sustainability

Article

Contribution of Roof Refurbishment to Urban Sustainability

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Abstract: Achieving sustainable urban environments is a challenging goal—especially in existing cities with high percentages of old and obsolete buildings. This work analyzes the contribution of roof refurbishment to sustainability, considering that most roofs are currently underused. Many potential benefits of refurbishment can be achieved, such as the improvement of the energy performance of the buildings and the use of a wasted space for increasing green areas or for social purposes. In order to estimate the degree of the improvement, a vulnerable area in Castellón (east Spain) was selected as a case study. A thorough analysis of the residential building stock was undertaken. Using georeferenced information from the Cadastral Office we classified them according to typology, year of construction and roof type. Some refurbishment solutions were proposed and their applicability to the actual buildings was analyzed under different criteria. The theoretical benefits obtained in the neighborhood such as energy and carbon emissions savings were evaluated, together with the increase of green areas. Moreover, other social uses were suggested for neglected urban spaces in the area. Finally, a more accurate analysis was performed combining different solutions in a specific building, according to its particular characteristics.

Keywords: urban regeneration; roof refurbishment; energy performance

1. Introduction

The 11th Sustainable Development Goals (SDG) proposed by the United Nations, focus on cities and sustainable communities to make cities inclusive, safe, resilient and sustainable. To this end, in recent years, many policies have been designed.

The European Union—through the energy performance directives of buildings (EPBD) and their transpositions into the national regulations of State Members—actively works to reduce both carbon emissions and the energy used in buildings. From the first Directive established in 2002 [1] to date, requirements have become significantly stricter [2–4] to accomplish reduction targets (UE key targets for 2030: at least 40% cuts in greenhouse gas emissions from the levels in 1990, 32% share for renewable energy and improved energy efficiency). Currently, the EPBD establishes that all new buildings constructed from 2021 (public buildings from 2019) must be nearly zero-energy (NZEB). As defined in Article 2 of EPBD2010/31/UE, NZEB means a building with very high-energy performance. Moreover, most of the energy required must be covered by renewable sources (sunlight, wind, rain, etc.), including those produced on-site or nearby, and nearly zero or very little energy must be provided by non renewable energy sources (essentially coal, petroleum and natural gas).

Although this is a very positive initiative to improve the building stock's sustainability, it is only applicable to new buildings, and there is a vast number of old and obsolete buildings in terms of thermal properties. According to the data reported by the Spanish National Statistics Office (INE) [5], approximately 54% of existing buildings were built before 1980, when there was still no regulation for the thermal performance that buildings should present. The first standard that regulated the thermal conditions that buildings should meet came into force in 1979 [6] and established quite relaxed thermal requirements. In 2006, the technical building code (CTE, standing for Código Técnico de la Edificación in Spanish) came into force in Spain [7], with new regulations aligned with the European EPBD. The requirements set out in the CTE have been progressively reviewed and updated to date so that, in line with the EPBD, the basic document on energy saving (DB–HE, through Royal Decree 732/2019) aims to build NZEB. However, as reported by the INE and according to the Spanish Government's updated data [8], almost 92% of existing buildings were built before 2006, prior to the CTE being implemented, which means that the contribution of the whole building stock to the NZEB target is minimum. Hence the energy refurbishment of existing buildings is crucial to improve the general energy performance of the building stock. To do so, different refurbishment options may be selected and combined to optimize their potential.

Besides the thermal requirement regulations for buildings, norms on roofing-load capacity should be checked to analyze their construction solutions and buildings' structural capacity should also be observed to specifically calculate overloads. Roldan [9] analyzed the building standards in Spain from the pioneering MV-101/1962 perspective (Decree 195/1963, 17 January). Since then, the overload for roofs of residential buildings has remained at 1 kN/m^2 and 2 kN/m^2 for non-walkable and walkable roofs, respectively, according to consecutive standards: NBE-AE/88 (Decree 1370/1988, 11 November), repealed by CTE-DB SE-AE-06 (Royal Decree 314/2006, 17 March and the 2008 and 2009 updates).

Logically as buildings are already built, applying passive design measures is quite limited, and energy improvement mainly depends on refurbishing the thermal envelope and using very efficient facilities. As improving the thermal envelope lowers energy demand, this should be the first step when undertaking energy refurbishment interventions. However, this is not what happens under actual conditions due to the high economic cost of refurbishment, usually with a long-term investment return. Therefore, non-economic arguments, such as environmental and social benefits linked with refurbishment, would support interventions.

Nowadays, cities are composed of different typologies of residential buildings, most of which were built in the 20th century and some in the 21st century. Their features are conditioned by many factors that can influence a region's urban development, such as historic and political events, regulatory frameworks (new legislation coming into force, general urban plans, etc.) and socio-economic factors (wars, migratory movement from rural to urban areas or new construction and material techniques emerging). The IEE Project "Typology Approach for Building Stock Energy Assessment" [10], devised with the collaboration of 15 partners from European countries, differentiates four main typologies in the Spanish building stock, which are: single-family house, terraced house, multi-family house, apartment block. The Valencian Institute of Building (IVE), which was responsible for the project in Spain, developed a guide which differentiated three climate regions and six construction periods (which depended on normative evolution). Therefore, homogeneous construction solutions were inferred for each period: <1900, 1901–1936, 1937–1959, 1960–1979, 1980–2006, >2006 [11]. As observed by Martín-Consuegra et al. [12], the analysis of the building regulations in force during the different time periods provided quite an accurate idea of the characteristic constructive features of the year of construction.

Objective and Main Conclusions

The present work focuses on the potential benefits offered by the refurbishment of roofs in residential buildings. To do so, constructive solutions were examined to analyze possible refurbishment solutions and the potential achieved benefits. Technical aspects, such as energy performance improvement and its profit, were estimated together with some externalities, such as social benefits linked with the enjoyment of a usually underrated and underused part of the building. This work aims to shed some light on the potential role of roofs in the sustainability of the urban environment.

As summarized by Braulio [13], three periods can be differentiated in Spain according to the construction solutions employed in roofs. Buildings constructed before 1940 generally used timber beams and wattle suspended ceilings in sloping roofs, with Catalan-style ventilated systems on flat roofs. The 1940–1979 period was characterized by the introduction of new materials, such as reinforced concrete, which provided new structural options (new slabs with concrete joists and ceramic or concrete blocks). Flat roofs became more popular during this period, when lightweight concrete was used to form the slope of roofing systems and waterproof materials were introduced. From 1980 onward, roofing systems have continuously evolved to the much more complex systems that can be currently used today, which are composed of different materials that fulfill diverse functions like drainage, waterproofing, thermal insulation, etc.

Although it is more difficult to establish such progressive evolution in roof use terms, in the beginning roofs were also employed for social life purposes. This provided homes with more protection from both weather agents and invading attacks. As explained by Graus [14], in pre-industrial societies a roof always embraced many uses. Given lack of space, the roof emerged as an outdoor room that allowed multiple purposes, such as a better use of space for a settlement on steep mountain slopes, drying grain, hanging food, sleeping on hot nights or even celebrating weddings. With time, social life moved to streets and roofs began to be left aside and even ceased being considered a useful space in the vast majority of cases. Although only the protective function of building roofs is generally valued today, sustainability development trends seek to optimize already built spaces instead of generating new urban expansions. Roofs must be seen as spaces that offer sustainable opportunities to improve the building's energy performance, to install green roofs, to provide renewable energy production systems or for inhabitants' own leisure.

