h^{-1} for the improved scenarios (1–4 and 4 *)
Renewal air flow	33 L/s
Night ventilation	4 h^{-1} (June–September; 1–8 h)
Activation of solar control in summer	Window shadingType: blind with low reflectivity slats (scenario 0), blind with high reflectivity slats (scenarios 1–4 and 4*) Position: outside Slat angle control type: fix; vertical Operation schedule: residential CTE shading: On: June–September; 30% 0–24 h Off: January–May; October–December

Note: * Additional 5% of DHW (in total 65%).

References

1. European Commission. Climate Strategies & Targets—European Commission. Available online: https://ec.europa.eu/clima/policies/strategies_en (accessed on 9 April 2020).
2. European Commission. Sustainable Buildings for Europe's Climate-Neutral Future | EASME. Available online: https://ec.europa.eu/easme/en/news/sustainable-buildings-europe-s-climate-neutral-future (accessed on 9 April 2020).
3. European Commission. EU Buildings Factsheets. Available online: https://ec.europa.eu/energy/eu-buildings-factsheets_en (accessed on 9 April 2020).
4. Palacios-Munoz, B.; López-Mesa, B.; Gracia-Villa, L. Influence of refurbishment and service life of reinforced concrete buildings structures on the estimation of environmental impact. *Int. J. Life Cycle Assess.* **2019**, *24*, 1913–1924. [CrossRef]
5. Palacios-Munoz, B.; Peuportier, B.; Gracia-Villa, L.; López-Mesa, B. Sustainability assessment of refurbishment vs. new constructions by means of LCA and durability-based estimations of buildings lifespans: A new approach. *Build. Environ.* **2019**, *160*, 106203. [CrossRef]
6. Trilla Bellart, C.; Bosch Meda, J. *El Parque Público y Protegido de Viviendas en España: Un Análisis Desde el Contexto Europeo*; Fundación Alternativas: Madrid, Spain, 2018; ISBN 978-84-15860-87-7.
7. Monzón, M.; López-Mesa, B. Buildings performance indicators to prioritise multi-family housing renovations. *Sustain. Cities Soc.* **2018**, *38*, 109–122. [CrossRef]
8. Ruiz Palomeque, L.G.; Rubio del Val, J. *Nuevas Propuestas de Rehabilitación Urbana en Zaragoza. Estudio de Conjuntos Urbanos de Interés*; Sociedad Municipal de Rehabilitación Urbana de Zaragoza: Zaragoza, Spain, 2006.
9. Rubio del Val, J. Veinte años rehabilitando en Zaragoza: Primeras actuaciones de rehabilitación edificatoria sobre Conjuntos Urbanos de Interés de vivienda social, impulsados por la Sociedad Municipal Zaragoza Vivienda (2004–2017). In *Nuevos Enfoques en la Rehabilitación Energética de la Vivienda Hacia la Convergencia Europea La Vivienda Social en Zaragoza, 1939–1979*; López-Mesa, B., Ed.; Prensas de la Universidad de Zaragoza: Zaragoza, Spain, 2018; pp. 55–74. ISBN 978-84-17358-41-9.
10. Rubio del Val, J. Presentación del Informe GTR 2018. Los Municipios, Pieza Clave en un Marco de Cooperación Institucional. Available online: https://catedrazaragozavivienda.wordpress.com/2019/07/01/videos-de-la-vi-jornada-de-la-catedra-zaragoza-vivienda-sobre-estrategias-locales-de-regeneracion-urbana/ (accessed on 10 April 2020).
11. INE. Censos de Población y Viviendas. 2011. Available online: https://www.ine.es/censos2011_datos/cen11_datos_resultados.htm# (accessed on 10 April 2020).
12. López-Mesa, B.; Tejedor Bielsa, J. The Cátedra Zaragoza Vivienda, in search of interdisciplinary solutions to the problem of obsolescence of housing and city. *Inf. Constr.* **2015**, *67*, ed009.
13. Kurtz, F.; Monzón, M.; López-Mesa, B. Energy and acoustics related obsolescence of social housing of Spain's postwar in less favoured urban areas: The case of Zaragoza. *Inf. Constr.* **2015**, *67*.
14. Van Hal, A.; Dulski, B.; Postel, A.M. Reduction of CO_2 emissions in houses of historic and visual importance. *Sustainability* **2010**, *2*, 443–460. [CrossRef]
15. Moorhouse, J.; Littlewood, J. The Low-Carbon Retrofit of a UK Conservation Area Terrace: Introducing a Pattern Book of Energy-Saving Details. In *Sustainability in Energy and Buildings*; Springer: Berlin/Heidelberg, Germany, 2012; Volume 12, ISBN 9783642275081.
16. Dowson, M.; Poole, A.; Harrison, D.; Susman, G. Domestic UK retrofit challenge: Barriers, incentives and current performance leading into the Green Deal. *Energy Policy* **2012**, *50*, 294–305. [CrossRef]
17. Ben, H.; Steemers, K. Energy retrofit and occupant behaviour in protected housing: A case study of the Brunswick Centre in London. *Energy Build.* **2014**, *80*, 120–130. [CrossRef]
18. Van Krugten, L.T.F.; Hermans, L.M.C.; Havinga, L.C.; Pereira Roders, A.R.; Schellen, H.L. Raising the energy performance of historical dwellings. *Manag. Environ. Qual. Int. J.* **2016**, *27*, 740–755. [CrossRef]
19. Oorschot, L. New ways in retrofitting postwar Dutch walk-up apartment buildings: Carbon neutrality, cultural value and user preferences. In Proceedings of the 15th International Docomomo Conference—Metamorphosis: The Continuity of Change, Cankarjev Dom, Ljubljana, Slovenia, 28–31 August 2018; IDC: Framingham, MA, USA, 2018; pp. 442–448.

