



Why district renovation is not leading the race? Critical assessment of building renovation potential under different intervention levels

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ABSTRACT

Building is one of the main sectors in which significant energy savings can be achieved with a consequent reduction in emissions. This paper assesses the large-scale renovation of buildings, exploring the quantitative and qualitative factors that determine their replicability potential from three different perspectives, namely dwelling, building and district intervention level. Different passive and active measures are assessed, covering energy saving measures, the improvement of energy supply systems and the integration of renewable energy sources. Different scenarios are defined for each intervention level, which are evaluated using the methodology developed in the IEA-EBC Annex 75 project. The methodology is applied to a residential district located in Bilbao (Northern Spain). The analysis is based on the results obtained from the simulation of 41 combinations of different renovation options, obtained by simulation in the Design Builder software. The assessment is carried out from the evaluation of different key performance factors, including annualised cost and annual primary energy consumption, as well as the CAPEX and OPEX requirements. The results show that energy renovation of buildings offers a great opportunity for energy reduction at affordable investment costs, obtaining the cost optimal values when the intervention focus on the energy system and reaching net NRPE values close to zero when the intervention is carried out in a comprehensive way, considering energy systems and thermal improvement of the envelope. Additionally, the different energy reduction scenarios show that, while interventions at district level offer the greatest potential for minimising annual costs and primary energy consumption levels, intervening at building level offers only slightly worse results. However, there are other issues which can better explain the current low rate of renovation works in the urban environment. Thus, if the additional existing social, material and legal barriers and constraints are included in the analysis, it becomes clear why renovation from a district perspective is not actually leading the race. Given this situation, some measures and policies are proposed to realise the true potential of large-scale building renovation.

1. Introduction

The efforts to reduce the impacts of global energy consumption and the related greenhouse gas (GHG) emissions have been stepped up during the last few decades all around the world. In the case of the European Union (EU), the “2020 Climate and Energy Package” [1] was approved in 2007, followed by the roadmap, updated in 2014, defining the “2030 Climate & Energy Framework” [2] and later, by the long-term strategy aimed at making the EU climate-neutral by 2050 [3]. The building sector is responsible for over 40% of global energy consumption and 30% of GHG emissions [4]. To tackle these, the EU introduced

the Energy Performance in Buildings Directive (EPBD) in 2002, which has been reinforced since then through successive updates and recommendations [5–9].

Even though the directive initially focused on new buildings, taking into account the fact that the building stock in several European countries is relatively old and shows a poor energy performance, specific efforts should be directed towards this sector. Nevertheless, current building renovation rates are very low [10], which contrasts with the general agreement on the need to accelerate the process [11]. Although many studies have been conducted focusing on the energy efficiency of existing buildings, these are usually directed from the “individual building perspective”, which usually involves a sub-optimisation of the

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Nomenclature		
ACH	Air Changes per Hour	HVAC Heating, Ventilation, and Air Conditioning
CAPEX	CAPital EXPenditure	IDAE Spanish Institute for Diversification and Saving of Energy
CHP	Combined Heat and Power	IEA-EBC International Energy Agency Energy in Buildings and Communities Programme
CTE	Spanish Technical Building Code	LCA Life Cycle Analysis
DER	Distributed Energy Resources	LCC Life Cycle Cost
DH	District Heating	MILP Mixed-Integer Linear Programming
DHW	Domestic Hot Water	NRPE Non-Renewable Primary Energy
EPAH	Energy Poverty Advisory Hub	OPEX OPERational EXPenditure
EPBD	Energy Performance in Buildings Directive	PE Primary Energy
ESM	Energy Saving Measure	PH Passive House
ESS	Energy Supply System	PHI Passive House Institute
EU	European Union	PV Photovoltaic
EUAC	Equivalent Uniform Annual Cost method	RES Renewable Energy Sources
GHG	Greenhouse Gas	SME Small and Medium-sized Enterprise
HP	Heat Pump	TDHC Total Design Heating Capacity

existing building stock as a whole [12], but which specifically considers the potential for reducing the total energy use when acting on higher scales.

In response to this, the European Commission recently approved the Renovation Wave, a strategy aiming to double annual energy renovation rates over the next 10 years [13]. One of the pillars of this strategy is to provide new tools and mechanisms to encourage the large-scale renovation of existing buildings, as well as to promote the use of distributed renewable energy sources. Therefore, the district or neighbourhood is identified as a most effective intervention level to step up the reduction of energy consumption in the building sector, as it allows economies of scale and potential synergies amongst the different buildings to be taken advantage of, as well as accelerating the process and easing the integration of renewable energy technologies.

However, interventions at district level present several barriers that should be properly considered. Sareen et al. highlight several challenges, such as the importance of multi-stakeholder engagement, the need for specific supportive regulatory frameworks, funding mechanisms, adaptive monitoring, and evolving typologies to enable replicability [14]. They also identify some key barriers that must be overcome to ensure the success of the interventions: a lack of technical capacities, limited citizen awareness, a lack of resources for public authorities and the tendency to carry out ad hoc interventions instead of the holistic deployment of a set of complementary measures for interoperability across interventions and sectors. This means that, in spite of the great potential that exists, renovation actions at the district level still present very low intervention rates. In general, the theoretically higher economic feasibility and energy performance of interventions at the district level do not usually take into account other qualitative issues that act as a brake on the deployment of high scale renovations. These are not exclusive to districts, but increase in weight as we move to higher intervention levels.

For instance, among the social factors that determine the success of building renovation, it can be found limited public willingness or acceptance, reinforced by the fact that the interests and priorities of property owners and tenants are different, making it difficult to reach agreements [15]. In this sense, a high number of dwellings can block the decision-making towards renovation, which is a barrier to interventions at district level and, to a lesser extent, building level. This effect is even more relevant in countries such as Spain, where 66% of the population live in multifamily buildings, as compared to the European average of 46% [16], and where 80% of those apartments are owner occupied, which is not the case in other northern European countries such as the UK, Sweden or Denmark (about 60–65%). In this sense, it has been demonstrated that social cohesion is of great importance for the success

of initiatives where agreement is a decisive element [17]. Heiskanen, from a comparative analysis of major barriers towards renovation in different European Member States, concluded that collective ownership is a common problem for all the countries under analysis, apart from the inability to face the upfront costs or CAPEX [18].

In addition, renovation at the district level usually implies specific challenges that make it qualitatively more complex to govern interventions at higher levels. Specifically, there is a diverse number of agents apart from the buildings' owners and tenants which makes it even more difficult to build a common agenda. For instance, several authors state that local governments are a key element to acting at district level [19] and highlight the fact that national policy must align with the vision of the local actors [20]. Additionally, when acting at the district level, there is a significant increase in the number of challenges and barriers to be faced, such as the necessity and importance of multi-stakeholder engagement, a lack of technical capacity and access to advisory services at the local level, and the lack of resources for public authorities to conduct systematic renovation through a top-down approach [14]. Top-down approaches usually require energy planning from the local authorities, who usually suffer from limited knowledge and a lack of personnel capacity [21]. Venstra and Kaashoek go further and state that a new ecosystem should be built where large buildings, SME and start-ups work together [22]. Leonhardt et al., while identifying principal government instruments for community energy, outline the importance of further research on community-focused instruments for renewable energy and the suitability analysis of current community-appropriate energy solutions [23]. This requires new mechanisms, such as new legislation and policies, technically innovative solutions, the integration of supply chains, local energy planning and financial agreements due to the high upfront costs.

The energy renovation of buildings includes one or several of the following elements: building envelope improvement (Energy Saving Measures or ESM), upgrade of Energy Supply Systems (ESS) and integration of Renewable Energy Sources (RES). The number of available renovation options depends on the intervention, which usually increases as the scale of the intervention increases. Thus, acting at the building level increases the renovation options compared to the dwelling level, but they are likewise increased when the renovation is applied to an entire district, which allows the implementation of district heating and cooling networks. Both EPBD and Renovation Wave define the renovation potential to the extent that the required investment can be regarded as cost-effective, which is understood as those measures that offer an economic benefit to the investor in relation to a reference situation.

Cost-effectiveness depends on several factors, such as the building typology, current building and HVAC characteristics, labour costs,

energy and infrastructure costs, climatic conditions, etc. The relationship between these internal and external factors determines the cost-effectiveness of the potential retrofitting actions. Even though a significant number of studies have evaluated cost effectiveness at the building level, the range of studies focusing on the district scale is still limited. Some studies have focused on evaluating the effect of implementing ESM in buildings connected to a district heating/cooling system. Thus, Milic et al. assessed the impact of the implementation of ESMs, and the interaction between them and the operation of the district heating [24]. The authors concluded that ESM demonstrated a significant reduction in PE consumption, but they reduced the revenue of the district heating system from the economic point of view. Similar conclusions can be obtained from the study published by Blomqvist et al. [25]. In this case, not only the implementation of ESM is evaluated, but also the replacement of the existing heating system (CHP) by a ground source heat pump (HP). Both studies, with case studies located in Sweden, point out that this issue can involve a barrier to implementing ambitious ESM at the district scale in building clusters connected to an existing district heating system (DH) located in cold climates, as in several cases in northern Europe.

Other studies have evaluated different alternatives in terms of ESM and ESS. Blázquez et al. assessed a generic district located in Italy, considering different combinations of ESM and ESS, as well as the possibility of implementing photovoltaic (PV) [26]. The results showed that envelope retrofit actions are cost-effective only in northern areas of Italy (colder climates); whereas decentralised systems are not convenient in any case with the current envelope. In the case of an insulated building envelope, moving onto district-neutral scenarios based on biomass or GSHP is always cost-effective if coupled with PV systems. Decentralised heat pumps present a reduction in PE consumption, but they significantly increase the costs. Similar conclusions can be extracted from the results presented by Barbosa et al. in [27]. They highlight that all centralised scenarios evaluated are cost-efficient, the optimal one being a centralised heat pump combined with an improvement of the envelope; whereas net scenarios are only achieved when PV systems are implemented.