In order to generate practical and applied results, a vulnerable area in the city of Castellón (east Spain) was selected. The city's recent land-use plan defined this area as vulnerable [15–18], and it is characterized by a mixture of building typologies, most of which are old and obsolete. Thus, it could benefit highly by hypothetical intervention. A previous diagnosis of existent roofs should be made to analyze structural limitations, thermal properties and other aspects like orientation, possible uses, and so on.

Some benefits are observed. On one hand, roofs are an important part of the thermal envelope, which is totally exposed to outer conditions. Their refurbishment could contribute to improve buildings' energy performance and to reduce CO_2 emissions. To this end, some representative buildings were selected, and the results were extrapolated to the neighborhood scale. On the other hand, using the space on some roofs could also contribute to increase green areas in the urban environment. Additionally, as roofs are currently underused [19], appropriate use and exploitation would contribute to sustainable cities and positively influence the social resilience of the city. Accordingly, some roofs could accommodate social functions, such as meeting places for residents.

The proposed solutions are meant to place in order the magnitude of benefits and other refurbishment solutions—even combinations of solutions—can be used. An actual intervention would require more accurate conditions to be observed in order to consider the legal framework, property regime issues and exact conditions of each building. A specific building is finally presented as an example to illustrate other options, where the combination of some proposed solutions could apply.

2. Materials and Methods

This work was undertaken in four main stages.

The first stage of the work involved data collection. First, a review was done on the regulations applied to build roofs and about constructive solutions at different times. Second, data on the selected area were collected. The chosen neighborhood is included as a regeneration and refurbishment area (ARRU, standing for Área de Regeneración y Renovación Urbana in Spanish) according to the recently developed land-use plan [12]. ARRU are vulnerable areas according to urban, residential, social and economic features and are meant to be prioritized to make urban regeneration interventions. Third, the data on the buildings in the area were collected using Cadastral Office information. This allowed us to identify buildings by their cadastral reference, and to address and provide information about plot area, built area, number of floors, number of dwellings and year of construction. Using the cadastral cartography and the Google Earth tool, roof types were identified and measured.

The second stage was meant to suggest refurbishment solutions for roofs. A cross-checking of roof types and refurbishment solutions was undertaken by considering parameters like load capacity, orientation, usable area, etc., to not dismiss any possible solution linked with a specific roof type and to select the optimum solution in every single case. A multicriteria analysis was used to assign applicable solutions to different roofs.

The third stage estimated the benefits for the area. Statistically representative buildings were selected to estimate quantifiable benefits. Improving buildings' energy performance by roof refurbishment was calculated with the CE3X energy certification software. This official software is approved by the Spanish Ecological Transition Energy Ministry [20–22], available at: https://energia.gob.es/desarrollo/EficienciaEnergetica/CertificacionEnergetica/DocumentosReconocidos/Paginas/procedimientos-certificacion-proyecto-terminados.aspx (last accessed 5 June 2020). Those buildings that statistically represented the whole building stock were simulated. To simulate the average buildings, the data obtained from dynamic Tables in Excel (Supplementary Materials) were used, which allowed the selection of real buildings whose characteristics came close to average values. This implied that real orientations, measures for façades and windows, and so on, could be inputs in the software by assuming that outputs gave an approximate order of magnitude. The outcome of the simulation provided information on energy demand, energy consumption and carbon emission savings. Other environmental benefits, such as greener areas in the neighborhood, were also calculated. Some social benefits linked to the enjoyment of roofs by dwellers were also considered.

In the fourth stage, these data were extrapolated to the whole urban area so that the benefits of a potential intervention on the neighborhood scale could be estimated. Besides the neighborhood scale, a specific building was selected for simulations to, by way of example, implement a combination of some refurbishment solutions.

This paper is structured as follows: the background section briefly introduces the general goal of achieving sustainable cities and the role of buildings as relevant elements in complex urban ecosystems. Then the evolution and use of roofs in history, how they have become underused and underrated in buildings and how roofs can contribute to sustainability, are highlighted. Moreover, an analysis of the evolution of regulations on roofs construction was done to understand the different construction solutions for each period. Regulations on structural requirements during different periods were reviewed to analyze the technical applicability of the refurbishment solutions. Regulations on the thermal performance of buildings and their evolution in recent decades were also examined as this is a key factor to consider in sustainability terms. The next section explains the methodology and the steps undertaken in this work. Then the urban area selected as a case study is introduced. We present a brief description of the buildings, roof types according to their year of construction and their current use. Then an analysis of the different refurbishment solutions was carried out and they were linked with the physical possibilities of current roofs. The optimum solution to each roof type was selected by considering technical and environmental criteria. Finally, the achieved benefits were analyzed and estimated on the neighborhood scale. The accomplished improvement and the optimum roof-type solution combinations offered valuable information that could help the municipal administration in its decision-making to allocate funds for regenerating the area. Finally, an analysis of a specific building is presented below to illustrate the combination of different solutions.

3. Results

3.1. Case Study

3.1.1. Urban Area

The urban area selected for this study is located in the city of Castellón de la Plana, a medium-sized Mediterranean coastal city located in east Spain, with about 170,000 inhabitants. According to the recent land-use plan, there are 17 vulnerable areas or neighborhoods in this city, called ARRU (standing for areas of regeneration, refurbishment and renewal). These areas are intended to be prioritized by the public administration to allocate funds in order to undertake regeneration and refurbishment [14,23]. Most of the neighborhoods in the city are located inland, about four kilometers from the sea coast, except for the neighborhood called Grao, which is stands by the sea, which especially distinguishes this area.

The Grao neighborhood was selected as the case study. This area corresponds to District 9 in the city and is formed by census Sections 09001, 9002, 9003, 9004, 9006, 09,007 and 9010. Together they form ARRU15 according to urban, building, socioeconomic and sociodemographic indicators [23]. All the vulnerability categories are present in census Sections 9002 and 9003. The worst vulnerability in buildings is present in 9001, 9002, 9003 and 9004, which coincide with a high-density urban area. The remaining area is formed mainly by single-family houses. In order to diagnose, propose solutions and quantify the benefit of refurbishing roofs, the area formed by census Sections 9001 to 9004 (presented in Figure 1) was selected.

