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The cost overrun of depopulation to improve energy efficiency in buildings: A case study in the Mediterranean Region

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ABSTRACT

The implementation of energy efficiency measures in public buildings is a complex process that hinges on multiple factors. A factor relevant for some European regions is their ongoing depopulation. In these regions, building energy retrofitting presents additional challenges to those in urban areas, such as over-dimensioned public buildings and low occupancy levels. This work analyses these challenges in the province of Teruel (Spain), one of the regions with the highest depopulation levels in Spain. To this end, a methodology has been developed to assess the effect of depopulation on the cost of upgrading public buildings to improve their energy efficiency. The results show that the investment required per inhabitant for building retrofitting is approximately four times as high in depopulated areas as in urban areas. Furthermore, the low occupancy levels of public buildings can triple the payback time of some energy efficiency measures. To overcome these barriers, in addition to specific policies for depopulated areas, energy planning is essential. An adequate action plan, combining the implementation of energy efficiency measures and the integration of renewable energies in buildings, is the most effective tool to improve the sustainability of public buildings circumventing the barriers created by depopulation.

Introduction

The improvement of the energy performance of buildings is essential to achieve the energy efficiency (EE) objectives imposed by the European Commission (EC) [1]. From the total EU building stock, 85 % of the buildings (more than 220 million) were built before 2000, under less restrictive energy regulations. Between 85 % and 95 % of today's buildings will exist by 2050 [2]. The building sector is responsible for 40 % of total energy consumption in the European Union and 36 % of greenhouse effect emissions [3]. To achieve the EU objectives, emissions from the building sector must be reduced by 60 %, its final energy consumption by 14 % and the energy consumption associated with air conditioning by 18 % compared to 2015 levels [4].

On average, the annual energy renovation rate reaches only 1 % of the total building stock, which is insufficient to achieve the climate targets [5]. Under this framework, the EC launched in 2020 the *Renovation wave* strategy to boost building renovation in Europe; for these targets to be achieved, the current building energy renovation rate must double by 2030 [2].

Public buildings represent approximately 10 % of the total building stock, so their energy renovation should play an exemplary role for the private sector since it can make the benefits of the building energy renovation significantly visible. The Energy Efficiency Directive 2012/27/EU [6] states that Member States should renovate 3 % of the total floor area of central-government-owned buildings each year (from 1 January 2014). Under the *Renovation Wave* initiative [2], public buildings are considered the spearhead of energy renovation, and the EC proposes extending the scope of this obligation to all public administration levels. This extension is already considered in national plans within the EU, as is the case in Spain [7].

The energy renovation of buildings is a complex process [8] since it involves technical, economic and social aspects. The selection of optimal solutions is a complicated task [9]. Furthermore, there are multiple barriers to overcome during the entire building renovation process. Numerous studies have analysed the challenges and barriers to building retrofitting in very diverse sectors and countries [10–18]. Most of the previous works, except Refs. [10,18], focus on barriers to the renovation of buildings in general, and do not address the specificities of public buildings. Thus, there is a lack of analyses of the barriers to the retrofitting of buildings in the public sector [10]. Alam et al. [10] investigated the barriers to the renovation of public buildings in Australia to

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Nomenclature

CDD	cooling degree day
DD	degree-day
D_m	number of days in month m
δ	material thickness (m)
E_m	average maintained illuminance (lux)
EE	energy efficiency
EPC	energy performance certificate
EPS	expanded polystyrene
HDD	heating degree day
HVAC	heating, ventilation and air conditioning
ICT	information and communication technology
k	material conductivity (W/mK)
NRPE	non-renewable primary energy
P	nominal power (W)
PBT	payback time (years)
S	illuminated area (m^2)
SCOP	Seasonal coefficient of performance
$T_{b.c}$	base temperature for cooling
$T_{b.h}$	base temperature for heating
$T_{e,d}$	external mean daily temperature
U	thermal transmittance (W/m^{2}K)
VEEI	value of energy efficiency in lighting installations (W/m^2·100 lx)

develop strategies to overcome them. Previous reports [11,12] analysed the status of the building energy renovation, performed surveys, collected the views of stakeholders and found the barriers to elaborate building renovation plans at the European [11] and national [12] levels. Weiss et al. [13] analysed the barriers to building renovation in the residential sector to improve policy instruments to support home renovation in Germany. Thomas et al. [14] indicated barriers to building renovation to support the design of effective policies to renovate buildings in Germany. Caputo and Pasetti [15] determined barriers to building energy renovation for the elaboration of energy action plans in Italian municipalities. Achtnicht and Madlener [16] studied the barriers to housing energy retrofits from the owner's perspective in Germany. Meanwhile, Hou et al. [17] and Castleberry et al. [18] reported barriers to the energy retrofitting of commercial buildings in China and public schools in Oklahoma, respectively.

Despite the different contexts, the reported barriers are common in most of the studies. The barriers can be classified into four categories [10]: i) knowledge barriers (lack of information and awareness, lack of motivation, lack of skills), ii) administrative barriers (multi-stakeholders issues, Government not acting as a strong driver, lack of interdisciplinary expertise and collaboration), iii) social barriers (interruption of building operation) and iv) financial barriers (lack of funds, investment priorities, uncertainties over financial gain). Many of these barriers are also present in public building renovation, although the public sector has relevant differences compared to the private sector: objectives, decision-making processes, financing, procurement processes and visibility.

Local public administrations must satisfy multiple societal demands, but budgets and debt ceilings are, in general, very restrictive [19]. Although energy efficiency is very relevant for local authorities, due to budget restrictions, they must prioritise the budget for other citizen demands such as social assistance or elderly people care, particularly in depopulated and ageing areas [20]. Also, the objectives of a public administration can change due to electoral cycles or pressure from society and political forces. Decision-making and procurement processes are slow and involve considerable bureaucracy. Sometimes these processes can depend on several administrations, leading to project failure. Procurement procedures sometimes are not well designed to consider energy efficiency properly. For example, lower investment costs are sometimes prioritised instead of energy consumption reduction over the building lifetime. As for financial barriers, public administrations often work with annual budgets, limiting the scale of EE actions. Furthermore, budgetary restrictions often make the implementation of EE measures extremely difficult. Finally, the visibility of the actions of a public administration is a double-edged sword. On the one hand, it allows EE measures to play an exemplary role. But excessive visibility causes the reluctance of the public authorities to invest in innovative projects that may involve some risk because any problem that may arise will also be more visible.

The PrioritEE project [21], funded by the Interreg MED programme [22], involved surveys to public authorities on the barriers to implement EE measures in their public buildings [19,23]. In the case of Spain, the Teruel province was involved, obtaining similar responses to those indicated in previous works [10]. The main barrier was the lack of budget for investments at the municipal level and the lack of debt capacity (such as debt ceiling regulations). The difficulty in preparing applications for funding calls was also an issue as well as the low success rate. Other problems were the lack of quality and independent technical support for decision-making and the difficulty in obtaining building energy data. Other barriers were electoral cycles, since priorities may change depending on the political party in power, the existence of other needs with a higher priority (e.g., social assistance in the case of depopulating, ageing regions) or the lack of coordination and support among different levels of the public administrations [20,23].

Depopulation hinders the renovation of public buildings, worsening some of the aforementioned barriers, such as lack of funding or lack of technical staff. It also adds more difficulties. In these municipalities, in general, the number or the surface area of public buildings per inhabitant is considerably larger than in municipalities without depopulation problems (see Appendix A). Therefore, the expenditure per inhabitant to implement EE measures is higher. This further strains the limited budgets. The use and occupancy levels of many of these public buildings are usually considerably lower in depopulating municipalities. Castleberry et al. [18] did not mention depopulation in their work, but they reported that rural schools have to face specific challenges to implement EE measures. These challenges include lower income levels among residents, higher unemployment rates, lack of human capital and skilled labour, and fewer opportunities for young people. Some of these challenges are common in depopulated areas.