As seen above, most of the scientific papers in the literature set the intervention level as a precondition of the analysis, that is, the intervention level is a constraint under which all the cost optimality is assessed. Unlike it, this paper presents, for the first time, a comparative technoeconomic assessment of three renovation intervention levels, specifically, dwelling, building and district. For that aim, the authors carry out a systematic evaluation to analyse the combined effect of the application of ESM, ESS substitution and integration of RES at the different intervention levels. Full dynamic simulations of both building and HVAC systems are performed for each case, resulting in more than 900 simulations. The assessment of each of the cases under analysis is carried out following the methodology proposed by the IEA-EBC [28]. The main objective is to carry out a quantitative and qualitative evaluation of the technoeconomic performance of the three intervention levels, identifying the main barriers and challenges that limit the actual potential of the solutions. This sheds light on the gap between the “best solutions” and those currently being implemented in the sector. Based on this, the authors propose some measures and policies that could contribute to narrowing this gap.

The rest of the paper is structured as follows. After the introduction, the methodology framework guiding the overall approach of the study is presented in Section 2. Section 3 characterizes the case study and the general assumptions taken for modelling the dwelling, building and district intervention levels. This is followed by Section 4, where the results are presented in the context of cost-effective and environmental alternatives of EMS and ESS applied within adopted indicators. Following that, the results are discussed in Section 5, where the main qualitative challenges and barriers that condition the success of the intervention levels are reflected through three established levels, as well as some measures and policies to mitigate them. Finally, the main

conclusions are detailed in Section 6.

2. Methodology

The methodology for the cost-effective evaluation of renovation actions was previously presented by the authors in [28]. There, the cost-effectivity of renovation works, combining demand reductions, energy efficiency and renewable technologies, was determined using the calculation framework of the IEA-EBC Annex 75 project. Under this approach, H. T. Walnum et al. in [29] evaluated the Norwegian case study and J. Rose et al. [30] applied it to exemplary renovation projects across Europe. The general guidelines can be easily adapted to different contexts and constraints.

In this work, the methodology is organised into four principal stages. The first (i) corresponds to the characterisation of the sample, which consists of gathering information on the current state of the buildings and energy systems. In the second stage (ii), the “reference case” is defined, based on the current status of the district, which serves as a baseline for the analysis. The third (iii) consists of the definition and assessment of renovation scenarios. The assessment is based on the combination of Energy Saving Measures, Energy Supply Systems and Renewable Energy Sources, which are evaluated through proper simulation software and the definition of several Key Performance Indicators: Equivalent Uniform Annual Cost (EUAC), annual primary energy (PE) and non-renewable primary energy (NRPE) consumption. Additionally, two more indicators are considered by splitting the costs into two parts: *investment costs (CAPEX)* and *operational costs (OPEX)*. Finally, the fourth stage (iv) involves interpretations of the results, where the relationship between the annualised costs and the primary energy consumption is obtained, allowing the definition of both cost-optimal and primary energy-optimal solutions. The methodology workflow is summarised in Fig. 1.

As justified in the Introduction section (Section 1), with the aim of exploring the effects of renovation at different implementation levels, the methodology presented above is applied to the three different intervention levels at which renovation can be approached, i.e., dwelling, building and district level. For this aim, dwelling is defined as a single housing unit within an apartment building, building the apartment building itself and district, an urban area within a city that includes several buildings.

Each of the renovation intervention levels presents its own set of candidate ESM, ESS and RES options, as well as specific costs for their implementation, which give rise to specific cost-optimal curves. The discussion of these quantitative techno-economic results is coupled to qualitative aspects that cover legal, social and technical constraints that usually condition the choice of the level of intervention for district rehabilitation. This assessment is included in the Discussion section (Section 5).

3. Case study

The methodology has been applied to a case study located in Bilbao (Spain). The case study’s general information is first outlined in Section 3.1. Secondly, different ESM (see Section 3.2) and ESS and RES (see Section 3.3) are introduced, explaining the scenario’s configuration. Thirdly, the set of scenarios combining the proposed measures is evaluated using the model established in Design Building software, where some assumptions and simplifications have been considered (evaluating their effects in the final results) for modelling the whole district (see section 3.4). Finally, the energy and economic criteria used for results interpretation are described in section 3.5 within the three centralisation levels evaluated. Fig. 2 depicts the eligible options for the three renovation intervention levels, describing the conceptual interconnections of renovation components in accordance with a set of measures (Fig. 3).

At a dwelling intervention level, the amount of measures that can be

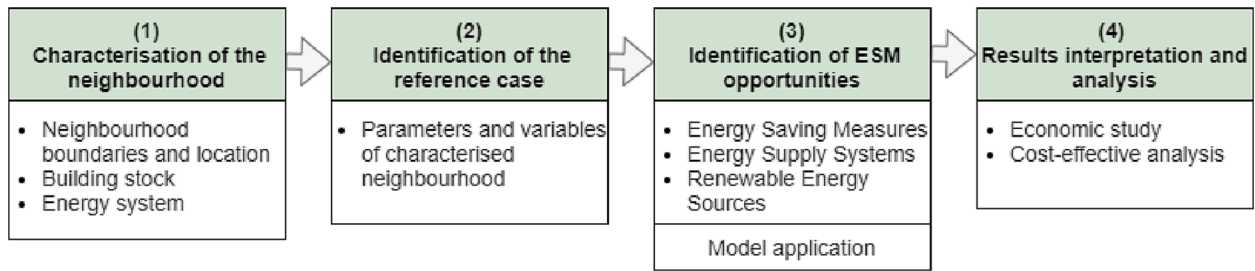


Fig. 1. Overview of the methodology framework.

	Energy Saving Measures	Energy Supply Systems	Renewable Energy Sources
Dwelling	facade roof windows separation from non-conditioned spaces infiltration levels	Individual	share of centralised installation
Centralised building	facade roof windows separation from non-conditioned spaces infiltration levels	Individual Centralised	✓
District	facade roof windows separation from non-conditioned spaces infiltration levels	Individual Centralised District	✓

Fig. 2. The adopted matrix of the methodological approach to the analysis of EMS and ESS measures at three centralisation levels.



Fig. 3. 3D view of Otarkoaga neighbourhood case study.

applied in energy renovation is strongly limited. In multi-apartment buildings in Spain, the renovation of windows is almost the only eligible option, since it does not need to be harmonised for the whole building (as long as the aesthetic codes are met). It is also possible to act on the envelope by means of punctual and specific actions (e.g., adding

thermal insulation on the internal surface of the façade), but it is not a widespread option. The building intervention level presents a wider set of eligible measures, including the implementation of renovation actions addressed to roof, windows or separation from non-conditioned spaces, as well as qualifying for centralised ESS. Finally, the district intervention

level involves the whole set of ESM elements eligible at building level, while additionally allowing increased options for ESS and RES components, as they can be considered from the perspective of the whole district. In addition, the approach for centralised district heating systems for the whole district could include additional issues to be considered within the evaluation and which are also considered in this study: (i) an introduction of nonlinearities for the specific cost of ESS technologies; (ii) district heating (DH) piping work investment costs which break down on the main equipment, the balance of plant, civil and structural works development cost [31]; (iii) a ground condition of the case study location, in association with the potential of heating grid thermal losses.

3.1. Description of the district

The area of analysis for this research is the Otxarkoaga neighbourhood, located in the eastern part of Bilbao city, in Northern Spain. The selected area covers about 24 ha, and the terrain is a steeply sloping hillside facing south. It can be described as an oceanic climate with relatively moderate summer and winter temperatures. In summer seasons, the average maximum outdoor air temperature is between 25 °C and 26 °C, while the average minimum in winter is between 6 °C and 7 °C.

The area covered by buildings takes about 6.2 ha (25%) of the selected neighbourhood's area, populated with 27,700 inhabitants [32]. Most of the buildings within the neighbourhood were built over two years (1959–1961) when 3672 apartments distributed in 114 buildings were projected and constructed. Later on, there was a renovation promoted by the city council that addressed the whole district in the 1980 s. As a consequence, the majority of the building stock in the district has many similar constructive characteristics, described in detail in [33,34]. Additionally, the morphological study of the buildings points out four different main typologies, presented in [35]. For that reason, within these four main types of buildings, which were distinguished in the study by different heights or base area, 6 buildings are classified as square towers, 78 buildings are rectangular, 4 are “comb” or E-shaped, and 15 are H-shaped. The non-residential buildings have different shapes, and since the scope of work was directed towards residential buildings with remarkably the same parameters, these non-residential buildings were excluded from the evaluation. Most of the buildings in the neighbourhood have a North-West/South-East (NW/SE) and North-East/South-West (NE/SW) layout. Still, there are buildings with other orientations such as East-West (E/W) or North/South (N/S).

As far as the construction is concerned, information was obtained from Bilbao Social Housing, the public municipal entity that manages social housing in the city. Although some energy renovations have been carried out in recent years in some buildings, a base case was assumed in this study, considering the construction features resulting from the aforementioned renovation works carried out in the eighties, i.e., a U-Value of 0.74 W/m² K for the façades, and 2.27 W/m² K for the roofs. As far as the thermal features of the windows are concerned, even though there is more heterogeneity in this case, most of them have double glazing ($U_{\text{glass}} = 3.44 \text{ W/m}^2 \text{ K}$) with a metallic frame without a thermal break ($U_{\text{frame}} = 5.7 \text{ W/m}^2 \text{ K}$). These values have been assumed as generalised for the whole district. A detailed description of the envelope is presented in [33].