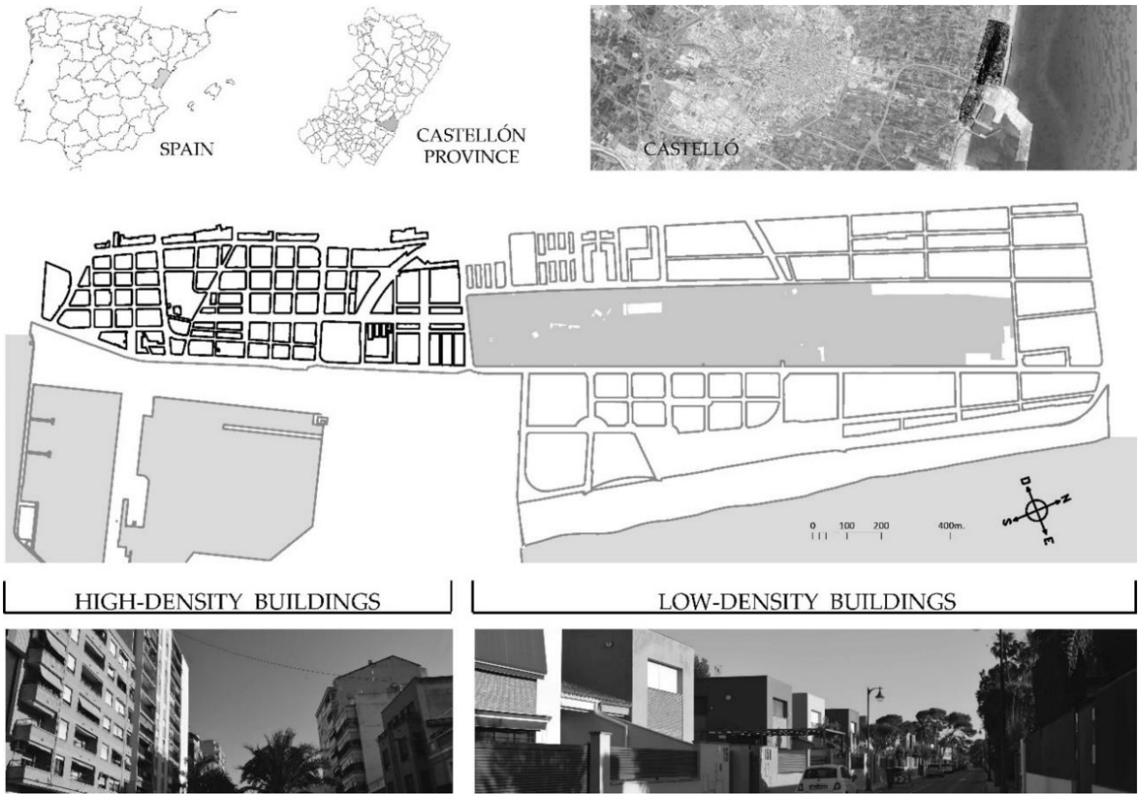


Figure 1. Location of the selected urban area.

3.1.2. Analysis of the Building Stock

In this study, buildings are grouped as typology and building period by considering two typologies, namely single-family house (SfH) and multi-family house (MfH), as suggested by Annex I, Section 5 of the EPBD for residential buildings. At the same time, they were structured according to five different constructive periods having been adapted to both normative periods and cadastral information: 1840–1936, 1937–1959, 1960–1979, 1980–2006, 2007–2012.

The selected area is made up of 794 buildings, of which 775 are residential buildings according to Cadastral Office information, with 335 MfH and 440 SfH.

Data were arranged after contemplating the period when they were built. By considering the total building stock, only about 3% were post-CTE built, which confirms the energy rehabilitation need. As observed in Figure 2, the greatest building activity corresponded to periods 1960–1979 and 1980–2006. About 44% of MfH were built during 1960–1979, followed by 38% during 1980–2006. Almost 70% of SFH were built from 1980 to 2006. During this period, a significant increase took place during 2000–2005, when major developments during the real-estate boom in Spain were built, mostly terraced houses.

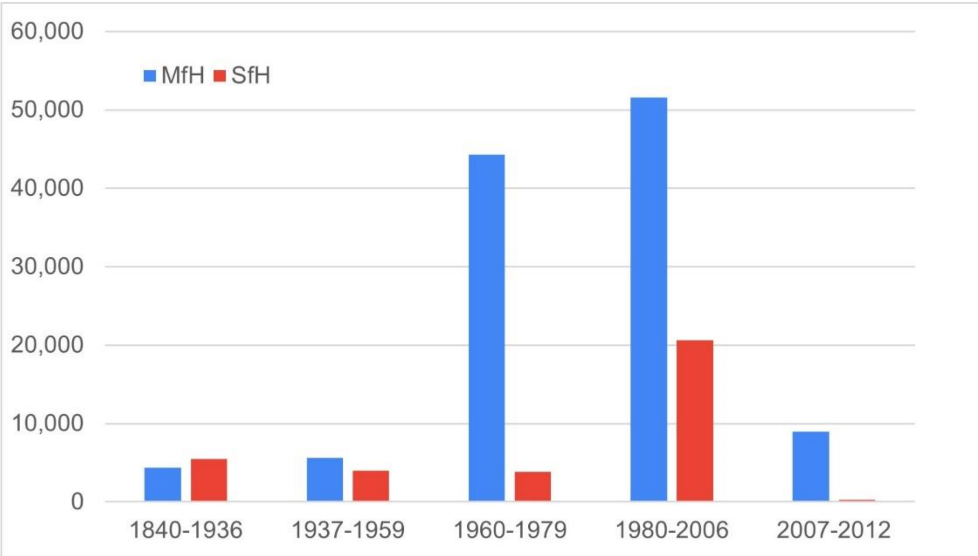


Figure 2. Number of residential building for year of construction and building typology.

3.1.3. Roof Types

To complete the previous quantitative analysis, this section examined roof types. This variable is crucial to assign possible refurbishment solutions, where the original constructive solution needs to be known. Accordingly, two main roof groups were found in the area: sloped and flat. In turn, the latter was subdivided into non-walkable or walkable. Finally, in some cases, roofs are located in inner courtyards. For practical purposes and in relation to potential refurbishment interventions, we also differentiated between roofs for community or private use. Consequently, the roofs in the present study were classified as follows:

- Sloped roofs (SR): roof whose slope is broken by an obtuse angle. A third of the roofs in the area are sloped roofs, finished mainly by ceramic gables
- Flat non-walkable roof (NWR): limited access and sometimes used to contain facilities. It is frequently found in nonresidential uses where facilities are centralized
- Flat walkable roof (WR): a flat roof that is almost level, unlike many of sloped roof types, up to approximately 10° for draining rainwater. Two WR can be distinguished depending on the property regime:
    - Community walkable roof (CWR), with access to all dwellers. They are usually intended for different purposes, such as clothes lines, storage rooms, etc.
    - Private walkable roofs (PWR) for personal use. They were not included in this study because they are terraces for private use.

- Flat roofs in inner courtyard (IC): the inner courtyard is a central space within the building that provides light and ventilation. In some buildings it is located on the ground floor. Two subtypes were considered:
    - ○ Private inner courtyards (PIC): often used by first-floor dwellers;
    - ○ Community inner courtyard (CIC).

To provide an initial idea of the variability and extension of these four main roof types, their area and location are plotted in Figure 3. Figure 4 quantifies this information.

Figure 3. Location of roof types in the area.