This article quantifies the economic impact of depopulation on the renovation of public buildings, evaluating the specific issues of depopulating areas. This quantification is necessary to properly plan the renovation of the public building stock in these areas. Generally, local governments are responsible for financing the implementation of EE measures in their public buildings (although they often request subsidies from the regional or national governments). Particularly, this article aims to evaluate the budgetary effort and the profitability (depending on the building usage hours) of implementing EE measures in public buildings in depopulated areas and compare them with high-density population areas. This budgetary effort is assessed as the investment in an activity per capita. Furthermore, possible solutions to overcome the barriers imposed by depopulation to renovate public buildings are proposed. The final objective is to help public authorities to develop strategies for renovating public buildings in depopulated areas considering these restrictions, viz budgetary effort and profitability. Another goal is to make the regional and national Administrations aware of the aforementioned added difficulties in depopulated areas, as they are in a better position to improve this situation to achieve the sustainable

Table 1
Current features of the selected public buildings.

Building use	Envelope			Heating system		Lighting system	
	Part	U-value (W/m^{2}K)	Area (m^2)				
School	**External walls**	1.69	300	**SCOP**	0.653	**Installed power** (W/m^2)	20.1
	Windows	single-glazed wooden frame		**Power**	50 kW	**VEEI** (W/m^2·100 lx)	5.0
		5.35[+]	36	**Fuel type**	Light fuel oil	**Illuminance** (lux)	400
Sports centre	**External walls**	1.4	2000	**SCOP**	0.670	**Installed power** (W/m^2)	7.2
	Windows	double-glazed PVC frame		**Power**	200 kW	**VEEI** (W/m^2·100 lx)	2.4
		3.08[*]	400	**Fuel type**	Light fuel oil	**Illuminance** (lux)	300
Multiservice building	**External walls**	2.06	580	**SCOP**	0.575	**Installed power** (W/m^2)	22.5
	Windows	single-glazed wooden frame		**Power**	12 kW	**VEEI** (W/m^2·100 lx)	7.5
		5.35[+]	35	**Fuel type**	Light fuel oil	**Illuminance** (lux)	300
Council office	**External walls**	2.7	542	**SCOP**	0.556	**Installed power** (W/m^2)	16.7
	Windows	single-glazed wooden frame		**Power**	61 kW	**VEEI** (W/m^2·100 lx)	5.6
		5.35[+]	5	**Fuel type**	Light fuel oil	**Illuminance** (lux)	300
Residential centre	**External walls**	1.52	548	**SCOP**	0.653	**Installed power** (W/m^2)	4.6
	Windows	single-glazed wooden frame		**Power**	50 kW	**VEEI** (W/m^2·100 lx)	1.5
		5.35[+]	24	**Fuel type**	Light fuel oil	**Illuminance** (lux)	300

[+] calculated considering 10 % frame fraction ($U_{glazing}$ = 5.7 W/m^{2}K and U_{frame} = 2.2 W/m^{2}K).
[*] calculated considering 20 % frame fraction ($U_{glazing}$ = 3.3 W/m^{2}K and U_{frame} = 2.2 W/m^{2}K).

transition objectives also in depopulated areas.

There are several studies on energy renovation of buildings in the scientific literature, some of which are summarised below. Several articles on the energy renovation of buildings [24,25] perform a technical–economic evaluation of different building renovation measures. Huang et al. [26] studied different strategies to retrofit the insulation of the building envelope to find the optimal strategy from technical and economic points of view. Borrás et al. [27] performed a techno-economic analysis of the influence of green roofs on building renovation. A similar analysis was undertaken by Li et al. [27] but focused on renovating the existing building ventilation system.

There are different alternatives or strategies for renovating a building. Youssefi et al. [28] performed a techno-economic analysis of alternatives for envelope renovation in institutional buildings. Recently, a multi-criteria decision-making framework was developed [29] to support decision-making in the building renovation process. Omar et al. [30] presented a methodology to convert educational buildings into Net-Zero energy buildings, which was implemented in an education building in Egypt. Similarly, Rabani et al. [31] proposed an optimisation method to automate the procedure of finding the best combination of measures which minimise the building energy use and achieve the nZEB target while enhancing both thermal and visual comfort conditions. In this line, renovation strategies in representative buildings of the public building stock to convert them into nZEB buildings were evaluated [32], by conducting an assessment in a university building.

Research on the energy renovation of buildings at a large scale includes, for instance, the evaluation of the energy-saving impact due to the implementation of EE measures in the residential sector in Italy [33]. Teso et al. [34] conducted a techno-economic study of the renovation of a low-income district in Venice, while Rose et al. [35] focused on analysing good practice examples of energy renovations at the district scale. Andersen et al. [36] investigated the possibilities of using information from public registers and databases on existing buildings as input data to inform designers and other stakeholders about the renovation potential of existing buildings in urban developments.

From the literature review, it is concluded that there is no optimal or best solution for the renovation of public buildings because it depends on the boundary conditions as well as on the specific needs and limitations of the municipality. To the authors' best knowledge, there is a lack of articles addressing the difficulties that local governments in depopulated areas face in public building renovation. The novelty of this article lies in the techno-economic evaluation of the energy retrofitting of public buildings related to depopulation. Depopulation generally involves less use (occupancy level) of public buildings along with a larger ratio of public building area per inhabitant. Both issues influence negatively the implementation of EE measures, particularly those whose profitability depends on the number of usage hours. These are the main limitations caused by depopulation in the renovation of public buildings.

In this work, a methodology is developed that estimates the energy and economic savings achieved through the implementation of EE measures in representative buildings. This methodology is implemented in a depopulated area to test its performance and analyse the results obtained. Nevertheless, this methodology is replicable in any depopulated area.

The work is structured as follows: Section 2 summarises the methodology developed to perform this research, and more information regarding the modelling details can be found in Appendix B. Details about the case study selected to implement this methodology to assess the depopulation effects are included in Appendix A. Section 3 shows the main techno-economic and environmental results of the proposed EE measures in the different building typologies (Section 3.1) and the influence of depopulation in the implementation of EE measures (Section 3.2). Section 4 includes further discussion on the topic, and finally, Section 5 summarises the main conclusions.

Methodology

This section describes the methodology used to evaluate the barriers attributable to depopulation in the energy renovation of public buildings. This methodology consists of three steps: 1) Selection of a real representative building for each of the building typologies; 2) Determination of the energy savings, non-renewable primary energy (NRPE) savings, CO_2 emissions reduction, economic savings, investment costs and payback time thanks to the implementation of the above EE measures; and 3) Assessment of the depopulation effects.

Details about the case study of the Teruel province are in Appendix A, including a detailed analysis of the public building stock as well as of the current EE status of the public buildings.

Buildings selected for the analysis

Teruel province has a transitional climate between continental and Mediterranean, with cold winters (down to −10 °C) and hot and dry summers (up to 35 °C), and a wide range of climatic conditions, with heating degree days (HDD) varying from 1,400 to 4,500, and cooling degree days (CDD) from 0 to 250 (see Appendix A). The buildings selected for this work are located in intermediate climatic conditions, with HDD of approximately 2,500 and CDD of approximately 100 (refer to Appendix A for more details about the degree-day method). The

Table 2
Current CO_2 emissions, heating demand and NRPE consumption of the selected public buildings.