3.2. Definition of the energy savings measures

Different ESM are evaluated for façade, roof, windows and internal partitions with non-conditioned spaces. Indirectly, these sets of actions have an effect on the reduction of infiltration levels, which has also been taken into consideration in this study. For each façade, roof, window and internal partition with non-conditioned spaces, 4 options are considered; “0” being the reference case (described in the previous section); while the first (1) refers to the minimal requirements set out by the current Spanish regulation, the Spanish Technical Building Code (CTE,

in Spanish). The second (2) refers to the same document, but in this case to the recommendations made in Annex E of the said document. This document collects a set of non-mandatory recommendations which promote going beyond the minimal requirements set in the regulation, aimed at improving the energy performance of the building. The third option (3) is an intermediate one between the second and the fourth, the latter (4) being the one used for Passive House Institute (PHI) certification. These hypotheses are presented in Table 1, where the column “ U_{max} ” shows the maximum value defined by the minimal requirements/recommendations of the different references considered and the column “insulation thickness added” presents the insulation thickness added to the existing building to reach the value indicated in the column “ U_{max} ”. As far as solar factor (g value) of the glazing area is concerned, a mean value of 0.79 was assumed in all scenarios evaluated.

Regarding infiltrations, it is assumed that a fixed value of 0.6 ACH for the reference case scenario and all scenarios where window replacement is not considered, and 0.3 for those combinations where original windows are replaced. Two additional levels are considered as additional improvements for the two combinations, where the third and fourth options are assumed for all elements (façade, roof and windows): in the third level, acting on the façades to reduce the infiltration rate (0.1 ACH) is assumed as an additional improvement; whereas, in the fourth level, it is assumed that the infiltration rate is reduced to 0.03 ACH by acting on the façades and internal partitions. These values are based on usual interventions required/proposed by different standards to reduce infiltration rates (e.g., the use of air tight adhesive tape to seal gaps between boards, or seals for service penetration through a membrane).

Additional measures, such shading devices for reducing solar gains in summertime are not taken into consideration, since, on the one hand, they are not usually implemented in residential building renovations in this region (they are not mandatory) as the summer conditions, as previously mentioned, are moderate in this area, and, in consequence, they have no effect on the total building energy consumption (residential buildings don't have cooling devices in this climate). Similarly, the installation of mechanical ventilation (and, eventually, heat recovery units) has not been taken into account in this study. If this can be in some new residential buildings, it is hardly used in renovations in residential buildings in general in this region. Moreover, its implementation is not feasible in this case study, due to the building characteristics.

Considering these scenarios, a set of 40 combinations (41, if the base case scenario is taken into account) has been evaluated (detailed in Appendix 1). Each combination is codified by a 4-digit number, where

Table 1
Evaluated energy efficiency measures.

	Code		U_{max} (W/ m ² K)	Ins. thickness added (m)	$U_{\text{resulting}}$ (W/m ² K)
Façade	1	CTE	0.49	0.04	0.43
	2	“Annex E”	0.29	0.08	0.29
	3	Envelope “B”	–	0.12	0.23
	4	PH	–	0.16	0.19
Roof	1	CTE	0.40	0.10	0.35
	2	“Annex E”	0.23	0.16	0.23
	3	Envelope “B”	–	0.18	0.21
	4	PH	–	0.20	0.19
Windows	1	CTE	2.10	–	2.10
	2	“Annex E”	2.00	–	1.80
	3	Envelope “B”	–	–	1.57
	4	PH	–	–	1.05
Partitions (NC)	1	CTE	0.70	0.04	0.60
	2	“Annex E”	0.48	0.06	0.47
	3	Envelope “B”	–	0.08	0.38
	4	PH	–	0.12	0.27

the first represents the renovation level in façades, the second in roofs, the third in windows and the fourth in internal partitions, based on the value indicated in the column “Code” presented in Table 1. Thus, the combination 1.2.0.3. indicates that this scenario considered the first renovation level (CTE) for façades, the second renovation level for roofs, no action on windows and the third renovation level for internal partitions with non-conditioned spaces. After an assessment of the energy demand obtained for these 40 scenarios, they have been combined with different energy systems at individual, building and district levels. The costs for the implementation of the passive scenarios involved three main components: material, working force and direct complementary costs (see Appendix 2).

3.3. Definition of the energy supply systems and renewable energy sources

Regarding energy systems, the case study includes space heating, domestic hot water (DHW) and electricity loads. Cooling needs are not included as, in general, they are not covered in residential buildings under these climate conditions.

3.3.1. Definition of energy supply systems

Four main technologies were considered in this study: electric heaters (base-case scenario), natural gas boilers, air heat pumps and biomass boilers. Table 2 presents the number of combinations of passive measures analysed by technology and intervention level. Altogether, 451 scenarios were evaluated. Additionally, the potential of PV systems in the district was also evaluated, giving as a result 451 additional scenarios.

The combination of technologies and centralisation levels poses a selective approach to decision-making on the applicability and feasibility of certain technologies. Mainly, a biomass boiler implemented on the individual scale involves some conditions to users, requiring ample fuel supply chain and emissions estimation. In contrast, an individual geothermal heat pump requires a feasibility estimation, which is a crucial component from an infrastructural point of view. In this way, those options were beyond the scope of this study. Centralised building and district scales are considered within the study as larger-scale solutions that consequently address a higher stake of heating requirements, such as both the space heating and DHW. Thus, technologies exclusively installed to meet DHW demand have been left aside.

3.3.2. Definition of renewable energy sources

The rooftop PV generation potential was evaluated for the whole district using the PV Syst tool [36]. To do so, the roofs of the district’s building stock were classified according to their shape, considering two principal types, tilted and flat, as well as the available areas. In the end, 8 different types of rooftop were differentiated, with a total estimated useful area of 56,260 m². In the case of tilted roofs, only the gable with the most favourable orientation was considered, assuming that PV panels are supposed to be installed directly on the gable, and considering the roof angle for the panel (20°); whereas, in the case of flat roofs, the optimum angle was calculated (35°). The same panel was considered for all PV installations, namely a mono-crystalline module of ERA. Panel spacing is also calculated and considered when calculating the PV

Table 2

Number of passive combinations evaluated by technology and centralisation level.

	Dwelling	Building	District
Electric heaters	41 comb.	–	–
Natural gas boilers	41 comb.	41 comb.	41 comb.
Air heat pumps (only for DHW)	41 comb.	–	–
Air heat pumps (for DHW and heating)	41 comb.	41 comb.	41 comb.
Biomass boilers	–	41 comb.	41 comb.
Geothermal - Ground HP (for DHW and heating)	–	–	41 comb.

potential of the district in order to minimise the shadowing effect. The RES potential considered in this study involves PV technology presented as an integratory part at each of the three levels, estimating the PV potential of the district within considered supply systems and passive measures. This potential has been calculated based on the following assumptions: 20 years of lifespan, assuming that the total of the energy generated by the PV installation is consumed by the district and, in consequence, the savings are calculated as a result of multiplying the electricity production times electricity costs from the grid (cost avoided since that electricity is produced in situ by the PV installation, and thus is not obtained from the grid).

3.4. Energy modelling

As previously mentioned, the building stock in the district evaluated is very homogeneous as far as the constructive characteristics of the different buildings are concern. Thus, with the aim of validating the model of the district, a reference building was assumed as the representative building of the building stock. A detailed monitoring study was performed in this reference building, and data obtained from this study was used later for validating a detailed building model, as presented in detail in [33].

From this, due to the complexity and the scale of the case study, some simplifications were carried out to enable the simulations of the whole. The principal scheme of model definition and validation is presented in Fig. 4. The applied simplifications can be classified into two groups: those related to the definition of the buildings (concerning the energy demand), and those related to the energy systems (concerning the energy consumption). To evaluate the reliability of the district model after the simplifications, a detailed model of a building located in this district was used, which was previously validated by the authors using monitoring data [37].

3.4.1. General assumptions

The different intervention scales were modelled using the Design Builder (DB) simulation software, an EnergyPlus-based graphic interface. In order to reduce the time required for each simulation, several assumptions were taken, as described and justified in Table 3.

Unlike heating demand, DHW demand is not affected by the ESMs adopted in the building. Thus, a general value of 2882.94 kWh/year per dwelling has been assumed, following the criteria set in the regulation for calculating this demand. Additionally, to simplify the simulation of energy supply systems at dwelling and building intervention levels, its performance was included through the seasonal performance factor of each technology under consideration. These values were obtained from the simulation of the different ESS presented in Table 2 for buildings of the district validated in [37]. Different parameters for the inlet temperature, outlet temperature, flow rate and mass flow rate were considered for the heating loop and the DHW loop, as summarised in Table 4. In the individual systems, the constant mass flow was selected, while in the centralised ones, variable mass flow was chosen. Real operating values from manufacturer’s datasheets were considered. In the case of aerothermal heat pumps, the curves of capacity and COP as a function of the outside temperature and condenser inlet temperature were also assumed in the simulations.

Once the seasonal performance of each energy system is known for each combination of passive measures, aggregated energy consumption for the whole district for those combinations was obtained by considering the energy demand for the whole district and the obtained seasonal performance for each combination.

Alternatively, in district level interventions, a district heating network is considered as the ESS for the whole neighbourhood. This is made up of two principal components: the heating plant and distribution network, which was preliminarily discussed in previous research work [35]. The key issues considered for the implementation of the district heating network are summarised in Table 5.