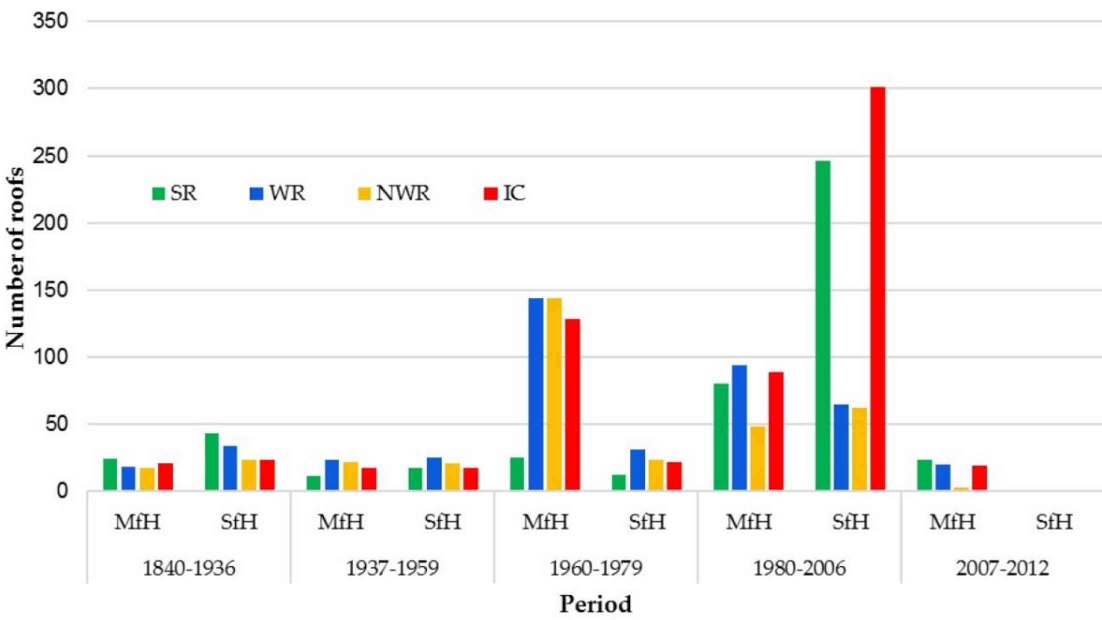


Figure 4. Number of roofs per building typology, roof type and period.

As seen in Figure 4, by considering the number of buildings, inner courtyards represent the highest percentage for period 1980–2006, followed by period 1960–1979 that represents 53% and 23%, respectively, for this type.

Figure 5 presents all the integrated information of the roofs in the neighborhood and considers the five building periods, the two building typologies (in columns) and the six roof types (in lines) that account for 60 groups. All the information is represented proportionally to the area in rectangles. walkable roof presents the highest percentage, 40%, followed by sloped roof, with 27% of the total area, inner courtyard with 23% of the area and non-walkable roof under 10%. Despite the large number of SfH, when considering the roof area almost 77% of this area corresponds to MfH, as we can see in Figure 5.

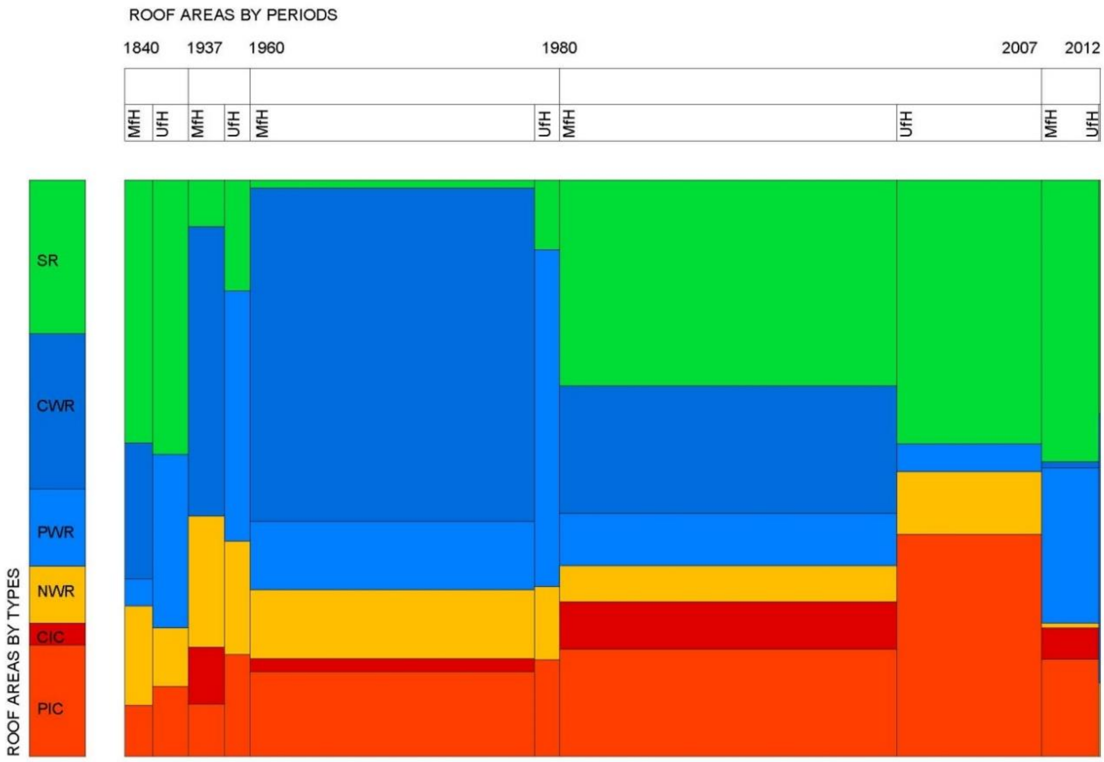


Figure 5. Roof areas per period, building typology and roof type.

The biggest area was found for the community walkable roof in MfH for the period 1960–1979 (1960–1979/MfH/CWR) combination, followed by the sloped roof in MfH for the period 1980–2006 (1980–2006/MfH/SR). When focusing on MfH, we found that they were built mostly during 1960–1979 and 1980–2006, with 45% and 60% of the area of their period, respectively. Regarding SfH, about 60% of the roof area corresponded to period 1980–2006, and the remaining 40% was distributed during the other periods. When considering each roof type, 72% of the area of sloped roof corresponded to period 1980–2006, 54% of the area of walkable roof was built during 1960–1979, most non-walkable roof also corresponded to periods 1960–1979 and 1980–2006, about 39% per period, and 65% of the area of inner courtyard were related to period 1980–2006, which coincides with the periods when building activity was more prominent.

3.2. Refurbishment Solutions

Roofs can benefit from being refurbished in many ways. Maintenance of buildings, energy savings, economic income and ecologic benefits can be obtained depending on the selected solution. However, as the solution must adapt to the specific conditions of the location and existing roof, not every solution would apply to each case.