Building	Area	Usage hours	CO_2 emissions	Heating demand	NRPE consumption (kWh/m^{2}y)		
	(m^2)	(h/year)	(kg CO_2/m^{2}y)	(kWh/m^{2}y)	**TOTAL**	**Heating**	**Lighting**
School	274	2504	59.5	87.8	262.9	158.5	98.2
Sports centre	3035	4592	76.8	120.5	326.2	212.0	65.0
Multiservice building	321	4593	125.8	157.2	563.1	322.4	202.1
Council office	905	3545	268.5	129.7	68.8	256.7	115.5
Residential centre	405	3545	75.2	140.7	307.9	244.2	31.7

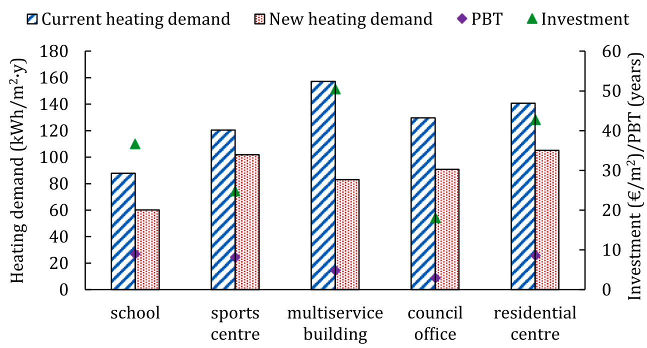

Fig. 1. On the left axis, current and new heating demand; on the right axis investment and the payback time (PBT) of the improvement of the building envelope in each of the selected buildings.

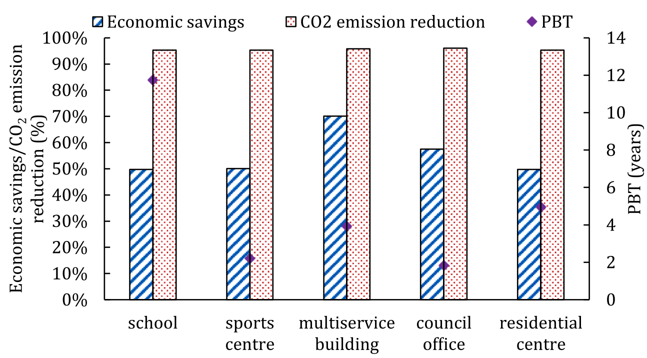

Fig. 2. On the left axis, economic savings and CO_2 emission reduction; on the right axis investment and payback time (PBT) of the boiler replacement in each of the selected buildings.

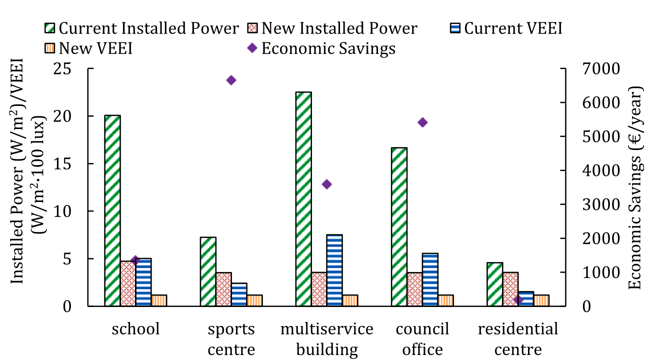

Fig. 3. On the left axis, installed power and VEEI before and after the lighting replacement; on the right axis economic savings of the lighting replacement in each of the selected buildings.

current main features of the selected buildings extracted from their energy performace certificates (EPCs) are used as a starting point to analyse potential EE measures (see Table 1 for more details).

All the buildings use light fuel oil for heating with a conventional and inefficient boiler, leading to high NRPE consumption (see Table 2). Only the sports centre and the residential centre comply with the lighting normative (maximum value of the energy efficiency of the installation (VEEI) and installed power, UNE-EN 12464–1: 2003 [37]), so they also have a considerable NRPE consumption due to lighting. Also, the heating demands are considerably high, with an energy label of E or worse (on a scale of A to G).

Modelling the energy efficiency measures

The most-widely used official EPC software in Spain, CE3X [38], is selected to assess the two first EE measures because it is the software used to perform the EPCs analysed in this work: improving the internal insulation of the building façade and window replacement. For the other two, boiler and lighting replacement, a GIS-based tool is developed, consisting of a set of Python routines that call several databases and perform the calculations [39]. Geolocalized data for the calculations and visualization are gathered from three main sources: the Spanish National Geographical Institute [40], the national infrastructure database [41] and the European PVGIS tool [42]. Data related to building regulations, CO_2 emissions and primary energy conversion factors and other data is collected from the national building legislation [43], and from other sources used in the official tools for building energy certification [44,45]. Information regarding types of envelope insulation and HVAC systems are imported from a price generator widely used by designers and architects in Spain [46]. The tool just described was validated using the Spanish official EPC software and with EPCs of public buildings [39].

For the improvement of the internal insulation, an additional layer of expanded polystyrene (EPS) is added to the building façade, decreasing the overall U-value of the walls to 0.36–0.39 W/m^{2}K (depending on the building). In the window replacement intervention, single-glazed windows are replaced by double-glazed ones, and metallic frames without thermal bridges are replaced with PVC frames. In the sports centre, which already has double-glazed windows, these are replaced with triple-glazed low-emissive windows to assess whether this replacement is worthwhile.

The EPC provides the building heating and cooling demands (kWh/m^2 year), which are used to estimate the final energy consumption, considering the HVAC system efficiency. These values can be converted to costs using the fuel price and to CO_2 emissions and NRPE consumption using the corresponding conversion factors for the fuel, specific for Spain in this case study [43] (see Appendix B for more details). Based on the current HVAC system efficiency and the fuel, the developed tool proposes alternative HVAC systems that either improve the current efficiency using the same fuel or reduce the CO_2 emissions and NRPE consumption by changing the fuel. In this study, the current boilers are replaced with efficient biomass boilers.

On the other hand, the current lighting system is replaced with LEDs. Based on the usage profile provided in the EPC (which can also be customised by the user), the tool estimates the current annual electricity consumption and the consumption of the proposed lighting alternatives.

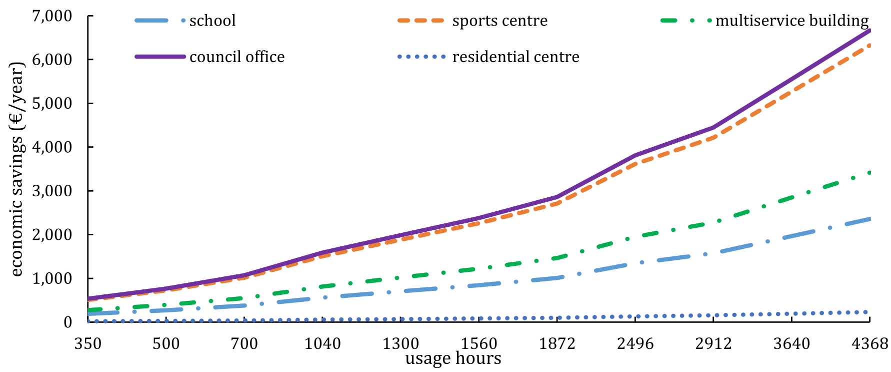

Fig. 4. Variation of the annual savings with the usage hours due to lighting replacement for each building typology.

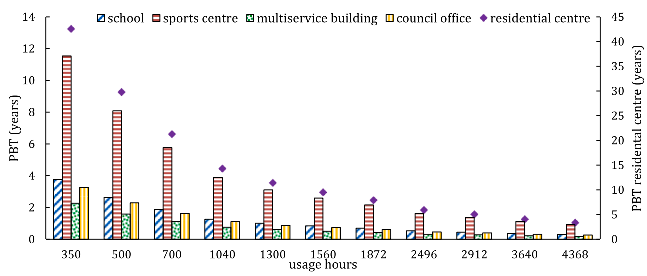

Fig. 5. Variation of the payback time (PBT) of the lighting replacement with the usage hours for each building typology.