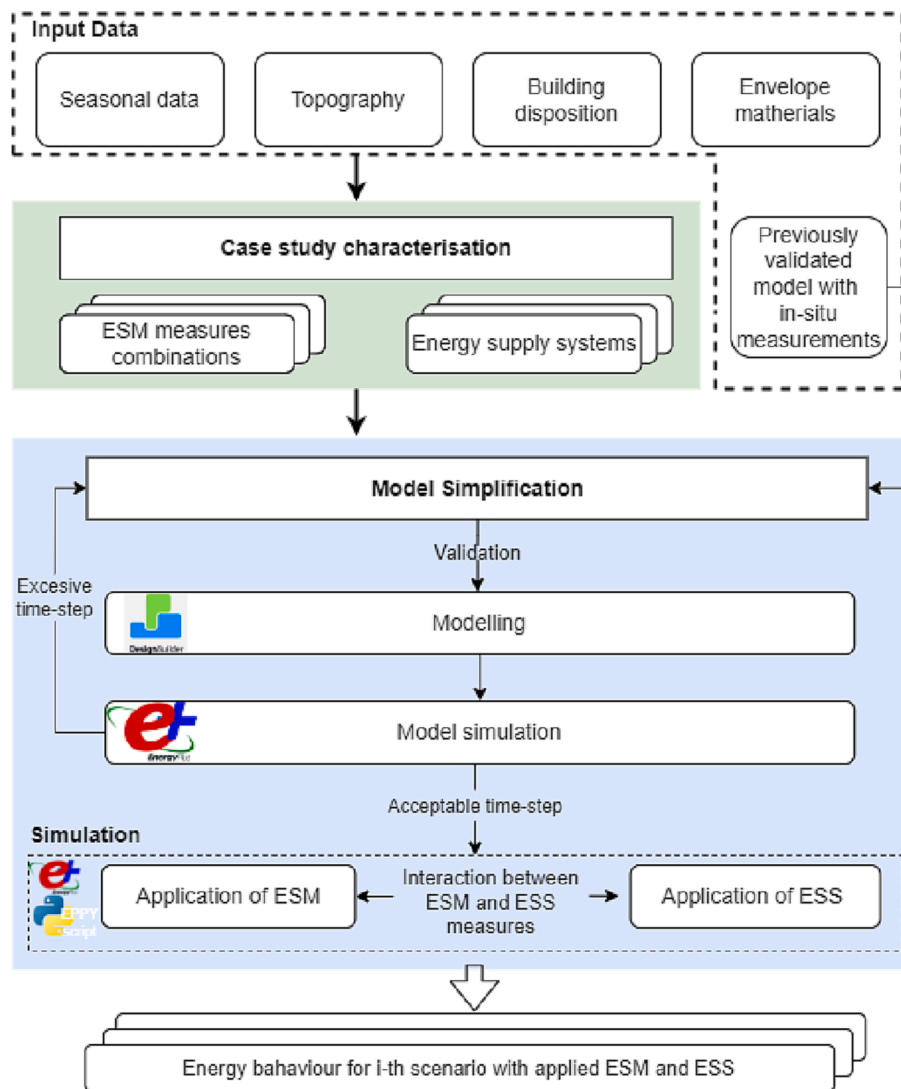


Fig. 4. Principal scheme of model definition and validation.

3.5. Cost-efficiency assessment

Three key performance indicators are selected to evaluate the cost-effectivity of the renovation actions: (a) PE consumption (kWh/m².year); (b) NRPE consumption (kWh/m².year); (c) EUAC (€/m².year), derived applying conversion factors in the Spanish building sector [39]. There are four parameters used to determine the annualised cost indicator: (i) investment costs (CAPEX); (ii) operational costs (OPEX); (iii) fuel costs (based on the energy results); (iv) expected lifetime of the different systems [40]. The investment costs for the different passive renovation measures have been assumed based on the current costs. Each of the passive measures combinations was calculated together with the costs of the corresponding energy system; while, in the case of district heating, the cost related to the distribution network was also considered.

To provide a comparative analysis of investment alternatives, the Equivalent Uniform Annual Cost Method (EUAC) was applied. The EUAC method expresses costs as an annualised estimate of cash flow instead of a simple estimate of the present value. Hence, the present value (*P*) of the cost of capital investment at a particular point in time is first calculated following Eq. (1), where *A* is the annual cost of a given scenario (both maintenance-related and fuel costs), *I* is the initial investment, *i* the interest rate assumed and *n* the project lifespan assumed. Once “*P*” is obtained, the EUAC can be calculated following Eq. (2):

$$P = I + A \cdot \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \tag{1}$$

$$EUAC = P \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \tag{2}$$

The investment costs for the different passive renovation measures (ESMs) have been assumed based on the current costs in Spain [41], as summarised in Appendix 2. Based on these costs, the investment cost for each scenario within the combinations is calculated as the sum of the cost related to the combination of energy efficiency measures and the cost related to the energy system assumed in each scenario (the costs for every combination are presented in detail in the supplementary data linked to this paper).

The annual maintenance and operating costs for ESS technologies are defined as a percentage of CAPEX per year and equal to 2.5%. Additionally, a discount rate (*i*) of 3%, and a lifetime (*n*) of 20 years were assumed for all combinations.

The specific cost for district heating solutions was calculated separately for each installation per scenario. The investment cost covers nonlinearities for the centralised district heating system sizing by specific cost equations applied for a natural gas boiler, biomass boiler, air thermal and geothermal ground heat pumps, as well as the water tank specified in Appendix 4. Based on the literature fixed values, the final

Table 3
Reduced complexities implemented in the simplified Design Builder.

	Complexity	Component	Addressed Simplification	Comment
Building unit	Annual heating demand	The aggregated value of a parameter for the building was lower than 3% (2.82%) compared to the value obtained in the validated model	Virtual internal mass	Thermal inertia was adjusted to represent the effect of the internal partitions.
	Thermal zones	Different zoning criteria were assessed	Zoning was neglected	The effect of zoning has been found as negligible when the annual heating demand was evaluated. Buildings are modelled as empty blocks.
Whole model	Buildings envelope	Approach to features of buildings envelope.	Same features of the envelope for every building	Detailed composition of each element derived from [33] (see Appendix 3).
	Infiltration and ventilation	Base case scenario Mechanical ventilation Ventilation schedule	The constant flow rate of 0.6 ACH; No mechanical ventilation; Manual ventilation schedule (7 am – 8 am) with an air change rate of 4 ACH.	-
	Internal gains and temperature set-point schedules	Temperature schedule 20 °C Temperature schedule 17 °C Internal Gains	Set from 8:00 h to 23:00 h; Set for the rest of the hours except from 7 am – 8 am, when the natural ventilation takes place. Following the hourly values given by IDAE.	4 ACH is a common assumption for natural ventilation, and it has been assumed in previous similar works [33] Schedules were defined taking into account the hourly values given by IDAE [38].
	Model's definition	Effect of the topography	Component block type – Ground	Each building has been defined considering its relative altitude regarding the others.

Table 4
Parameters assumed for individual and centralised systems at the building level.

		Inlet Temp. (°C)	Outlet Temp. (°C)	Flow rate (l/s)	Mass flow rate
Individual systems	Heating Loop	60	50	0.133	Constant
	DHW Loop	55	50	0.002	Constant
Centralised systems (at building level)	Heating Loop	60	50	4.204	Variable
	DHW Loop	55	50	0.059	Variable

equation built on cost models was used. For that, specific cost equations were adopted from technologies assessed in [46], where the authors self-tailored a top-down analysis of the Spanish market, and published cost data of the techno-economic performance of large-scale heating and cooling in the EU [31].

Based on the above, the investment required for implementing the proposed distribution grid was calculated as a constant cost for ESS scenarios, being estimated as 474 €/m, and a total investment of 4.46 M€ (3.65 M€ for the main ring, and 0.81 M€ for connections). Finally, the PV system investment was calculated based on types of roof and orientation. After evaluating the suitable roofs for installing PV systems (section 3.3.2), a total power of 1981.5 kWp was calculated, to be installed for the whole district, assuming a total investment of 2,973,437.64 €.

The price for the different energy sources was obtained from the Eurostat report on household consumers [42]. Thus, a natural gas cost of 8.97c€/kWh has been assumed and 30.71c€/kWh for electricity, according to data concerning household consumers in Spain for the first half of 2022. In the same way, the fuel costs approaching district ESS included the main technology fuel cost (natural gas, wood pellets, electricity), and backup technology fuel costs considered for heat pump scenarios (i.e., natural gas). Also, for all scenarios, the auxiliary consumption of electricity (i.e., required for pumping) was included in the assessment.

4. Results

In this section, the results from the scenarios under evaluation for the three intervention levels are presented and assessed. The whole detailed set of results can be checked at [43], an open-source online data repository hosted at Mendeley.

Attending to the impact of the different ESMs evaluated, Fig. 5 presents the specific space heating demand for the whole district when applying the different combinations of energy-saving measures presented in section 3.2. Based on these calculations, the heating demand of

Table 5
Parameters implemented for District level energy supply system deployment in Design Builder simplified model.

Parameter	Modelling	Comment
ESS installation elements	• space heating DHW pumping through the distribution system	“Detailed HVAC” simulation model is used in Design Builders.
Splitting of load capacity	Separate installations according to ESS technology and load intervals	DHW demand remains relatively constant during the year compared to heating demand, the load capacity split into a few separate installations was assumed.
Sizing the heating equipment	<i>Total design heating capacity (TDHC)</i> value	The value used for sizing the heating equipment, ensures meeting the coldest winter design weather conditions and is estimated by DB as <i>Zone Sensible Heating</i> of the model, and multiplied by the <i>safety factor</i> ; Multiplication factor used to derive TDHC value.
Safety factor	1.5	
Design pump head parameter	155 Pa/m	Pumping demand introduced as a pressure drop simplified theoretical calculation into one of the pumps of the circuit based on specified potential distribution network topology.
Topology length	9412 m	Considered the length of the main ring and its connections for <i>heat pump parameter</i> potential topology of a distribution network based on a previous study [35].

the reference case for the whole district reaches 7742.61 MWh/year (34.61 kWh/m².year). Additionally, DHW demand is 9764.52 MWh/year.

Looking at these results, one of the most significant effects can be observed when window replacement is considered. Thus, the 16 scenarios with the lowest heating demand involve window replacement, and the difference between the scenario with the highest consumption amongst the scenarios which consider window replacement (1.1.1.0.), and the best scenario without replacing windows (in terms of heating demand, 4.4.0.4.) goes from 12.67 kWh/m².year to 18.46 kWh/m².year, respectively, a reduction of more than 30% in the energy demand. This means a 35% of the heating demand of the reference case scenario. This trend is obviously replicated when energy consumption results are evaluated, outlining the particular impact of window replacement. Regardless of the energy technology and implementation scale, the results can be referred to as those energy efficiency measures that include window replacement, and those that do not. Additionally, in most cases, the cost-optimal solution presents a low degree of energy efficiency measures.