20. Oorschot, L.; Spoormans, L.; El Messlaki, S.; Konstantinou, T.; de Jonge, T.; van Oel, C.; Asselbergs, T.; Gruis, V.; de Jonge, W. Flagships of the dutch welfare state in transformation: A transformation framework for balancing sustainability and cultural values in energy-efficient renovation of postwar walk-up apartment buildings. *Sustainability* **2018**, *10*, 2562. [CrossRef]
21. Karoglou, M.; Kyvelou, S.S.; Boukouvalas, C.; Theofani, C.; Bakolas, A.; Krokida, M.; Moropoulou, A. Towards a preservation-sustainability nexus: Applying LCA to reduce the environmental footprint of modern built heritage. *Sustainability* **2019**, *11*, 6147. [CrossRef]
22. Bowman, J. *Home Truths: A Low-Carbon Strategy to Reduce UK Housing Emissions by 80% by 2050*; University of Oxford Environmental Change Institute: Oxford, UK, 2007.
23. Blessing, L.T.M.; Chakrabarti, A. *DRM, A Design Research Methodology*; Springer: Dordrecht, The Netherlands; Heidelberg, Germany; London, UK; New York, NY, USA, 2009; ISBN 9781848825864.
24. Chakrabarti, A.; Blessing, L. A review of theories and models of design. *J. Indian Inst. Sci.* **2015**, *95*, 325–340.
25. Monzón-Chavarrías, M.; López-Mesa, B. Identificación y catalogación de los casos de estudio: Los Conjuntos Urbanos de Interés de Zaragoza. In *Nuevos Enfoques en la Rehabilitación Energética de la Vivienda Hacia la Convergencia Europea. La Vivienda Social en Zaragoza, 1939–1979*; López-Mesa, B., Ed.; Prensas de la Universidad de Zaragoza: Zaragoza, Spain, 2018; pp. 95–123. ISBN 978-84-17358-41-9.
26. Kurtz, F.; López-Mesa, B. Definición constructiva de los casos de estudio. In *Nuevos Enfoques en la Rehabilitación Energética de la Vivienda Hacia la Convergencia Europea. La Vivienda Social en Zaragoza, 1939–1979*; López-Mesa, B., Ed.; Prensas de la Universidad de Zaragoza: Zaragoza, Spain, 2018; pp. 125–167. ISBN 978-84-17358-41-9.
27. Monzón, M.; López-Mesa, B. Simplified model to determine the energy demand of existing buildings. Case study of social housing in Zaragoza, Spain. *Energy Build.* **2017**, *149*, 483–493.
28. Monzón-Chavarrías, M.; López-Mesa, B. Caracterización energética y acústica de las soluciones constructivas de la envolvente. In *Nuevos Enfoques en la Rehabilitación Energética de la Vivienda Hacia la Convergencia Europea. La Vivienda Social en Zaragoza, 1939–1979*; López-Mesa, B., Ed.; Prensas de la Universidad de Zaragoza: Zaragoza, Spain, 2018; pp. 169–187. ISBN 978-84-17358-41-9.
29. López-Mesa, B.; Monzón-Chavarrías, M. El desarrollo de indicadores de obsolescencia física más precisos para la definición de estrategias de rehabilitación de vivienda social. In *Nuevos Enfoques en la Rehabilitación Energética de la Vivienda Hacia la Convergencia Europea. La Vivienda Social en Zaragoza, 1939–1979*; López-Mesa, B., Ed.; Prensas de la Universidad de Zaragoza: Zaragoza, Spain, 2018; pp. 243–265. ISBN 978-84-17358-41-9.
30. Domínguez-Amarillo, S.; Fernández-Agüera, J.; Sendra, J.J.; Roaf, S. The performance of Mediterranean low-income housing in scenarios involving climate change. *Energy Build.* **2019**, *202*, 109374. [CrossRef]
31. Rossi, M.; Rocco, V.M. External walls design: The role of periodic thermal transmittance and internal areal heat capacity. *Energy Build.* **2014**, *68*, 732–740. [CrossRef]
32. Bienvenido-Huertas, D.; Rubio-Bellido, C.; Pulido-Arcas, J.A.; Pérez-Fargallo, A. Towards the implementation of periodic thermal transmittance in Spanish building energy regulation. *J. Build. Eng.* **2020**, *31*, 101402. [CrossRef]
33. CEN/TC 89. *EN ISO 13786:2017 Thermal Performance of Building Components—Dynamic Thermal Characteristics—Calculation Methods (ISO 13786:2017, Corrected Version 2018-03)*; European Committee for Standardization: Brussels, Belgium, 2018.
34. AICIA (Universidad de Sevilla). *Escala de Calificación Energética. Edificios Existentes*; IDAE, Ed.; Gobierno de España: Madrid, Spain, 2011.
35. AICIA (Universidad de Sevilla). *CALENER-VYP: Viviendas y Edificios Terciarios Pequeños y Medianos. Manual de Usuario*; IDAE, Ed.; Gobierno de España: Madrid, Spain, 2009.
36. Rose, J.; Thomsen, K.E.; Mørck, O.C.; Gutierrez, M.S.M.; Jensen, S.Ø. Refurbishing blocks of flats to very low or nearly zero energy level–technical and financial results plus co-benefits. *Energy Build.* **2019**, *184*, 1–7. [CrossRef]
37. Harkouss, F.; Fardoun, F.; Biwole, P.H. Passive design optimization of low energy buildings in different climates. *Energy* **2018**, *165*, 591–613. [CrossRef]
38. Aguacil, S.; Lufkin, S.; Rey, E.; Cuchi, A. Application of the cost-optimal methodology to urban renewal projects at the territorial scale based on statistical data—A case study in Spain. *Energy Build.* **2017**, *144*, 42–60. [CrossRef]
39. AICIA (Universidad de Sevilla) HULC. Available online: https://www.codigotecnico.org/index.php/menu-recursos/menu-aplicaciones/282-herramienta-unificada-lider-calener.html (accessed on 28 February 2020).