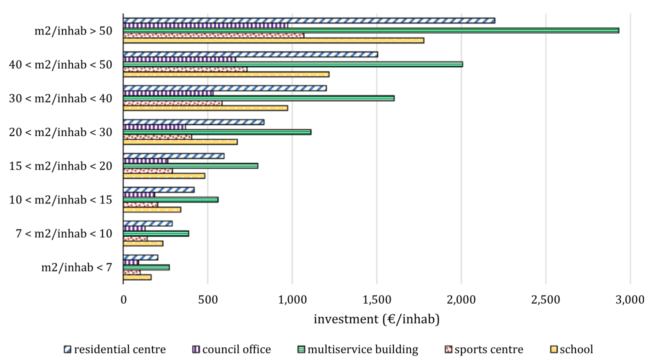

Fig. 6. Variation of the investment per inhabitant for the improvement of the internal insulation of the building walls as a function of the building surface area per inhabitant, for each building typology.

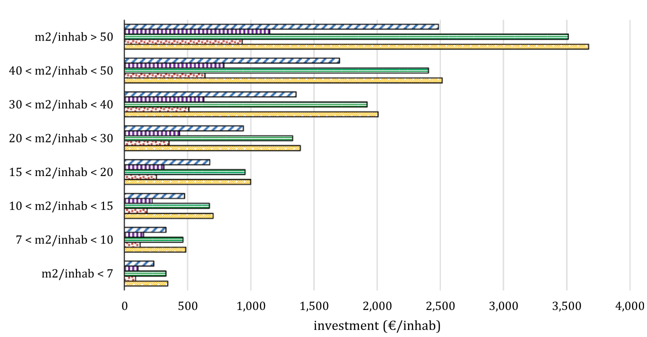

Fig. 7. Variation of the investment per inhabitant for boiler replacement as a function of the building surface area per inhabitant, for each building typology.

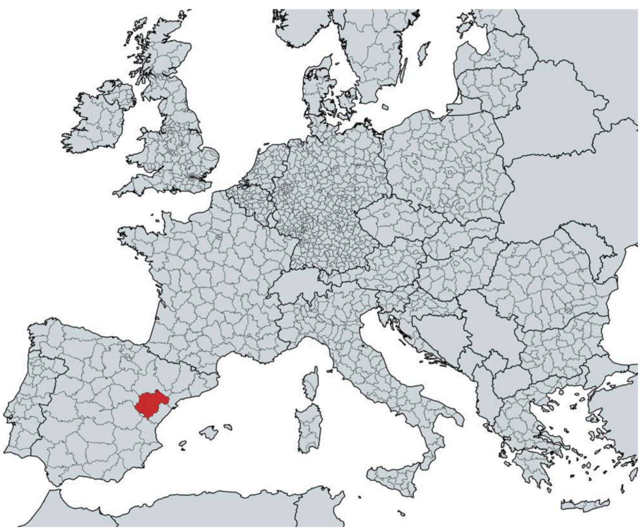

Fig. 8. Location of Teruel Province (highlighted in red) in Europe. Map obtained from Ref. [62]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The same methodology as above is followed to estimate energy, cost, CO_2 emissions and NRPE savings, as well as capital costs [46] for the refurbished building; these values are then used to estimate the simple payback time (PBT) of the proposed EE measures.

Assessment of depopulation effects

Depopulation is also a barrier to the implementation of EE measures due to two main reasons. Depopulation increases the surface area of public buildings per inhabitant and, therefore, increases the investment cost per inhabitant compared to areas not affected by depopulation. Additionally, depopulation may cause the underuse of public buildings, increasing the payback time of the measures.

Most of the buildings analysed in this work, such as the multiservice building or the council office, are often old (and sometimes historical) buildings which did not have a specific use, so the public authorities decided to use them for those purposes. Furthermore, in small municipalities, some buildings do not have permanent staff working. Instead, staff and/or other visitants only work and/or visit the building occasionally.

Based on the results of the EE measures, a sensitivity analysis is performed to evaluate the influence of the number of usage hours and the ratio of public building area per inhabitant (m^2/inhab) in the techno-economic benefits of the proposed EE measures.

To assess the influence of the ratio of public building area per

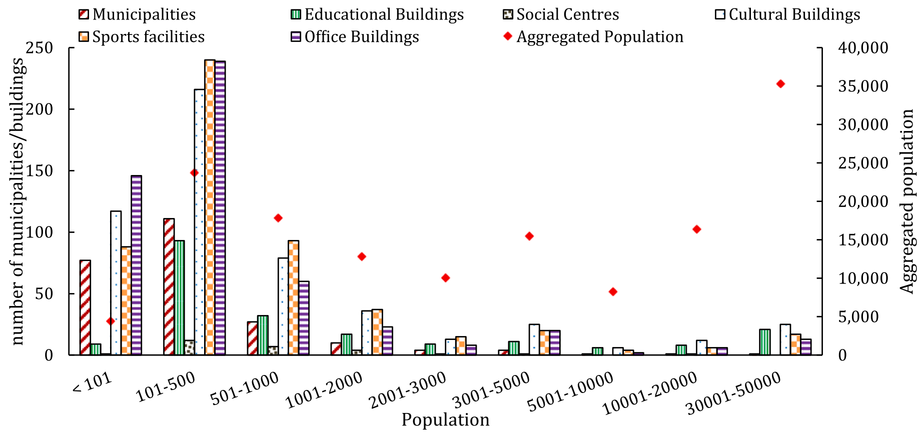

Fig. 9. Number of municipalities, aggregated population [40] and number of public buildings per type of building in the Teruel Province, sorted into population-range bins [41].

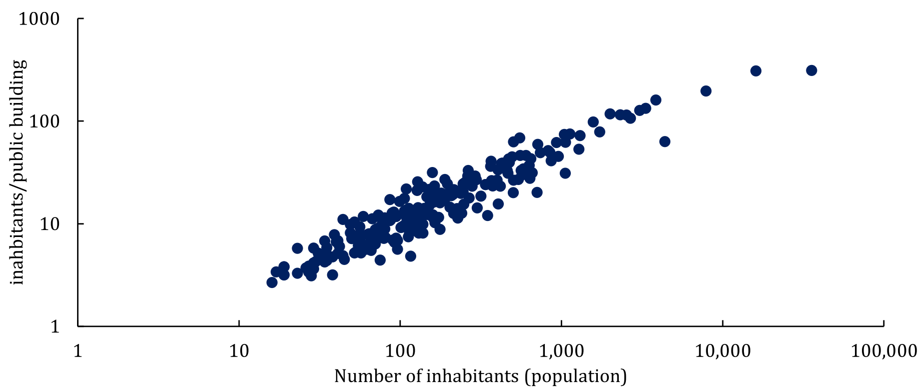

Fig. 10. Number of inhabitants per building vs number of inhabitants (population) in each municipality in the Teruel Province (log–log scale).

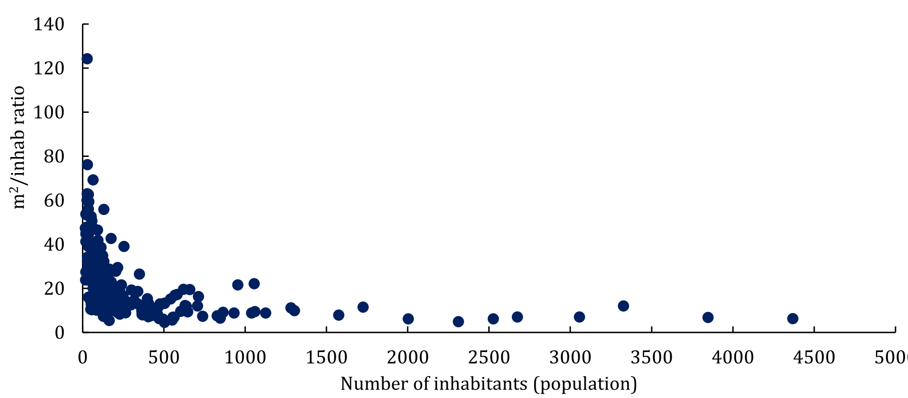

Fig. 11. Public building area (m^2) per inhabitant vs number of inhabitants (population) in each municipality in the Teruel Province.

inhabitant (m^2/inhab), the cost of implementing each EE measure per inhabitant (€/inhab) is calculated considering the investment of each EE measure (in €/m^2) for each building typology and the m^2/inhab ratio for the categories shown in Fig. 12 of Appendix A.