Regarding the ESS and RES, dwelling (section 4.1), building (section 4.2.), and district (4.3.) intervention levels are independently assessed. For that aim, several plots were drafted where the EUAC is related to the PE and NRPE consumption. Additionally, as CAPEX and OPEX are recognised as important factors that condition decision-making, they are also presented for each case, as they are related to the NRPE consumptions. This allows “cost-optimal” solutions to be determined using different criteria. In addition, the annual electricity supply of the PV installation resulted in 2,030.4 MWh/year, based on the district’s estimated useful rooftop area for solar PV. This involves a reduction of the NRPE consumption of 4,075.05 MWh/year and 4,879.09 MWh/year, which equals a corresponding reduction of 18.22 kWh/m².year and 21.81 kWh/m².year when the total heated area of the district is considered.

4.1. Dwelling intervention level

Fig. 6 shows the graphs where the relation between CAPEX and OPEX with NRPE for the different scenarios at individual level are presented, as well as the EUAC with PE and NRPE consumption. Each colour represents the main technology for supplying DHW and heating. Additionally, those scenarios which include PV are represented by triangles; whereas circles are used for those scenarios where PV is not implemented (the same visualisation logic is kept throughout the next subsection of the building and district intervention level). For the sake of clarity, some meaningful scenarios are identified in each graph (those

which bring maximum or minimum values of EUAC, NRPE consumption, OPEX and/or CAPEX...) with a brief description and an ID number. This ID number allows each scenario to be easily identified in the supplementary data set available together with this article.

As observed when energy demand results are evaluated, EUAC related graphs show how the results corresponding to each ESS system are gathered into two different clusters: those where window replacement has not been considered (with an EUAC significantly lower) and those where window replacement has been assumed (even doubling the EUAC in some technologies).

When cost effective solutions are targeted, natural gas boiler solutions are the most favourable at individual level. Namely, the cost-effective option is identified as a natural gas boiler with no intervention in the envelope or windows (ID 493). This is a convenient solution when the energy cost is considered to remain constant during the whole lifespan. However, when the focus is put on energy consumption, air heat pumps become the most interesting technology. An individual air heat pump with window replacement reduces the PE consumption to around 50–60 kWh/m².year (reaching values slightly lower than 50 kWh/m².year in some cases). However, at the same time, it also presents one of the highest values of EUAC, only being exceeded by those scenarios where the reference heater is not replaced (electric heater). In this way, the scenario with the lowest energy consumption (both in terms of PE and NRPE) is that with an air heat pump installed with the highest level of energy efficiency in the envelope. When the integration of PV also takes place, the results are shifted left, along the x-axis within the abovementioned specific PE and NRPE indicators calculated for PV, leaving individual measures within 30–40 kWh/m².year of the PE indicator.

In the case of measures implemented at individual level, trends remain similar when CAPEX and OPEX values are compared for the different technologies. Scenarios with natural gas boilers show the lowest values of OPEX (in a similar way to the trend observed when EUAC is addressed), followed by the scenarios with air heat pumps. Similarly, omitting those scenarios where the energy system is not replaced, natural gas boilers present the lowest CAPEX values, followed by the scenarios where a compact HP is assumed, the scenarios where the implementation of an air heat pump has been assumed being those with the highest CAPEX values.

4.2. Building intervention level

The data for centralised building alternatives are depicted within scatter plots in Fig. 7. Data follow the same representation logic as for the dwelling scale, showing a general shift of the dots to the left side of

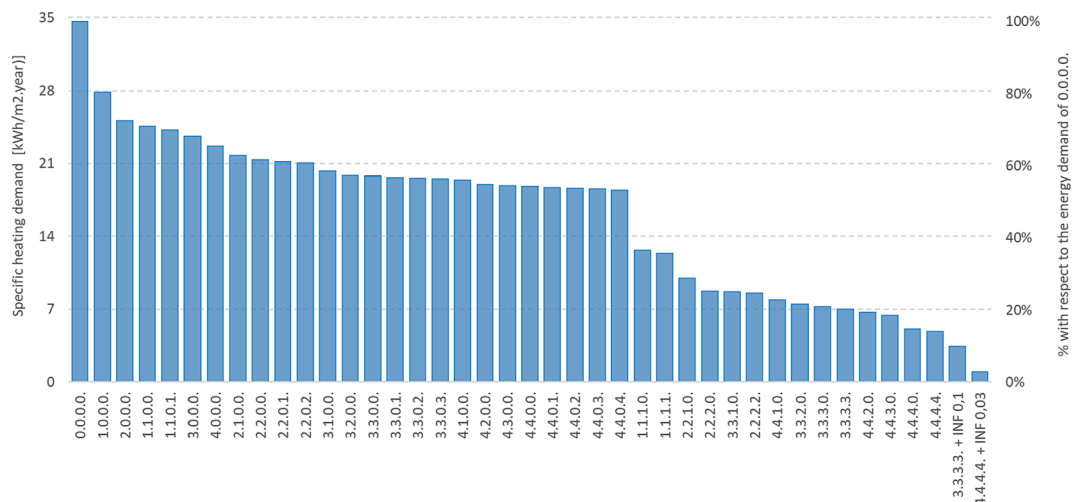


Fig. 5. Specific heating demand obtained for the 40 scenarios evaluated.

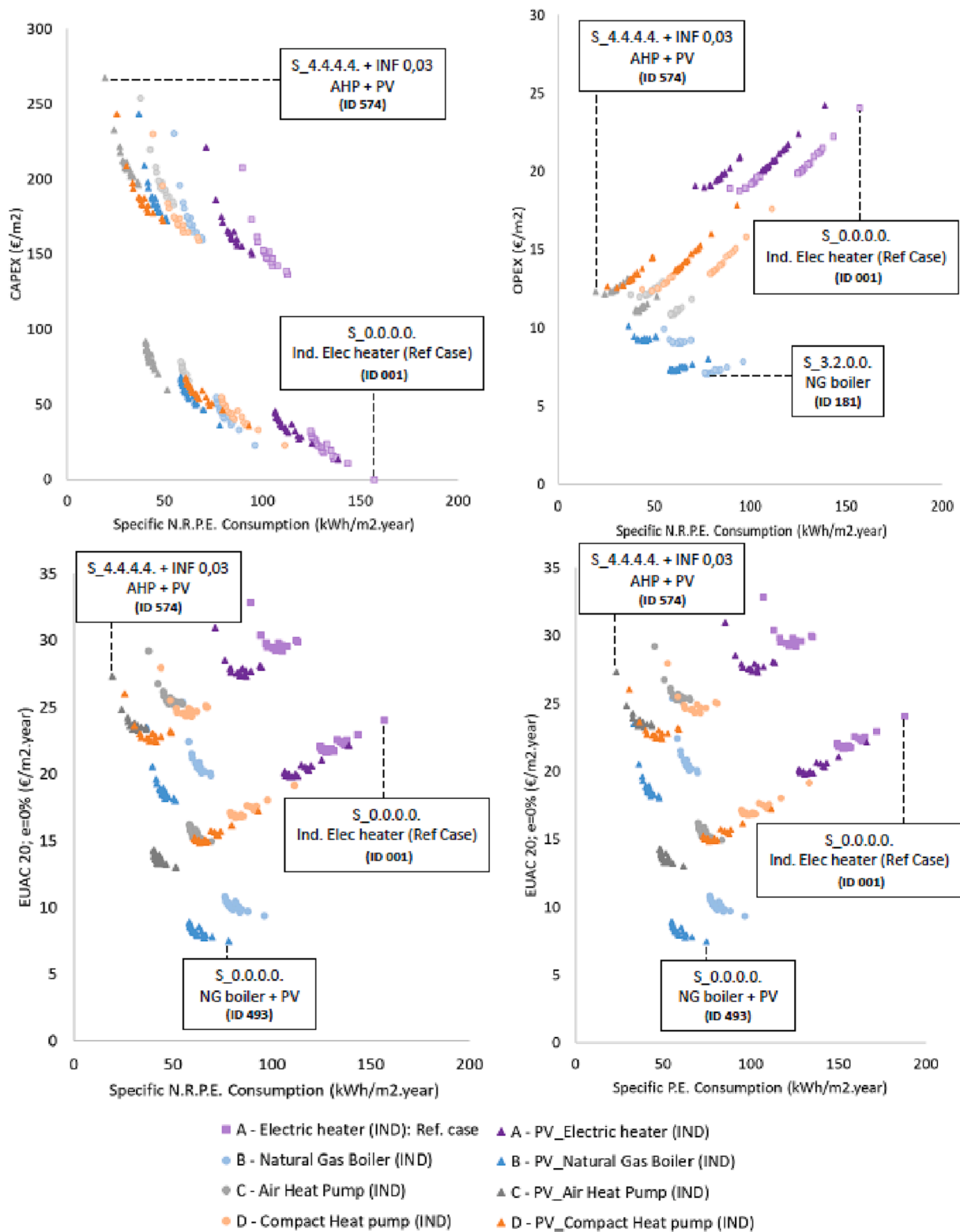


Fig. 6. Dwelling level: cost distribution (CAPEX and OPEX) and EUAC indicator in relation to non-renewable (NRPE) and primary energy (PE).

the graph. In this case, there are some scenarios very close to zero PE consumption. As previously highlighted, these values have been calculated based on the key assumption that the results presented in this paper refer only to that energy consumption data related to DHW and heating purposes, omitting the electricity requirements for other uses. Thus, negative values (in some biomass boiler scenarios) do not mean that a positive energy district is reached with that solution, but only that

the total NRPE consumption related to the heating and DHW system is compensated, as well as a part of the electricity demand related NRPE consumption.