Hence, depending on the starting conditions, different factors will determine the solution. Some limiting factors are to do with urban and architectonical issues. Sometimes there are legal limitations according to urban plans that determine the interventions to be made to roofs, linked with the allowed buildable area, number of floors, height, etc. Another crucial aspect must do with structural resistance and the loads the system can support, which must be checked. Moreover, the area, orientation and geometry of roofs are decisive for implementing certain solutions; for example, if there is enough room to install some facilities, if the orientation is appropriate for solar radiance gains or if there are solar obstacles to be considered, etc. Other factors are related to the economic cost of the intervention, such as the investment and maintenance cost of the solution.

The benefits obtained from the intervention should be observed in the decision-making process as they may add value to the building. For example, some solutions could improve a building's energy performance and reduce energy bills and carbon emissions from using the building which, therefore, makes the urban environment more sustainable. Other solutions may be beneficial for different reasons, such as their contribution to reinforce the social relations of dwellers, if they consider it convenient to take advantage of this underused space for community purposes.

In nonresidential buildings such as hotels, office buildings or commercial buildings, leisure uses, such as sports, restaurants, cafes, and so on, increasing the usable surface of some businesses is a possibility. Some large roofs can be employed for advertising to provide extra income to owners.

Considering the residential building stock, some refurbishment solutions are described in the following subsections.

3.2.1. Green Roofs

Green roofs (GR) can cover a roof with vegetation either partially or completely. Therefore, it needs a growing medium placed on top of a waterproofing membrane and must also contain a root barrier layer and a drainage and irrigation system. The literature review shows that this entails many benefits, such as providing insulation, which improves the building's thermal performance by making energy savings [24–26] and could be achieved with the addition of thermal insulation. However, this solution entails other added benefits. It also combats noise pollution and can reduce noise annoyance by road traffic [27]. Other environmental benefits are linked with improved urban environment resilience, such as better rainwater absorption, more green areas in the urban environment, carbon sequestration, better air quality, lower urban air temperatures, mitigating the heat island effect, etc. [28–30]. It also contributes to create a habitat for wildlife, reduces people's stress by providing a more esthetically pleasing landscape [30,31] and contributes to solve the shortage of green spaces and land resources [32]. There are many varied technical solutions for installing green roofs. Some can be considered intensive systems and require thicker ground layers to support a wider variety of plants. However, they are heavier and require more maintenance. On the contrary, thickness of extensive roofs can range from 6 to 20 cm, are less maintenance-demanding and lighter than intensive solutions. Finally, some solutions exist in between, which are called semi-intensive [32–34]. Theoretically, this solution could be placed on any roof. However, on sloped roofs, inclination could complicate both installation and maintenance. Moreover, minimum solar radiation should be guaranteed for vegetation. Therefore, flat roofs with solar access seem, a priori, the most appropriated roof type for this solution.

3.2.2. Solar Panels

According to Fuentes et al. [35], domestic hot water (DHW) accounts for about 20% of the total primary energy use by housing. A study by Pomianowski et al. [36] compared the energy use for DHW in some European countries and found that the final energy use percentage falls between 15 and 40%, and around 15% in Spain. The study by Gautama et al. [37] demonstrates the long-term economic feasibility of solar water heating systems, although the payback period depends on many factors like price of fossil fuels, solar insolation, etc. The implementation of solar panels (SP) will depend on the roof area and orientation, as well as on its location in the urban area. In the study area, the proper solar orientation is southern or slightly southeastern [13]. Northern-oriented roofs would not be suitable for this solution or these roofs are surrounded by solar obstacles like taller buildings. The installation of solar panels to contribute to DHW demands can be a suitable solution in the study area, especially for SR for which other options are not considered. They can also be seen as a good solution for some flat roofs, such as non-walkable roofs or small walkable roofs, where other options are inadequate. Installation on sloped roofs is slightly cheaper because they do not need a substructure to support panels. solar panels would increase the renewable energy supply in the neighborhood and reduce energy use and, therefore, energy bills.

Photovoltaic panels are also very interesting—especially in locations where solar radiance is high [38]. Other authors have demonstrated the profitability of this solution in non residential buildings [39,40]. Even the combination of solar panels with green roofs can be found in the study of Berto et al. [41]. They produce energy that is an interesting alternative to achieve economic and environmental benefits. Unfortunately, however, this solution is not completely standardized in Spain for residential building, probably due to the solar energy tax established by Royal Decree 900/2015. Later this law was derogated by Royal Decree 15/2018. As a result, the system has been rarely used—especially in MfH. Nevertheless, it undeniably offers a high potential in the near future and is, in fact, currently being promoted by the government [42].

3.2.3. Residents' Association Meeting Area

The available area misused on walkable roofs can be used for many purposes, such as meetings, social encounters, installation of urban orchards (included in green roofs), solariums or other uses to promote the social interaction of dwellers [31,43,44]. Considering the legal and structural limitations, a residents' association meeting area (RA) could be placed. This could feature various possibilities, from light pergolas to heavier constructions—depending on the starting conditions. Load, complexity and cost will vary depending on the selected solution.

3.2.4. Adding a New Floor on the Existent Building

If this option is allowed by the urban plan—and the structural capacity permits it—adding a new floor (NF) would add a noteworthy economic benefit to ownership.

3.2.5. Selecting the Proposed Solutions

For this work, the new floor solution was rejected because it is a very limited solution that can be applied in a few cases due to urban plan limitations and, moreover, because structural capacity should be enough to support the loads of the added floor. Photovoltaic solar panels were not considered due to lack of experience to date in residential buildings, but they are an interesting and very convenient proposal to be analyzed in the near future as they can imply potential economic profit and energy savings. Therefore, the green roof, solar panels for DHW and residents' area solutions were considered for the scope of this work. Regarding green roofs, an extensive solution was selected over the intensive or semi-intensive options because of the lightest structural requirements and the lowest economic investment and maintenance [31,33,45]. Regarding the solar-panel solution, it is considered to be most appropriate for the neighborhood as it receives high solar radiation most of the year. Castellon is classified solar zone IV in the Spanish territory, with an scale from I to V from the lowest to highest radiation, (according to DA DB–HE/1, document complementing the HE document), which means high mean annual global solar radiation (4.6–5 kWh/m^2). Moreover, this solution supports norm CTE, Section HE4, which requires a minimum contribution of renewable energy to cover the DHW demand, which is 60–70% in the study area. As regards residents' area, we selected a multipurpose light wooden pergola solution to minimize both load and cost. This solution could provide an area where neighbors can gather for their meetings and other agreed uses according to dwellers' interests.

Table 1 summarizes the selection for the undertaken analysis:

Table 1. Selection of refurbishment solutions.

Refurbishment Solution		Pros	Cons	Select	Reason	Selected Solution
NF	New floor	Economic profitability	Scarce applicability	No	Urban and technical limitations	
GR	Green roof	Thermal and acoustic insulation; More green areas Carbon sequestration Reduction of the heat island effect	Maintenance cost Insulation; Noticeable on the top floor of the building	Yes	Entails many environmental benefits	Extensive solution
SP	Solar panels for DHW	Savings in energy and carbon emissions	Savings only for DHW; Maintenance costs	Yes	Frequent solution	Standard model
	Solar photovoltaic panel. Community energy	Huge potential of savings in energy and carbon emissions	Still not standardized in residential uses in MfH; Depends on community agreement	No	Little experience in residential buildings	
RA	Residents association area	Enjoyment of underused space; Multipurpose	Depends on community agreement; Solution depends on final use	Yes	Use of underrated common area in buildings; Social uses.	Light wooden pergola

3.3. Type of Roofs Vs. Refurbishment Solution

The descriptive cadastral data were analyzed using the dynamic Tables in Excel. Some aspects were completed with the available cartography (Spanish Cadastral Virtual Platform) to verify certain aspects, such as orientation or inner courtyards and to identify the private uses to be ruled out for the study.