To evaluate the influence of underusing a public building, the techno-economic performance of the proposed EE measures for different usage hours is analysed. To this end, usage hours are varied from 4368 h (highly intensive use: 12 h/day, 7 days/week, 52 weeks/year), to 350 h (low use: 1 h/day, 7 days/week, 50 weeks/year). This, together with the reduction in installed power with the LED replacement, are used to estimate the energy savings per year (kWh/year), which are then converted into economic savings (€/year).

Results and discussion

This section shows the main techno-economic and environmental results of the proposed EE measures in the different building typologies. Then, based on these results, the influence of depopulation in the implementation of EE measures is assessed.

Assessment of energy efficiency improvements in public buildings

The improvement of the internal insulation of the building façade achieves between 12 % and 47 % reduction in the heating demand. The largest reduction is achieved in the multiservice building, which initially

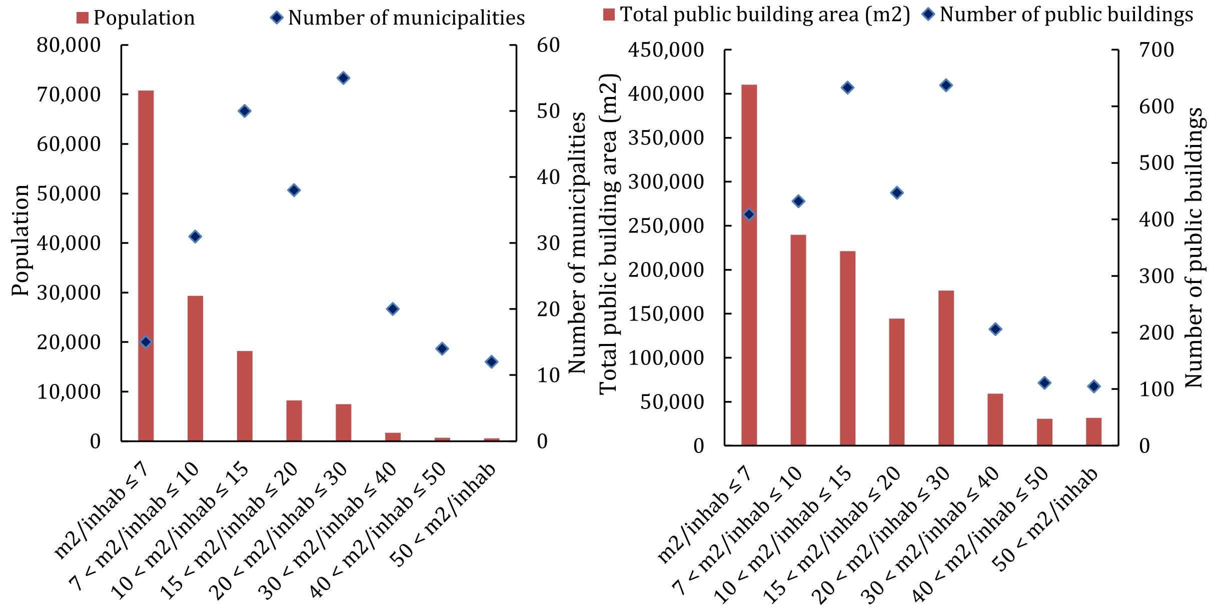

Fig. 12. Public building area (m^2) per inhabitant vs number of inhabitants (population) in each municipality in Teruel Province.

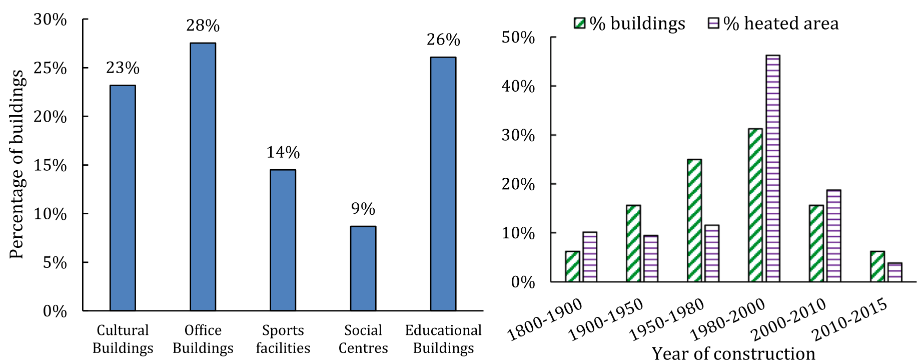

Fig. 13. Distribution of the assessed buildings by building typology (left) and by construction year (right).

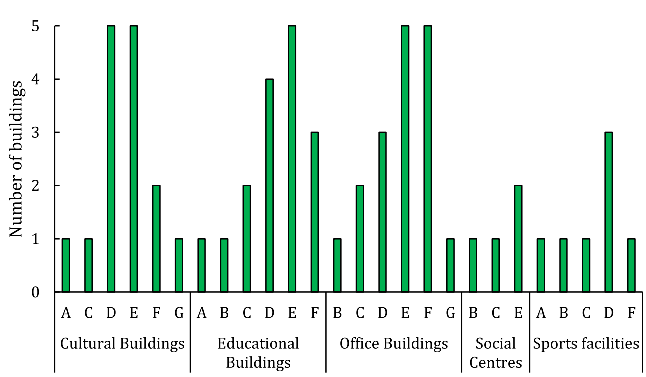

Fig. 14. Distribution of the EPC energy label regarding the CO_2 emissions for the building typologies assessed in this work.

had a considerably high heating demand (157.2 kWh/m^2 per year). The estimated investment for the implementation of this EE measure range between 17 €/m^2 and 46 €/m^2, and the PBT varies from three to nine years (see Fig. 1).

Window replacement leads to a considerably lower reduction of the heating demand (less than 10 % reduction) and thus longer payback times. These results are aligned with those published in the scientific literature [47–50]. The improvement of the wall insulation is typically the EE measure with a higher impact on energy demand in a building. However, window replacement has a low impact and high payback time.

Fig. 2 shows that there is an important potential for CO_2 emissions reduction (95 % reduction) with the replacement of the current boilers, which burn light fuel oil, with efficient biomass boilers, due to the almost negligible emission factor of biomass compared with light fuel oil. The annual economic savings are 50–70 %, with the largest savings achieved in the multiservice building, which has the highest heating demand. These savings are achieved thanks to a more efficient boiler (seasonal coefficient of performance, SCOP, of 0.800–0.831) and a lower fuel price (see Appendix B).

The estimated PBT is between 2 and 12 years. The difference in the PBT is associated with the larger heating demand of the sports centre compared to the school, so the boiler investment is recovered in less time in the school than in the sports centre.