Regarding cost-effective solutions, as in the case of individual interventions, natural gas boiler solutions still appeared as a competitive cost-effective solution, showing low values of EUAC. However, in this case, the scenarios with biomass systems are the most favourable at

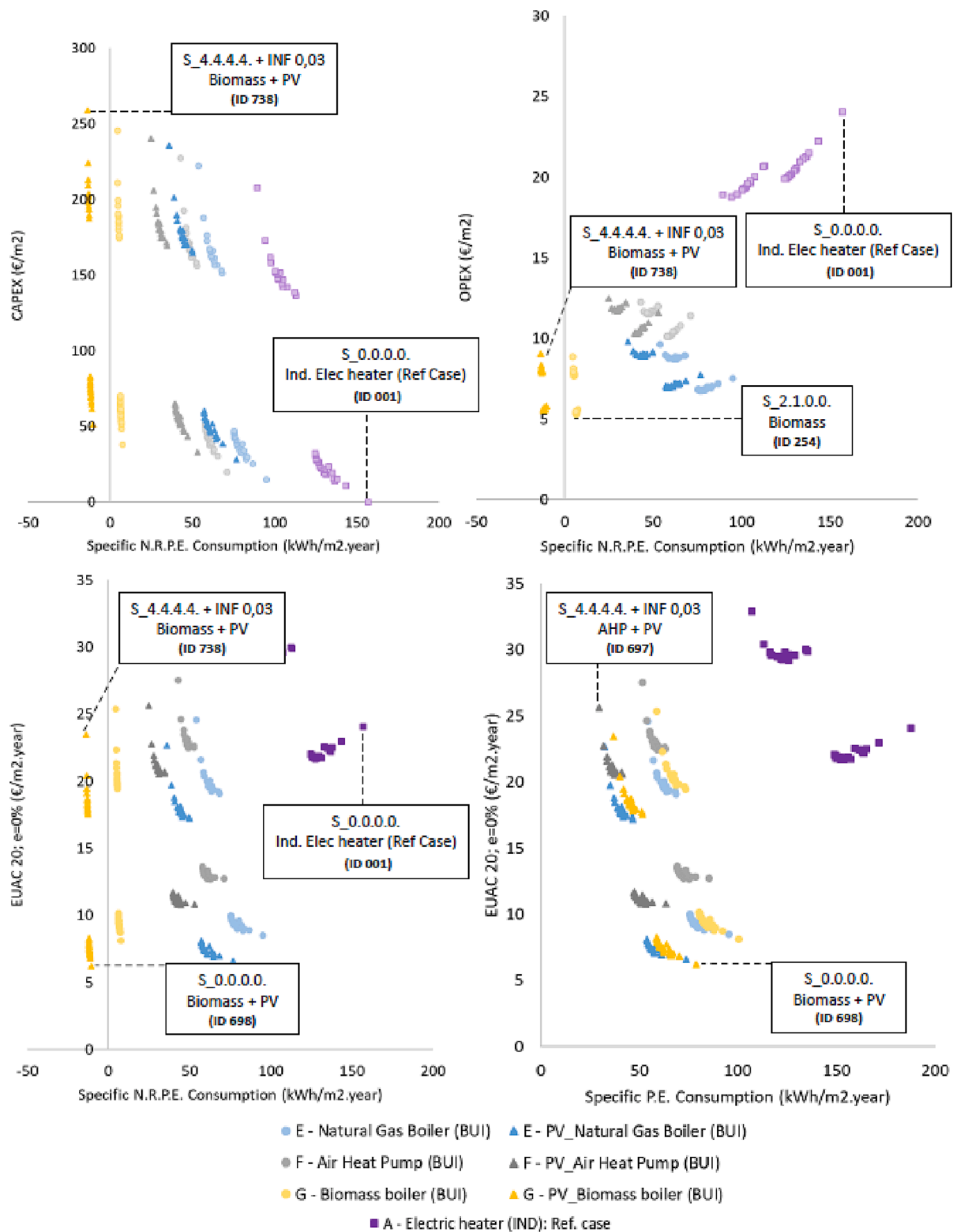


Fig. 7. Building level: cost distribution (CAPEX and OPEX) and EUAC indicator in relation to non-renewable (NRPE) and primary energy (PE).

building level, with EUAC values slightly lower than the scenarios with natural gas boilers. Namely, the cost-effective option is identified as a biomass boiler with no intervention in the envelope or windows (ID 698). Also in this case, for scenarios with biomass or natural gas boilers, the lower the intervention in the envelope, the lower the EUAC values. This trend changes slightly in the case of scenarios with an air heat pump, where the optimum level (in terms of cost-effectiveness) requires,

to some extent, an intervention in the envelope. Biomass boiler scenarios are also the best option when NRPE consumption is evaluated, reaching negative values when it is combined with PV systems. Scenarios with an air heat pump, however, take the lead when total PE consumption is considered. Thus, when a deep renovation is combined with PV and biomass boilers at building level, total PE consumption is reduced by up to 36.81 kWh/m².year (ID 697).

In this case, this advantage is offset by the initial investment required. As also shown in Fig. 7, biomass related scenarios (with or without PV) bring the highest CAPEX values, as compared to the other technologies evaluated, with values that range between 51.12 and 83.33 €/m² when windows are not replaced, and between 187.63 and 258.78 €/m² when window replacement is included in the renovation package. This is counterbalanced by their lowest OPEX values, giving as a result the aforementioned low EUAC values for this technology.

4.3. District intervention level

The district ESS solutions represented in Fig. 8 demonstrate better-positioned values with lower PE consumption and EUAC, also bringing some negative values for NRPE in some scenarios with biomass boilers combined with PV. As in building centralised solutions, biomass boilers show the lowest values of NRPE, closely followed by heat pump related solutions (first aerothermal, second geothermal). What is more, in this case, scenarios with aerothermal heat pumps forge ahead when total PE consumption is evaluated, the scenario with the deepest energy renovation combined with air heat pumps and PV system again being the one

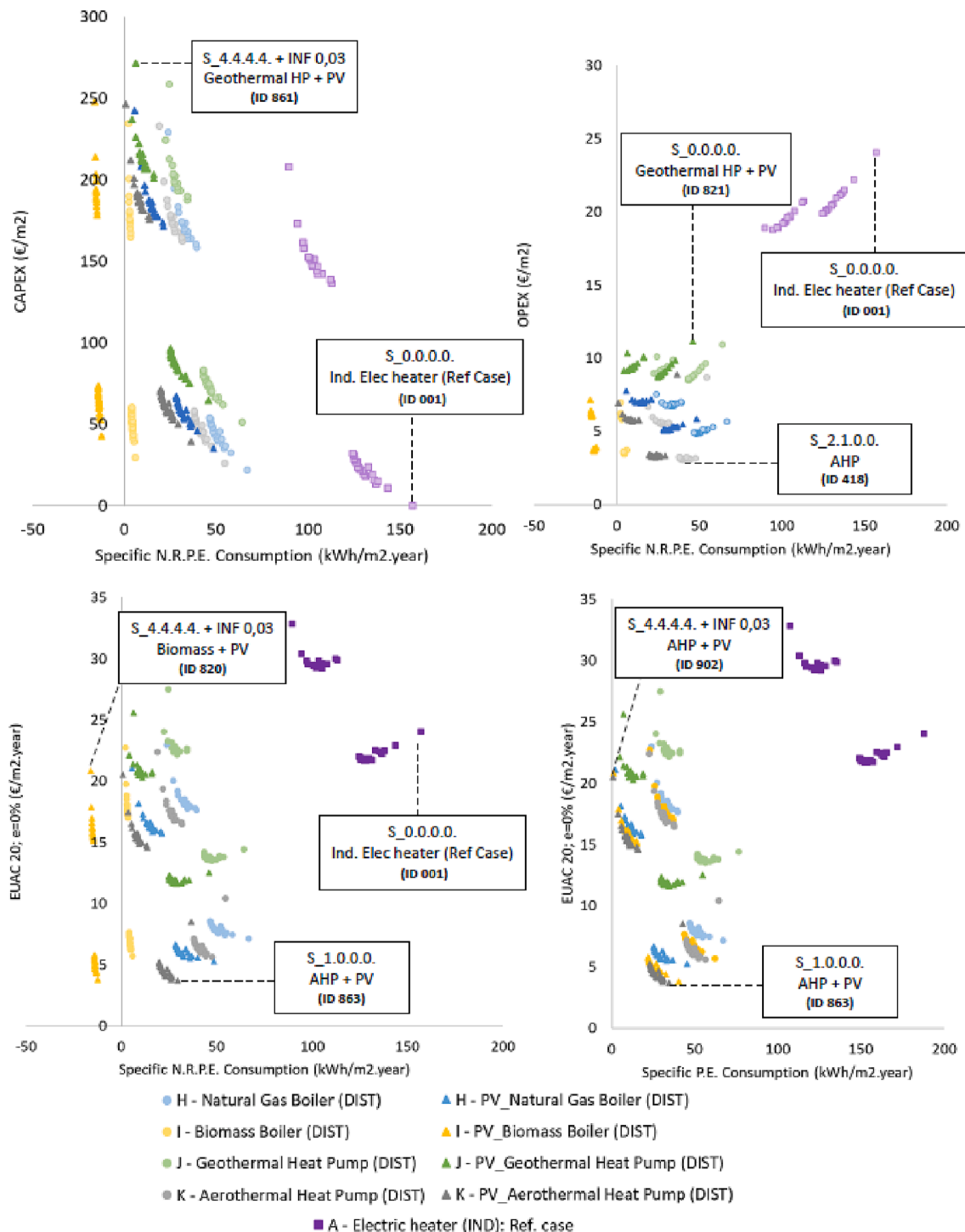


Fig. 8. District level: cost distribution (CAPEX and OPEX) and EUAC indicator in relation to non-renewable (NRPE) and primary energy (PE).

with the lowest PE consumption (0.63 kWh/m².year, ID 902).