The applicability of the refurbishment solution to roofs was done by a multicriteria matrix, where all the analyzed information of roofs was crossed with the technical possibilities of the selected solutions (see Supplementary Materials). Of all these premises, some starting hypotheses were put forward:

1. All the combinations representing under 2% of the area were not considered;
2. Roofs that imply private uses (private walkable roofs and private inner courtyards) were not included;
3. Green roofs were not considered a solution for sloped roofs. According to the German norm on green roofs, slopes > 26.8% (15°) require special consideration and slopes > 100% (45°) are not recommended [46,47];
4. Solar panels for DHW are considered in sloped roofs, preferably in solar orientation;
5. For community inner courtyards, only the residents' area solution is considered. As community inner courtyards are located on ground floors, green roof and solar-panel solutions are most likely to be affected by solar obstacles.

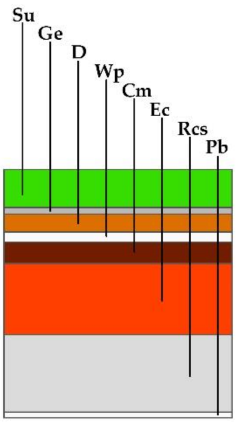
After assuming all these hypotheses, five combinations of refurbishment solutions/roof types appeared (see Supplementary Materials):

1. SP-SR: Solar panel/Sloped roof;
2. GR-NWR: Green roof/Non-walkable roof;
3. GR-CWR: Green roof/Community walkable roof;
4. RA-CWR: Resident area/Community walkable roof;
5. RA-CIC: Resident area/Community inner courtyard.

3.4. Estimating the Benefits of Refurbishment

A statistical analysis of typologies provided us with the average values for number of floors, number of dwellings, usable area, roof area and energy requirements for DHW (based on Regulation CTE-DB-HS4) to obtain representative buildings for energy performance simulations. By doing so, the results of energy savings and carbon emission reductions due to the refurbishment could be extrapolated to the neighborhood scale to obtain an order of magnitude of the potential improvement to the whole area. The area is mainly made up of MfH, of 6–7 floor buildings, with 20–30 dwellings ranging from 1440 to 2968 m^2 of usable area and 2016–3427.20 L/day requirements for DHW. The average SfH building has three floors, 168 m^2 and 112 L/day requirement for DHW.

Energy demand will lower in those scenarios that consider the GR solution because roofs form part of the thermal envelope. This must do with the solution's higher thermal resistance (1.969 m^{2}K/W) and, consequently, the lowest thermal transmittance (0.508 W/m^{2}K), which would improve energy performance. Figure 6 shows the composition of the selected extensive solution and the detail of its thermal properties [48].



Layer i	Thicknes s e_i (mm)	Density (Kgm^{-3})	Thermal conductivity λ_i (Wm^{-1}K^{-1})	Thermal resistance R_i (Wm^{-2}K^{-1})
Substrate (Su)	100	2,000	0.52	0.192
Geotextile (Ge)	1.5	120	0.05	0.300
Non-ventilated air chamber (NvAc)				0.160
Drainage and storage (D)	20			0.090
Root barrier waterproof (Wp)	1.5	1,100	0.23	0.065
Cement mortar (Cm)	20	1,525	1	0.020
Expanded clay (Ec)	100	537.5	0.148	0.676
Slab-reinforced concrete (Src)	250	1,220	0.908	0.275
Plasterboard (Pb)	20	900	0.4	0.050

*Total thermal resistance $R_T = R_{si} + \Sigma R_i + R_{se}$, $R_{si} = 0.1$; $R_i = e_i/\lambda_i$; $R_{se} = 0.04$, $R_T = 0.1 + 1.829 + 0.04 = 1.969$
*Thermal transmittance $U = 1/R_T = 0.508$

Figure 6. Green roofs (GR) extensive solution. Composition and thermal properties (* according to CTE-DB-HE1).

Considering that the residents' area solution does not influence the building's energy performance, and that the thermal resistance value does not vary from community walkable roof to non-walkable roof during the same period, the simulation cases amount to five buildings, represented by Period/Building Typology/Roof Type:

1. 1960–1979/MfH/CWR-NWR: multi-family houses built during period 1960–1979 with community walkable roof and non-walkable roof;
2. 1980–2006/MfH/SR: multi-family houses built during period 1980–2006 with sloped roof;
3. 1980–2006/MfH/CWR-NWR: multi-family houses built during period 1980–2006 with community walkable roof and non-walkable roof;
4. 1980–2006/SfH/SR: single-family houses built during period 1980–2006 with sloped roof;
5. 2007–2012/MfH/SR: multi-family houses built during period 2007–2012 with sloped roof.

Table 2 presents the five combinations, the main features of the representative building (average values for number of floors, dwelling units, usable area, roof area and DHW requirements) for simulation purposes and the total roof area of each combination in the neighborhood.

Depending on the combination, the achieved benefit can be estimated. Some environmental benefits are obtained with the green roof and solar-panel solution as they improve the building's energy performance. The energy demand (kWh/m^2.year), final energy consumption (kWh/m^2.year) and carbon emission (kg CO_2/m^2.year) reductions can be estimated by the energy performance simulation software CE3X. Moreover, green areas in the neighborhood increase by 8530.70 m^2 (Table 1). Although the Residents Area solution cannot be valued in terms of environmental or economic benefits, it entails social advantages that contribute to the sustainability of the urban area.

Table 2 summarizes the benefits obtained by simulating the refurbishment scenarios using CE3X. Table 2 indicates that energy demand lowers when green roof is implemented as the thermal transmittance of roof decreases (Figure 7); second, energy use savings are made in the green roof and solar-panel solution scenarios, together with lower carbon emissions. All the software outputs are calculated per square meter and then extrapolated to the neighborhood scale by considering the potential improvement accomplished for the total roof area in the neighborhood.