Fig. 3 shows that the current installed lighting power is larger than the maximum allowed power (10–15 W/m^2) in the school, multiservice building and council office. In these types of buildings, the current VEEI is also higher than the maximum allowed (3–4 W/m^2 100 lx). Therefore, there are important potential savings with the replacement of the current lighting system for LED tubes. The results show potential economic savings between 1350 €/year and 5400 €/year, except in the residential centre where the current installed power and VEEI cannot be improved much further. The results considerably vary with the lighting hours, so a

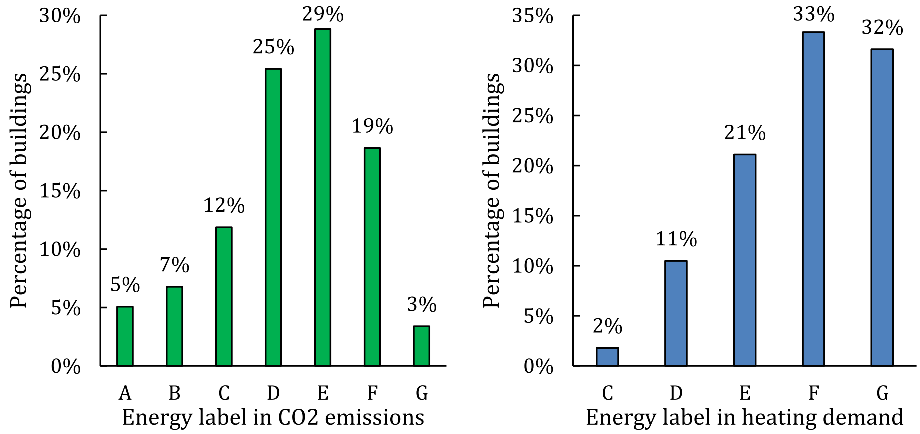

Fig. 15. Distribution of the EPC energy label regarding the CO_2 emissions (left) and the heating demand (right) for the buildings assessed in this work.

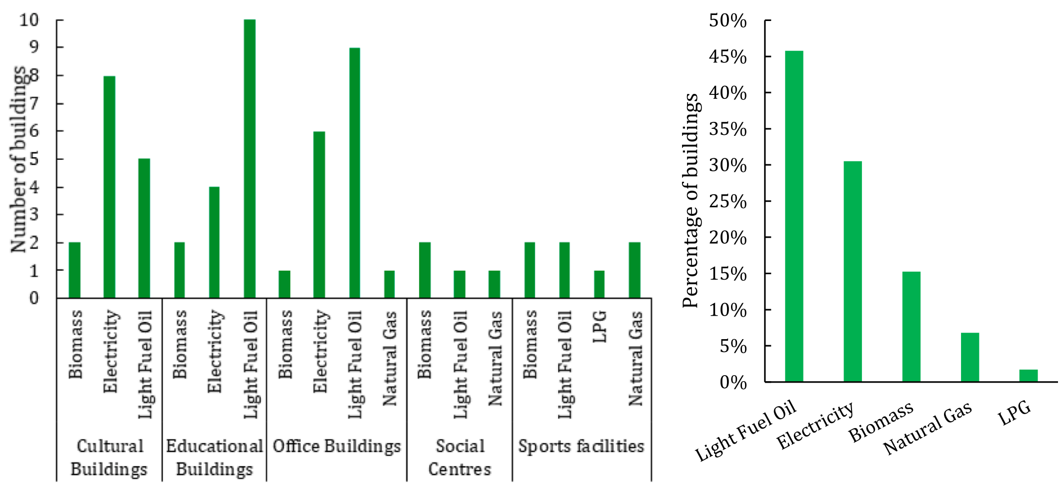

Fig. 16. Share of the fuel used for the heating system as a percentage of the heated area in the buildings assessed in this work.

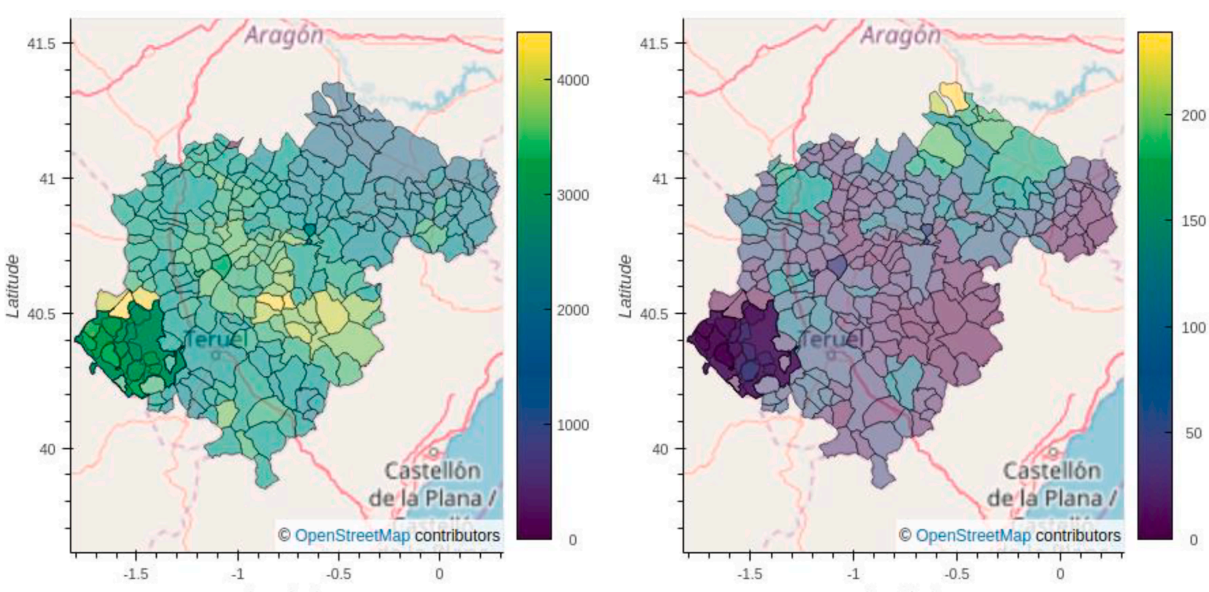

Fig. 17. Calculated HDD (left) and CDD (right) for the municipalities of Teruel province.

good estimation of the usage hours is required to obtain an accurate result. In this particular case, due to the lack of actual data, the usage profile available in the EPC is used.

Assessment of depopulation effects on energy efficiency

This section shows how depopulation influences the techno-economic potential of EE interventions. To this end, the impacts of the number of usage hours and the surface area of buildings per inhabitant are analysed.

Influence of the number of usage hours

The energy and economic savings of EE measures are directly related to the number of hours that a building is used and its occupancy levels. In depopulating areas, buildings are typically under-used, with council offices, multiservice buildings and sports centres normally used only a few hours per week. Other buildings such as schools and residential centres might be used the same number of hours but usually have lower occupancy levels than if they were located in more populated areas. To consider this under-use, and also to properly illustrate the trend, the usage hours are varied from 350 h (low use) to 4368 h (highly intensive use).

Fig. 4 shows that the economic savings associated with the replacement of the current lighting system increase with the usage hours due to the higher energy consumption and thus larger potential savings. The economic savings strongly depend on the type of building because the installed power in each of them is considerably different (see Fig. 3).

As a consequence, the payback time of the lighting replacement with LED decreases with the usage hours (Fig. 5). Therefore, one of the main barriers to the implementation of EE measures in depopulating areas is that the low use of public buildings makes it more difficult to recover the investment.

Influence of the building surface area per inhabitant

The investment per inhabitant necessary to improve the internal insulation of the building walls increases significantly as the m^2/inhab ratio increases (see Fig. 6), that is, in less populated areas. The results also show differences depending on the type of building, which are attributed to the building current features. Similar results are obtained for the boiler replacement (see Fig. 7).