However, when the cost-effectiveness is taken into account, scenarios with aerothermal heat pumps bring the lowest EUAC values in this case, namely, with a low implementation of ESM (1.0.0.0.) and combined with PV (ID 863). It should be noted that, in contrast to the previous sections, in this case, although the difference is slight, the lowest EUAC value is reached when the improvement of the envelope is also included in the renovation package.

In this case, when the cost impacts are split into investment and operation, geothermal heat pumps show the highest values of both CAPEX and OPEX, reaching a maximum CAPEX value of 271.78 €/m² in the case of the deepest energy renovation of the envelope combined with PV (ID 861). The maximum value for OPEX is also for this technology, reaching of 11.16 €/m².year, also when combined with PV but, in this case, assuming no energy intervention to improve the energy performance of the envelope (ID 821). On the other hand, no significant differences are found in terms of CAPEX for the rest of the technologies: e. g., when window replacement is not considered, values range between 35.29 €/m² (ID 739) to 73.82 €/m² (ID 814), mainly depending on the energy renovation assumed in the envelope and with slight differences between technologies. The lowest CAPEX values are found in those scenarios where neither PV implementation nor intervention in the envelope are assumed: the aforementioned 35.29 €/m² in the case of natural gas boilers (ID 739), 39.40 €/m² in the case of aerothermal heat pumps (ID 862) and 42.71 €/m² in the case of biomass boilers (ID 780). In terms of OPEX, the air heat pump is the most favourable technology (the minimum values are reached with a medium intervention in the envelope and without including PV, ID 418), closely followed by the biomass.

In general terms, it can be observed that the options with the lowest levels (if any) of ESM stand as “cost-effective”. It can be partially explained by the fact that the winter severity in the case study is not too high and the weight of the investment cost is not compensated by the energy savings achieved by the energy efficiency measures during the lifespan (20 years). This trend only differs in the case of those scenarios which include technologies that, either as a consequence of a poor energy performance and high energy consumption (electric heater) or its operational specificities (geothermal), the lowest EUAC is reached in those scenarios where a deep energy renovation of the envelope is assumed.

It should also be noted that, even though the aggregation of the electricity consumption of the district would enable an important share of self-consumption, it is difficult to reach the ideal 100%. A detailed analysis would be necessary to calculate an accurate value of the self-consumption ratio, which, at the same time, would also be related to the technology used for heating and DHW (e.g., potential synergies when the PV system is combined with heat pump technologies). This analysis is beyond the scope of this paper, but, at the same time, the possible energy cost variations in the future, but mainly the self-consumption ratio, play a key role when calculating the EUAC of the system. The individual systems, applied at dwelling level, appear to be the most unattractive option within the considered PE and NRPE indicators, while also considering investments and targets towards zero energy concepts, as compared to the building and district levels, which can provide nearly zero combinations with certain important assumptions described above. To discuss the results in a wider context, [section 5](#) provides key reading as well as a systematised comparative reflection on constraints, barriers and drivers at the three renovation levels.

5. Discussion

In the previous section, the cost-efficiency analysis of the retrofitting potential at different intervention levels was presented. [Table 6](#) sums up the main results for each of the implementation scales, characterising each of them by the definition of the cost-optimal and minimum-primary energy cases.

Several readings can be made from these results:

- The higher the implementation level, the higher the potential of the retrofitting action; both in terms of primary energy consumption and EUAC. This confirms the conclusion drawn by Dirutigliano et al. for a district located in Torino (Italy) [44], which can be justified by the higher efficiency and lower specific cost of energy supply systems of higher size and the broader set of potential actions when the interventions are taken from upper levels. This is also backed by the assessment carried out by other authors, who highlighted that interventions at the district level allow the identification and valorisation of site-specific potentials, which can help to increase the feasibility of the intervention [45,46]. Even though this could be taken as a general rule-of-thumb for retrofitting assessments, this is not valid for all cases, since, as stated by Pozzi et al., district solutions are not always feasible against individual systems [47].
- The development of the rooftop PV potential is selected as the retrofitting action for all the cases, since it allows the primary energy consumption to be reduced at a relatively low CAPEX increment.
- For each intervention scale, the EUAC is notably higher for the minimum primary energy consumption case in relation to the cost-optimal one. This is mainly justified by a noticeably higher CAPEX, which varies from 6 to 11 times the CAPEX of the cost-optimal cases, but also by a slightly higher OPEX for all the cases, which ranges from 1.5 to 2.2 times the OPEX of the cost-optimal cases.
- Passing from the cost-optimal to the minimum primary energy consumption case implies a significant increase in the EUAC, but it also brings an important primary energy reduction. This is not the case for the building intervention scale, where the minimisation of the consumption implies a much higher EUAC, but a limited reduction in the primary energy consumption.
- Of all the cases, the intervention at the building level shows the best compromise between EUAC and primary energy consumption. The high marginal EUAC increase needed to reduce the primary energy consumption below that corresponding to the cost-optimal does not justify minimising the primary energy consumption. Interventions at the district level only allow the primary energy consumption to be reduced for the minimum primary energy consumption case.

Building on these results, it can be seen that the energy renovation of buildings offers a great opportunity for energy reduction at reasonably affordable investment costs. However, these figures by themselves do not explain the current low rates of renovation actions in the urban environment, nor the lack of correlation between the economic feasibility of the intervention levels presented in [Table 6](#) and the actual number of interventions at those levels. Indeed, the majority of interventions are carried out at the dwelling level, despite its relatively low potential when compared to the other levels.

Although this could be partially explained by the actual lack of qualified assessments on the potential of different solutions under different conditions, it would be naïve to associate this trend with this single fact. Specifically, apart from the existing relations between economics and energy performance, other less energy-related issues can better explain the actual rate of renovation works in the urban environment. Amongst these issues, some are common barriers to exploiting the renovation potential and others are exclusive to some of the intervention levels under analysis. It should be noted that increasing the aggregation level of the intervention (i.e., from dwelling to building intervention level) implies a larger number of barriers, which explains the additional difficulties in effectively exploring the techno-economic potential of the solutions.

5.1. Common barriers to interventions at dwelling, building and district level

The assessment covered in this paper has proved that optimal

Table 6
Summary of the cost-optimal and minimum primary energy consumption for the different intervention levels.

Intervention level	Case	ESM	ESS		CAPEX (€/m ²)	OPEX (€/m ²)	EUAC (€/m ²)	NRPE (kWh/m ² .year)
			Heating + DHW	RES				
Dwelling	Cost-optimal	0.0.0.0.	B-Natural Gas	+	35.99	8.03	7.46	78.10
	Min NRPE	4.4.4.4. + INF 0,03	C-Aerothermal	+	267.36	12.32	27.30	19.46
Building	Cost-optimal	0.0.0.0.	G - Biomass boiler	+	51.12	5.79	6.24	-10.54
	Min NRPE	4.4.4.4. + INF 0,03	G - Biomass boiler	+	258.78	9.04	23.45	-13.74
District	Cost-optimal	1.0.0.0.	K - Aerothermal Heat Pump	+	49.91	3.36	3.73	29.40
	Min NRPE	4.4.4.4. + INF 0,03	I - Biomass Boiler	+	247.90	7.16	20.83	-16.08

solutions are largely case-dependent, in such a way that we can rarely talk about a “best solution” for all the intervention levels. However, when renovation actions taken in a given urban context are assessed, some biases set technological preferences that are systematically applied to any case. These preferences are the result of very different reasons, such as legal constraints, existing subsidies for certain solutions, or preferences by the contractor in charge of the renovation project. In addition, some technological options are excluded for historic buildings due to heritage protection measures.

These facts strongly limit the true economic feasibility and energy reduction potential of the interventions. Additionally, despite the efforts placed in the legal arena to promote renovation works, there is a great imbalance in the situation of the renovation sector, which currently lacks professionals with experience in this field. In some Member States, such as Spain, the energy performance of the building is still not a key factor in acquiring a house, which implicitly acts as an additional barrier to renovation. All of this aligns with the usual psychological barriers to change, explained at the same time by the traditional role of citizens as passive consumers.

5.2. Additional barriers to interventions at the building level

When moving from the dwelling to building intervention level, the number of constraints that condition renovation works increases significantly. Firstly, there is an increase in the number of agents involved, which makes the decision-making difficult due to the existence of different motivations, different tenure regimes, or socioeconomic realities. In Spain, this is governed by the Horizontal Property Act, which sets the ground for reaching joint decisions and allows the

intervention to be blocked if more than 40% of the owners oppose a certain intervention. This obstacle is reinforced by the lack of cohesion that is common to condominiums.

One important reason that prevents reaching agreements is that all the residents do not share the same starting point, which means that the economic feasibility differs greatly from dwelling to dwelling. This is explained by the fact that different residents make different use of the apartments or, even more significantly, the fact that some of the residents may have made previous interventions at dwelling level. It is a true challenge to set investment and cost-sharing ratios that consider this reality.

5.3. Additional barriers to interventions at the district level

Additionally, some specific barriers appear at the district intervention level, especially linked to the implementation of district heating networks. All the factors explored at the building level take on a new dimension at the district level. One important barrier is the decision-making that now involves many more people, many of them unknown to each other, which leads to the lack of trusting relationships that could help as a basis for the initiative. Even when decisions are taken, it is not clear how to size the installation to enable future upgrades for the incorporation of new users.

Governance is also an issue, since there is no legal form that represents the neighbours. This fact means that a new legal entity would have to be created (cooperative, energy community, association, etc.), which in turn is usually also a work-intensive process. As an alternative, neighbourhood associations can be used for this purpose, or can even be seen as an opportunity for creating energy communities of a different

Table 7
SEt of potential actions to overcome the main barriers affecting renovation at different intervention levels.