40. Design Builder Software Design Builder. Available online: https://designbuilder.co.uk/ (accessed on 28 February 2020).
41. Fernández-Agüera, J.; Domínguez-Amarillo, S.; Sendra, J.J.; Suárez, R. An approach to modelling envelope airtightness in multi-family social housing in Mediterranean Europe based on the situation in Spain. *Energy Build.* **2016**, *128*, 236–253. [CrossRef]
42. Almeida, R.M.S.F.; Ramos, N.M.M.; Pereira, P.F. A contribution for the quantification of the influence of windows on the airtightness of Southern European buildings. *Energy Build.* **2017**, *139*, 174–185. [CrossRef]
43. Ministerio de Transporte, M.y.A.U. DA DB-HE/1 Cálculo de parámetros característicos de la envolvente. Available online: https://www.codigotecnico.org/index.php/menu-ahorro-energia.html (accessed on 8 May 2020).
44. Parkinson, T.; de Dear, R.; Brager, G. Nudging the adaptive thermal comfort model. *Energy Build.* **2020**, *206*, 109559. [CrossRef]
45. Sol-Arq CONFADAPT-ASH55. Available online: https://www.seiscubos.com/recursos/confadapt-ash55 (accessed on 8 May 2020).
46. CYPE Ingenieros CYPE Generador de Precios. España. Available online: http://www.generadordeprecios.info/ (accessed on 22 June 2020).
47. Capacity4dev Cost-Effectiveness Analysis. Available online: https://europa.eu/capacity4dev/evaluation_guidelines/wiki/cost-effectiveness-analysis-0 (accessed on 23 April 2020).
48. Imessad, K.; Derradji, L.; Messaoudene, N.A.; Mokhtari, F.; Chenak, A.; Kharchi, R. Impact of passive cooling techniques on energy demand for residential buildings in a Mediterranean climate. *Renew. Energy* **2014**, *71*, 589–597. [CrossRef]