The 20 % smallest municipalities of Teruel province, where 2 % of the total population lives, have 14.2 % of the total public buildings (442 buildings), which leads to an area-to-inhabitant ratio larger than 30 m^2/inhab (see Fig. 12 in Appendix A). In these buildings, the improvement of the internal insulation of the building walls costs between 500 €/inhab and 1,600 €/inhab (Fig. 6), while the replacement of the boiler costs between 500 €/inhab and 2000 €/inhab (Fig. 7). For comparison, at the other end of the spectrum, the 6 % largest municipalities of Teruel province, where 52 % of the total population lives, have 13.7 % of the total public buildings (409 buildings), which leads to an area-to-inhabitant ratio smaller than 7 m^2/inhab. In these buildings, the improvement of the internal insulation of the building walls costs between 90 €/inhab and 200 €/inhab (Fig. 6), while the replacement of the boiler costs between 90 €/inhab and 350 €/inhab (Fig. 7).

Since depopulated municipalities (with large m^2/inhab ratios) usually have lower municipal budgets (these are, generally, proportional to the population of a municipality), this additional investment cost per inhabitant hinders the implementation of the EE measures by public authorities. This is a relevant barrier to the implementation of EE measures in depopulating areas.

Further discussion

Considering the lifetime of public buildings, the payback times calculated are reasonable for most of the measures studied (except for window renovation). However, high-impact measures, such as improving wall insulation or replacing light fuel oil boilers with biomass boilers, are difficult to implement. First, they require relatively large investments that strain the municipal budget. Besides, enhancing wall insulation requires a significant intervention in a public building, which may cause inconvenience to its users. For these reasons, the retrofitting of façades to improve insulation is only considered when a partial or complete building restoration is needed [47]. In the case of biomass boilers, they require specialised management and maintenance. Trained staff is needed to perform biomass loading, boiler cleaning and other maintenance tasks. This represents a barrier to adopt biomass boilers in small municipalities, which usually prefer boilers with simpler operation and maintenance (e.g., gas boilers) [20]. For these reasons, the EE measures implemented in small municipalities are often those that are easy to implement (e.g., upgrading lighting systems, windows renovation) [47], although their impact is lower or, in some cases, even negligible.

This work has also quantified how the limited usage of public buildings in depopulated areas increases the payback time for investments made in energy efficiency. Furthermore, the oversizing of public buildings in depopulated areas increases the budgetary effort per inhabitant required to install EE measures compared to areas with higher population density. A direct solution to this problem is the creation of funding lines and grants exclusively for small municipalities. Thus, the Spanish Ministry for the Ecological Transition and the Demographic Challenge has recently launched the PREE 5000 [51] program, which offers economic support for building energy renovation in municipalities with less than 5,000 inhabitants.

However, proper energy planning can be much more effective [47] and provide enough resources for municipalities to improve the sustainability of their public buildings. The evaluation of EE measures and their prioritization is essential. For instance, measures with short payback times and low investment can be selected to be implemented in the short/medium term. The economic savings from these measures can be used to finance long-term measures, with higher investment costs and payback times. Furthermore, integrating renewable energy sources [52], such as solar thermal collectors [53] or PV panels [54], offers an excellent opportunity [55].

The oversizing of public buildings in depopulated municipalities leads to a larger available roof area per inhabitant to install PV modules than in populated areas. Currently, there are multiple options to exploit the building roof, such as public–private collaboration [47] or energy communities [56]. The profits obtained with the integration of PV energy in the building can be used to finance EE measures that require high investments. Therefore, some of the disadvantages created by depopulation in implementing EE measures can in turn lead to opportunities for the integration of renewable energies.

Conclusion

This work has quantified the impact and requirements of implementing EE measures in actual public buildings in depopulated areas for several building typologies. From this quantification, the economic barriers that depopulation creates for the adoption of EE measures in buildings are assessed.

The results show that upgrading the lighting system requires a limited investment (in general, lower than €2,000), and its payback time is relatively short (less than two years). New lighting systems can reduce the lighting electricity consumption by 50–75 % compared to old lighting systems. The replacement of old light fuel oil boilers with modern biomass boilers requires a relatively high investment (€15,000 to €45,000). The energy consumption can be reduced between 20 % and 30 % thanks to the higher efficiency of the new biomass boilers. The lower energy consumption along with the lower price of biomass compared to light fuel oil leads to a moderate payback time (two to five years). An additional advantage of using biomass boilers is the reduction of CO_2 emissions (95 %). Improving the façade insulation is the measure with the highest impact on energy consumption reduction (15–45 % reduction). Its implementation needs a relatively high investment (€15,000 to €50,000), and its payback time is longer (five to nine years). Window replacement is the least effective measure to reduce energy consumption (around 3 % to 6 %), with an investment in the analysed public buildings larger than €10,000. This leads to a payback time of more than 15 years.

Bearing in mind these results, the following is concluded for public buildings in small municipalities:

- High-impact measures, such as improving wall insulation, are usually only considered when a partial or complete building restoration is needed, due to the larger investment and need for works to implement it.
- The need for trained staff to operate and maintain biomass boilers hinder their use in this type of building, despite the large economic and CO_2 emission savings that their implementation would involve.
- The limited use of these buildings leads to longer payback times for some EE measures. This, together with the larger budgetary effort per inhabitant due to the building oversizing, also deter the implementation of EE measures.
- Proper energy planning is essential to optimise the implementation of EE measures considering the resources available and the potential energy savings.
- Combining renewable energy integration with the implementation of EE measures is a good strategy for small municipalities to improve the environmental performance of their public buildings and to overcome barriers due to depopulation.

Further work is proposed in training public authorities in energy efficiency and also providing them with easy-to-use tools that allow them to have an idea of the current status of the building stock, along with potential EE measures that can be implemented.

CRediT authorship contribution statement

María Herrando: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Ramón Chordá:** Software, Formal analysis, Data curation, Visualization. **Antonio Gómez:** Conceptualization, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Norberto Fueyo:** Conceptualization, Writing – review & editing, Visualization, Supervision, Resources, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. The case study of the Teruel province: Analysis of the current situation

The province of Teruel is the testbed for the analysis provided in this paper, as it has several of the aforementioned barriers to the renovation of public buildings. The province of Teruel has an average population density of 9.01 inhabitants per km^2, and therefore it is considered an area with a high risk of depopulation [57–60]. Additionally, many of the areas in Teruel are currently declining in population [60].

This province is located in the North-Eastern part of the Iberian Peninsula. The boundaries of the province of Teruel coincide with one of the territorial levels defined by the EU statistical analyses, specifically, with NUT3,[1] as is shown in Fig. 8. Its orography is varied, with low-altitude areas coexisting with mountain areas. As a consequence, this province has three main climate regions according to the Köppen-Geiger climate classification [61]: cold semi-arid (BSk), warm summer Mediterranean (Csb) and temperate oceanic (Cfb). The surface area of the Teruel province is 14,809 km^2, it has 236 municipalities, and its population is 134,176 inhabitants. The Teruel province is therefore a suitable region to analyse the additional burdens of public building renovation in depopulating areas.

In this Appendix, it is quantified how depopulation decreases the ratio of inhabitants per public building in Teruel municipalities. The current energy performance status of the public buildings in the province is also analysed.

In Spain, the national infrastructure database [41] gathers public building information organised by building typology. It details, for each building, surface area, current status, location (municipality), owner and operator. For this study, five types of public buildings are considered: schools, residential centres, multiservice buildings, sports centres and council offices (council offices often include doctor clinics). The population in each municipality is compiled by the Spanish National Geographical Institute [40].

Fig. 9 shows, sorted into population-range bins for the Teruel province, the number of municipalities in each bin, the number of buildings in each building typology and the aggregated population of the municipalities. It is interesting to note that the combined population of all municipalities smaller than 1,000 inhabitants (215 municipalities) is almost the same as the combined population of all municipalities between 1,000 and 10,000 inhabitants (19 municipalities), and not far from the combined population of the only two municipalities between 10,000 and 50,000. Meanwhile, the total number of educational buildings in municipalities of less than 1,000 inhabitants is three times the number of educational buildings in municipalities between 1,000 and 10,000, according to the aforementioned database [41]. Similarly, there are three times as many social centres in small municipalities compared to medium ones, five times more cultural buildings and sports facilities, and eight times more office buildings. Smaller municipalities have therefore a lower ratio of inhabitants per public building (analysis in Fig. 10), which indicates that the public building occupancy will be, in general, lower. For instance, in the smallest municipality, with 16 inhabitants and six public buildings, the ratio is 2.7 inhabitants per public building; for larger municipalities, the ratio is around 100 inhabitants per public building.