Intervention levels	Barriers	Recommendations
Dwelling, building and district	There are biases that set technological preferences	- Site-specific retrofitting assessments should be made, taking into account local construction, constraints and weather conditions. - Subsidies can help promote the technologies with the greatest retrofitting potential
	There is general lack of professionals with experience in this field Energy performance of the building is still not a key factor in acquiring a house	- Training programs can increase the number of professionals in the sector - Apart from the environmental and social, specific materials should be developed to raise social awareness of the economic and comfort benefits from retrofitting
Building and district	There are a larger number of actors involved, which makes decision-making more difficult. In Spain, the Horizontal Property Act needs 60% of the votes to make a decision.	- New actors are needed to facilitate the decision-making processes. - The Horizontal Property Act should be modified in order to ease the adoption of decisions for renovation purposes.
	Not all the residents share the same baseline situation, which means that the benefits from renovation varies from case to case.	- Cost sharing and feasibility assessment should consider a detailed definition of the reference case. - Public funds may be approved to help cover the investment needs of those facing financial problems.
District	It is not clear how to size the installation to allow for future upgrades and the addition of new users.	- Upgradability must be present from the beginning of the project. - Modularity is essential for phased construction. - Neighbors participating in the project from the beginning could recover part of the initial investment as the number of participants increases.
	In general, there is a lack of energy criteria in urban planning.	- The urban plan should be modified to include this type of development and facilitate its integration.
	There is a lack of references for this kind of actions.	- There is a need to share existing experiences and quantify their benefits. - A good practice guide can help to disseminate the benefits. - Training programmes should include these technologies - Specific business models should be developed

nature. These initiatives are hardly boosted from below; instead, top-down models are a common way for their development. Legal constraints are one of the most important barriers to the success of district-level interventions. In Spain, there is a general lack of legislation at the national level for shared energy installations, which is associated with the lack of municipal legislation and the lack of energy criteria in urban plans. As a result, there are usually conflicts with other uses of the public space.

It should be considered that the impact of energy generation can be higher when it is distributed in buildings or dwellings. As an example, biomass boilers concentrate the emissions, increasing the local impact of pollution in those areas close to the chosen location for the boiler room, which at the same time can serve as a vector for social opposition, especially from those neighbours that do not take part in the initiative. Last but not least, in Spain, there is a general lack of references for this kind of action that could serve as examples, as well as an absence of stakeholders, agents, tools, etc., to complete the necessary chain to materialise this kind of intervention. In this sense, many of the district-level interventions that exist today come from research projects working on demonstrators. This alone helps to understand the low level of penetration of interventions at the district level.

From these barriers and limitation; it is possible to develop measures and policies to mitigate them. Accordingly, a set of actions and initiatives are listed in [Table 7](#).

6. Conclusions

Addressing the rapid and cost-effective decarbonisation of the building sector is an indispensable cornerstone towards a sustainable society. This study has evaluated building renovation considering energy saving measures, energy supply systems and renewable energy sources for three different intervention levels: dwelling, building and district, for the Otxarkoaga neighbourhood in Bilbao, Northern Spain. In general terms, results have shown that NRPE values close to zero could be reached in existing buildings through deep energy renovations, when the intervention is carried out comprehensively, improving the energy efficiency of building envelopes, replacing energy systems and implementing renewable energy sources. The cost optimal values, however, usually are reached when the actions are focus on energy systems.

Although district-level interventions offer the best solution in terms of cost optimisation and allow the renovation of a large number of buildings at the same time, there are several reasons that prevent their application on a larger scale. While there are technical reasons that can

help explain this, there are also other social, environmental and material reasons that are often left out of the analysis.

It is widely known that the techno-economic benefits of housing renovation are much more limited than those of interventions at higher levels. However, for the climatic conditions of Northern Spain, the techno-economic benefits of district interventions, although they show the highest benefits in terms of NRPE and PE and EUAC energy consumption reduction, they are not significantly higher than those of building-level interventions. This is justified by the mild climatic conditions which, in contrast to Northern Europe, do not fully justify the higher investments needed to build district heating networks.

In view of this situation, it is not difficult to understand the low rates of renovation actions at district level, especially due to the additional barriers and challenges that appear when increasing the level of intervention. Among these barriers, we can list the lack of awareness and capacities; resistance to change and the passive role of users; the absence of governance tools for decisions at district level; incompatibility with other local legislations, etc. All this highlights the urgent need for comprehensive approaches that, in addition to energy and economic aspects, include measures and policies to address the identified barriers and respond adequately to the challenges of larger-scale intervention.

Data availability

Supplementary data related to this article can be found online at <https://data.mendeley.com/datasets/9gr3t3bvtt>, and open-source online data repository hosted at Mendeley [\[43\]](#).

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.

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Appendix 1. Combination of scenarios considered

Combination of scenarios evaluated (in bold, those combinations where the windows are replaced).

	Façade (S 1)	Façade (S 2)	Façade (S 3)	Façade (S 4)
Roof (base case)	1.0.0.0.	2.0.0.0.	3.0.0.0.	4.0.0.0.
Roof (S1)	1.1.1.0. 1.1.1.1. 1.1.0.0. 1.1.0.1.	2.1.0.0.	3.1.0.0.	4.1.0.0.
Roof (S2)		2.2.1.0. 2.2.2.0. 2.2.2.2. 2.2.0.0. 2.2.0.1. 2.2.0.2	3.2.0.0.	4.2.0.0.
Roof (S3)			3.3.1.0. 3.3.2.0. 3.3.3.0. 3.3.3.3 3.3.0.0. 3.3.0.1. 3.3.0.2	4.3.0.0.

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	Façade (S 1)	Façade (S 2)	Façade (S 3)	Façade (S 4)
Roof (S4)			3.3.0.3. 3.3.3.3 + INF 0,1	4.4.1.0. 4.4.2.0. 4.4.3.0. 4.4.4.0. 4.4.4.4. 4.4.0.0. 4.4.0.1. 4.4.0.2 4.4.0.3. 4.4.0.4. 4.4.4.4 + INF 0,03

Appendix 2. Specific costs of energy savings measures

Specific costs (investment and maintenance costs) of the different energy saving measures considered.

		Scenario 1	Scenario 2	Scenario 3	Scenario 4
FAÇADE	Unit (€/m ²)	5.88	10.7	15.54	20.36
	Labour (€/m ²)	5.95	5.95	5.95	5.95
	Maint (€/m ² .year)	0.024	0.03	0.044	0.053
ROOF	Unit (€/m ²)	13.6	21.4	23.96	26.54
	Labour (€/m ²)	4.8	4.5	4.48	4.48
	Maint (€/m ² .year)	0.04	0.05	0.058	0.063
WINDOWS	Unit (€/m ²)	502.2	502.6	507.2	533.6
	Labour (€/m ²)	89.0	89.0	89.0	89.0
	Maint (€/m ² .year)	6.2	6.3	6.4	6.9
Int. Part	Unit (€/m ²)	5.7	8.3	10.8	15.89
	Labour (€/m ²)	7.0	7.0	7.2	7.4
	Maint (€/m ² .year)	0.13	0.16	0.184	0.237
"Infiltrations"	Unit (€/m ²)	–	–	11.21	11.21
	Labour (€/m ²)	–	–	13.88	13.88
	Maint (€/m ² .year)	–	–	0.281	0.281

Appendix 3. Construction data

Detailed construction data of buildings envelope.

	e(m)	Conductance (W/m-k)	Capacitance (J/kg-K)	Density (kg/m ³)	Thermal resistance (m ² -K/W)
FAÇADE					
Gypsum	0.01	0.5	1000	900	
Hollow brick	0.045	0.4889	900	1200	
Vertical Air gap (No Vent)	0.04	–	–	–	0.1692
Hollow brick	0.125	0.4889	900	1200	
Fibre glass	0.02	0.04	840	12	
Hollow brick	0.045	0.4889	900	1200	
Cement mortar	0.035	1.4	1100	2000	
Façade U-value (W/m²K)	0,75				
ROOF					
Cement and sand mortar	0.01	1	1000	1800	
Hollow brick	0.045	0.4889	900	1200	
Cement and sand mortar	0.01	1	1000	1800	
Horiz. Air Gap	0.02	–	–	–	0.0792
Roof tile	0.01	1	800	2000	
Roof U-value (W/m²K)	2.842				
FLOORS AND CEILINGS					
Conifer wood flooring	0.01	0.14	2800	600	
Horiz. Air Gap	0.01	–	–	–	0.1512
Hollow tiled Floor (20 + 4)	0.24	1.0417	1000	1500	
Gypsum covering	0.01	0.4	1000	1000	
Floors and ceilings U value (W/m²K)	1,453				
INTERNAL PARTITIONS					
Cement and sand mortar	0.01	1	1000	1800	
Hollow brick	0.125	0.4889	900	1200	
Cement and sand mortar	0.01	1	1000	1800	
Indoor walls U value (W/m²K)	1.453				

Note: Composition of the windows: $U_{\text{frame}} = 5.7$ (W/m² K), $U_{\text{glass}} = 3.44$ (W/m² K). The original summary of data regarding façade, roof and windows construction details available in [33].

Appendix 4. District ESS technologies specific cost nonlinearity equations

Technology	Specific Cost (€/kW _{th})
Conventional natural gas boiler [46]	$c = 1,589.7 \bullet P_r^{-0.475}$
Biomass boiler [46]	$c = 1,584.4 \bullet P_r^{-0.305}$
Air-to-water heat pump [46]	$c = 381.99 \bullet P_r^{-0.144}$
Geothermal heat pump [47]	$c = 1600 \bullet P_r^{-0.11}$
Water tank [47]	$(-64 \bullet load + 184000) \bullet 10^{-3}$
DH piping network [47]	$c = (270 + 2.2 \bullet DN_{pipe}) \bullet (1 + f_{GroundCondition}) \bullet (1 + f_{PipingSyst})$

Note: The ground formula is based on ground condition “inner-city area”. The factors $f_{GroundCondition}$ and $f_{PipingSyst}$ describe correction factors that reflect different construction areas and pipe materials. In this study, it was assumed + 0.25 (inner-city areas) for $f_{GroundCondition}$, and + 0.4 (steel jacket pipe) for $f_{PipingSyst}$.

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