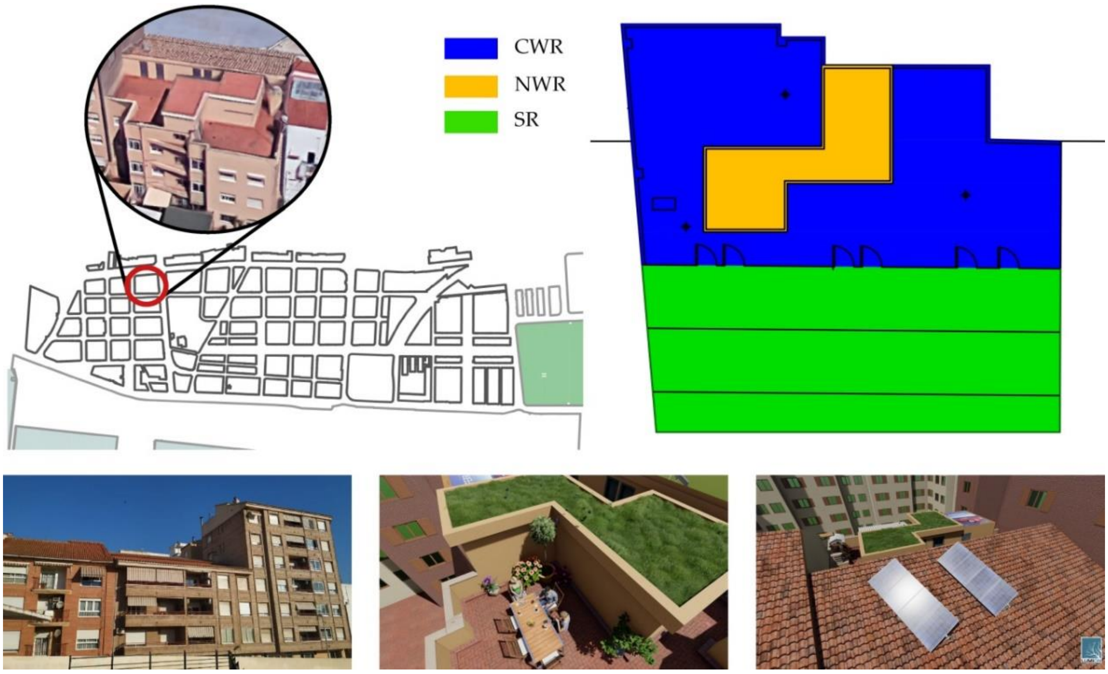


Figure 7. Specific building and refurbishment rendered.

As observed in Table 2, a solar panel for DHW provides greater energy use reductions than green roof. Implementing a solar panel leads to a 10% reduction in SfH, and values rise to around 30% for MfH. Regarding the green roof solution, studies suggest reducing buildings' energy consumption by up to 5% [37]. The results obtained with the case study via simulation ranged from 1.7% to 3.2%, which are similar to those given carbon emissions. Energy demand also reduces with green roof due to lower roof thermal transmittance. All the obtained reductions are worth considering when the results are extrapolated to the neighborhood scale, with savings of 40,782.85 kWh/year in energy demand, 579,595.70 kWh/year in energy consumption and 148,364.94 kg CO_2/year in carbon emissions.

Table 2. Scenario features of representative buildings and total savings in the area.

Period	Building	Roof	Solution	Representative Building; Cadastral Reference Floors; Number of Dwellings; DHW Requirement (L/day)	Usable Area m^2	Roof Area m^2	Total Roof Area m^2	Energy Demand		Final Energy Consumption		Carbon Emissions	
								kWh/year		kWh/Year		$kgCO_2$/Year	
								Per sqm % Saving	Total	Per sqm % Saving	Total	Per sqm % Saving	Total
1960–1979	MfH	NWR	GR	7395404YK5279N 6; 20; 2016	1440	36.70	5285.90	3.51 4.0%	18,553.51	3.87 3.2%	20,456.43	1.30 3.2%	18,553.09
		CWR			1680	254.00	25,596.53		89,843.82		99,058.57		33,275.49
1980–2006	MfH	SR	SP	7496107YK5279N 7; 36; 3427	2912	234.00	18,717.40	–	–	17.99 27.2%	336,726.03	4.5 26.4%	84,228.30
		NWR	GR	7392307YK5279S 6; 30; 2856	2304 2968	67.60	3244.80	0.72 3.6%	2336.26	1.26 1.7%	4088.45	0.3 1.8%	973.44
		CWR				173.90	11,652.45		8389.76		14,682.09		3495.74
	SfH	SR	SP	7697301YK5279N 1; 3; 112	168	41.80	10,292.80	–	–	10.12 10.3%	104,163.14	2.60 10%	26,761.80
2007–2012	MfH	SR	SP	7496404YK5279N 7; 30; 2856	2184	189.33	4354.70	–	–	19.94 36.2%	86,832.72	5.0 34.9%	21,773.50
Total savings area									119,123.35		666,007.43		189,061.36

The calculations suggest an interesting benefit regarding energy savings and carbon emissions, along with other environmental and social advantages, such as the increase in green areas in the urban environment, 8530.70 m^2 in non-walkable roof and 37,248.98 m^2 in community walkable roofs.

As mentioned earlier, it is an order of magnitude and the particular conditions of each building should be observed to obtain more accurate results. Scenarios may vary to accomplish the optimum solution. A combination of the proposed solutions can even be suggested in buildings where different roof types coexist. By way of example, a building where community walkable roof, non-walkable roof and sloped roof are present and all the analyzed solutions can be implemented, was selected. Knowing the exact building features can offer a more accurate scenario of the refurbishment.

Table 3 presents the main building features and summarizes the benefits obtained from the refurbishment proposal, which is completed by the estimation of the intervention's economic cost. It is an MfH building formed by six dwellings, two commercial premises and 10 parking lots. It was built in 1994 in accordance with both Regulation NBE-AE-88 on structural requirements and Regulation NBE-CT-79 on thermal requirements. The building combines three roof types: non-walkable roof over the staircase, community walkable roof and sloped roof facing southeast, with 25, 108.50 and 134.64 m^2, respectively. After checking the structural capacity with NBE-AE-88, which came into force in 1994, the following solutions are proposed: green roof suggested for non-walkable roof, as shown in Figure 7; the resident's area is suggested for community walkable roof by estimating a wooden pergola of 60 m^2. Finally, solar panels for DHW are proposed for sloped roof with the proper orientation. The load resulting from the solution and the improved transmittance value in green roof are also presented in Table 3. The cost of the intervention was estimated from the construction prices database (CYPE) [49], with a total amount of 18,142.45€ (2267.80 €/owner, 6 dwellings + two commercial premises, not including professional fees, licenses and taxes). The combination of these roof refurbishment solutions provides economic and social benefits that are all relevant in sustainability terms.

Table 3. Description of the specific building.