Based on the data shown in Fig. 11, the public building stock is classified into eight groups according to the public building area (m^2) per inhabitant. Fig. 12, left, shows that 52 % of the total provincial population lives in municipalities with less than 7 m^2/inhab of public buildings, 21 %

[1] NUTS: Nomenclature of Territorial Units for Statistics.

lives in municipalities with a ratio of 7–10 m^2/inhab, and 13 % in municipalities with 10–15 m^2/inhab. However, 59 % of the municipalities have a ratio greater than 15 m^2/inhab. Similar results are found regarding the number of public buildings and total public building area (see Fig. 12 right), with 51 % of the public buildings having a ratio larger than 15 m^2/inhab, but 66 % of the total public building area (m^2) having a ratio smaller than 15 m^2/inhab.

Fig. 11 shows that smaller municipalities, which are a majority in the Teruel Province as shown in Fig. 9, have a much larger ratio of public building area per inhabitant, up to 124 m^2 per inhabitant.

This analysis is consistent with the two barriers indicated in the Introduction. The number of public buildings (and their surface area) per inhabitant is much higher in depopulating areas than in areas without depopulation. This increases the budgetary effort per inhabitant required to implement EE measures. On the other hand, the probability that a public building is underused in depopulated areas is greater. Low use of public buildings increases the payback time of EE measures, decreasing their profitability.

The current status of energy efficiency in public buildings in Teruel province is evaluated through an analysis of the energy performance certificates (EPCs) of 59 public buildings. Another relevant barrier was found during certificate collection: the lack of quality data and EE assessments for public buildings. The European Directive 2010/31/EU [63] on the energy performance of buildings makes EPCs compulsory (Article 12) for public buildings with a surface area greater than 500 m^2 (greater than 250 m^2 for buildings after 9 July 2015) if they are frequently occupied by the general public. However, both conditions are not simultaneously met for many buildings in Teruel province, resulting in most public buildings not having an EPC.

Fig. 13 left shows the distribution of buildings by typology for the sample of EPCs analysed in this work. Almost 80 % of the buildings were built before 2000 (see Fig. 13 right) when the energy efficiency regulation of buildings was less strict.

Further EPC analysis shows that the predominant energy labels in terms of CO_2 emissions are D (25 %) and E (29 %) (on a scale of A to G, see Fig. 15 left), particularly in cultural, educational and office buildings (see Fig. 14). All building typologies except social centres have at least one building with an F energy label, and cultural and office buildings have one building with G-rating (the worst energy label). The energy label regarding the heating demand is in general worse; 33 % of the buildings have an F energy label, and 32 % have a G energy label (see Fig. 15 right). Therefore, there is considerable room to improve the energy efficiency of these buildings, in particular the building envelope, given their low ratings for heating demand.

The slightly better ratings for total CO_2 emissions can be attributed to 11 % of the buildings being heated by pellet boilers (see Fig. 16), which considerably reduces the CO_2 emissions associated with heating energy consumption. Fig. 16 shows that all building typologies have at least one building with a biomass boiler. Still, the predominant fuel used is light fuel oil (in 45 % of the total heated area) so there is also a significant potential for CO_2 emissions reduction by upgrading the heating system. It is concluded that the implementation of EE measures will be needed to meet the objectives established by the ambitious climate-energy transition strategy [64].

The degree-day (DD) method assumes that energy consumption is proportional to the difference between ambient (i.e., outside air) temperature and the internal temperature of a building in long-term calculations [65]. Therefore, an indicator used to obtain an idea of the heating demand of a building is the heating degree day (HDD), while cooling degree day (CDD) is used for the cooling energy demand [66]. A widely-used method to calculate HDD/CDD is following the ASHRAE standard [67], which uses the external mean daily temperature [68], defined as the arithmetic mean of the maximum and minimum temperatures in a given day ($T_{e,d}$). Then, the HDD/CDD for a location are the sum of the differences between this external mean daily temperature and a base temperature over all days of a conventional twelve-month period, as shown below [69],

$$HDD = \sum_{d=1}^{D_m} \left(T_{b,h} - T_{e,d}\right)^+ \tag{1}$$

$$CDD = \sum_{d=1}^{D_m} \left(T_{e,d} - T_{e,c}\right)^+ \tag{2}$$

where $T_{b,h}$ and $T_{b,c}$ are the base temperatures for heating and cooling respectively and D_m is the number of days in month m. The sign + indicates that only positive values are added. A base temperature of 15.5 °C for heating is considered representative of a European country [70], and a base temperature of 26 °C is selected for cooling [68,71]. Fig. 17 shows the HDD and CDD of Teruel province.

Table 1 summarises the current main features of the selected buildings extracted from their EPCs, which are used as a starting point to analyse potential EE measures. The table includes the thermal transmittance, also known as the U-value, of the two main envelope components that influence the thermal performance of the building and over which EE measures are proposed. Thermal transmittance refers to the heat transfer rate through a structure, in this case, the envelope, divided by the temperature difference across that structure. The U-value of a building component (e.g. external walls) composed of several layers is calculated as follows,

$$\frac{1}{U} = \sum \frac{\delta}{k} \tag{3}$$

where U refers to the thermal transmittance (in W/m^2K), δ is the material thickness (in m) and k is the material conductivity (in W/mK). The U-value provided for the windows includes both the glazing and the frame. It should be noted that only the values that are modified in the present work to assess EE measures are shown in Table 1, but also other building features such as the ceiling, floor and partitioning walls (internal walls) are considered in the simulation.

Appendix B. Modelling details

There are several alternatives to model the energy performance of buildings along with potential EE measures, such as Energy Plus [72], Design Builder [73,74], esp-r [75], DOE-2 [76], BLAST [65], TRNSYS [77] or BSim [78]. Some countries have developed ad-hoc software to perform EPCs, such as HULC [79] and CE3X [38] in Spain, ETU in Austria [80], iSBEM [81] in the UK and Malta, or TEE-KENAK [82] in Greece.

The most-widely used official EPC software in Spain, CE3X [38], is selected to assess the two first EE measures. The improvement of the internal insulation of the building façade and window replacement are analysed by changing directly these parameters in the corresponding file of the selected building in the Spanish official EPC software, CE3X.

The final energy consumption is converted to costs using the fuel price (0.045 €/kWh for biomass and 0.073 €/kWh for light fuel oil in the case of Spain [83]), and to CO_2 emissions using the corresponding conversion factors for the fuel [43] (0.018 Kg CO_2/kWh for biomass and 0.331 Kg CO_2/kWh for light fuel oil in the case of Spain [44]).

The EPC provides the installed power (W/m^2), VEEI and average illuminance level of the current lighting system. The tool database includes a set of lighting replacement options with their respective nominal power and luminous efficiencies (Lm/W). The tool analyses whether the current lighting system complies with the norm (maximum VEEI and installed power, UNE-EN 12464-1: 2003 [37]), and it also offers potential lighting alternatives to decrease the energy consumption while providing the illuminance levels recommended for the specific building use. The VEEI is calculated as follows [43],

$$VEEI = \frac{P \bullet 100}{S \bullet E_m} \tag{4}$$

where P is the nominal power of lighting devices and auxiliary systems (W), S is the illuminated area (m^2) and E_m is the average maintained illuminance (lux).

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