<table>
<tr><th colspan="2">Building</th><th colspan="4">Roofs</th></tr>
<tr><td colspan="2" rowspan="4">MfH
6 dwellings
2 commercial premises
10 parking lots
Address: Alcalá Galiano, 1
Cadastral reference: 7191303YK5279S
Orientation: East–West
Year 1994</td><th>Type</th><th>Area (m^2)</th><th>NBE-AE-88 Load/Overload (kg/m^2)</th><th>NBE-CTE-79 Transmittance (kWh/m^2)</th></tr>
<tr><td>NWR</td><td>25.00</td><td>618/140</td><td>0.93</td></tr>
<tr><td>CWR</td><td>108.25</td><td>618/190</td><td>0.93</td></tr>
<tr><td>SR</td><td>134.64</td><td>346/134.64</td><td>1.12</td></tr>
<tr><th colspan="6">Refurbishment</th></tr>
<tr><th>Roof</th><th>Solution</th><th>Added load (kg)</th><th>Transmittance (kWh/m^2)</th><th>Budget * (€)</th><th>Benefits</th></tr>
<tr><td>NWR</td><td>GR</td><td>2735.50</td><td>0.51</td><td>2421.25</td><td>E. demand: 18 kWh/year
E. consumption: 31.5 kWh/year
C. emissions: 7.5 kg CO_2/year
25 m^2 increase in green area
Others: sound insulation, heat island effect reduction, etc.</td></tr>
<tr><td>CWR</td><td>RA</td><td>2043.14</td><td>–</td><td>3658.80</td><td>Social</td></tr>
<tr><td>SR</td><td>SP</td><td>5900.00</td><td>–</td><td>12,062.40</td><td>E. consumption: 2422,17 kWh/year
C. emissions: 605.88 kg CO_2/year</td></tr>
</table>

* Prices: RA—60 m^2 wooden pergola, unit price—60.98 €/m^2; GR—25 m^2, unit price 96.95 €/m^2; SP—8 panels, unit price 1507.80 €/panel.

The economic analysis of the viability of the global cost (investment, running and disposal costs and the entailed energy savings), according to the comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements (Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012, supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings), is not very optimistic. Even when considering the macroeconomic perspective of the methodology that assigns a price for carbon emissions (public cost) that would be included as savings when energy performance improves, the payback is too long, over 30 years. So, the proposed solution is not very appealing from the economic perspective. However, that term could be shortened if some funds were allocated to the intervention (up to 40% of the cost of the investment and up to 75% for low incomes, according to Order 1/2019, 18 February, of the Regional Administration in Charge of Housing, Conselleria de Vivienda, Obras Públicas y Vertebración del Territorio, which approves funds for ARRU for the National Housing Plan 2018–2021) (see Supplementary Materials). Moreover, there are other gains that would be obtained from the activation of the refurbishment economic sector, e.g., from the generated taxes (VAT, licenses, etc.), together with increased property value due to the intervention. Then there other costs that should be included in the balance of payments in sustainability terms, namely public costs, which means that they are difficult externalities to monetize. Those could be the benefits linked with an increase in green areas in the neighborhood or social benefits associated with the use of wasted space.

Other solutions that were ruled out in the proposal of this work could also be considered. For example, the use of photovoltaic panels could be supported by considering the economic profitability of the investment. A basic simulation was performed for this specific building using the European Commission's simulation tool, Photovoltaic geographical information system (available at https://re.jrc.ec.europa.eu/pvg_tools/es/#TMY, last accessed 12 August 2020). According to the obtained results, installing 25 PV panels on the sloped roof would save 13,232.61 kWh/year. This facility would increase the energy and carbon emission savings significantly compared to the 2422.17 kW/year obtained with DHW panels. The global cost economic approach shows that, when DHW solar panels are replaced with PV panels, the payback period shortens substantially, with positive values for the net present value and the investment return is even obtained in about five years in the funded scenario (see Annex A, tabs 10 to 13).

4. Discussion and Conclusions

Current urban areas are complex environments that include most of the population and need varied and combined solutions to enhance sustainability. Buildings' improved energy performance has become a crucial target in recent years to seek low carbon economies. Moreover, today's roofs are underused and have been devalued compared to their use of old. From this viewpoint, roofs can be seen as an opportunity because they form part of the thermal envelope and can contribute to improve buildings' energy performance—especially old and obsolete buildings where energy refurbishment and updates are necessary. Besides the environmental benefits, some roof refurbishment solutions offer many other advantages that can be hard to monetize but are extremely interesting in sustainability terms by contributing to ameliorate citizens' lives as social benefits.

This work analyzed the improvement potential of consolidated urban environments through roof refurbishments. It focuses exclusively on roofs to analyze the possibilities linked with an underused part of the building. One of the achieved benefits is the building's energy performance improvement, which is especially needed in vulnerable dwellings that usually present very poor thermal performance. In this regard, the roof's contribution is partial and integral energy refurbishment of housing would be advisable to achieve optimal results. Some suggested solutions allowed savings to be estimated in terms of energy and carbon emissions and other more social-oriented benefits. To consider the neighborhood scale, an area was selected, and a thorough analysis of the building stock was performed. The existent constructive solutions of roofs were analyzed with the georeferenced information from the Cadastral Office of the actual buildings. The actual constructive solution is crucial for suggesting adequate refurbishment solutions in practical applicability terms (load capacity, orientation, geometry, surrounding conditions, etc.). refurbishment solutions were assigned depending on the roofing system. To estimate some figures, the study focused on a specific vulnerable residential area in the Grao neighborhood in the Spanish city of Castellón, defined as ARRU in the Urban Plan. Three simple solutions were selected as being most likely implemented, although some others could also be included. Based on these assumptions, the study obtained savings of 119,123.35 kWh/year in energy demand, 666,007.43 kWh/year in energy consumption and 189,061.36 kg CO_2/year in carbon emissions. In addition, 35,779.58 m^2 of new green area were added to the area. The suggested solutions include other social benefits linked to the use, enjoyment and advantage of some wasted spaces in the urban area. However, we must bear in mind that the study provides an order of magnitude based on representative buildings, and a more accurate calculation would require an individual analysis of the parameters in every single building. This is illustrated by the example performed in the selected building, which combined three roof refurbishment solutions. Considering the economic analysis of the intervention, and based on the global cost calculation, it shows that the payback period is too long, and the investment is not profitable. However, the term could be shortened if some funds were allocated to the intervention when the area is considered to be ARRU. Moreover, in sustainability terms, other costs should be placed in the balance of payments when considering public costs, such as those linked with the increase in green areas in the neighborhood or those connected to the social benefits associated with the use of wasted space.

This work is based on a simplified and fixed theoretical scenario to gain a potential quantifiable amount of energy savings, an increase in green areas and carbon reduction and other non quantifiable benefits linked with the non economic factors that affect urban sustainability. A myriad of scenarios can occur under today's conditions and this is the main limitation of our analysis. In real applicability terms, the legal framework, property regime, etc., should also be observed as actual conditions because they are too complex, and an accurate estimation is unattainable. Further research is needed to explore different solutions and scenarios. Rooftop architecture could become an interesting solution for the energy retrofit of the entire building and could represent an important economic opportunity in multifamily buildings whenever applicable. Real projects with different solutions can also shed some light on current results. The influence of the photovoltaic energy option should be further studied because it potentially provides renewable energy for a real NZEB scenario. The development and standardization of this technology in residential buildings could be a means to achieve higher energy savings and to improve the economic viability of refurbishment. Hence further research should be conducted to seek new market strategies—especially in MfH—where a community meter could be installed in the building [46]. However, the results found in this study could be useful for decision-making to allocate funds for urban regeneration interventions, especially in vulnerable areas that usually present an old and obsolete building stock.

Although a previous analysis of the characterization of buildings, roof types and boundary conditions in the area is necessary, this estimation method can be replicated in other case studies.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/19/8111/s1, Excel file.

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