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The role of the design and operation of individual heating systems for the energy retrofits of residential buildings

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ABSTRACT

The feasibility of individual natural gas fired boiler-based heating systems in the retrofitting of buildings constructed in the 50-60s in Bilbao (northern Spain) is evaluated in this paper. A holistic approach through dynamic simulations using TRNSYS is employed for the purpose. An existing dwelling previously monitored and used to validate the model applied is selected as a case study. 54 different scenarios are evaluated, which arise from the combination of 3 different envelope options, 2 types of heat production units, 3 heat production temperatures and 3 comfort temperature set-points. The cases are evaluated in terms of energy results, economic aspects, and the influence of user behaviour. Regarding the latter, the influence of the potential rebound effect is also evaluated. The results show energy savings nearby 10% when condensing boilers are compared with high efficiency boilers. In relation to hot water production temperature, energy savings between 5 and 10% are found when the temperature is lowered from 60 to 50°C. The greatest impact on energy consumption is related to the occupants' behaviour: reductions up to 89% are achieved if the indoor temperature set-point is lowered

2°C. This is reinforced with the results related to the rebound effect, which show significant differences on energy consumption values. These evidences demonstrate that the user behaviour is an essential feature to be considered in studies regarding buildings energy performance. As a consequence, the holistic approach herein employed emerges as a key tool to be applied in further works related with the topic.

Keywords: *Energy supply systems; Holistic approach; Building Energy Retrofit; Energy efficiency; Rebound Effect*

Nomenclature

BAU	Business as usual
BO	Best option
C	Theoretical heating energy consumption (calculated)
C_{op}	Operating cost
C_{en}	Current cost of energy
CB	Condensing boiler
DHW	Domestic Hot Water
E	Actual energy consumption
e	Annual escalation rate of energy
ESM	Energy Saving Measures
I	Current cost of investment
LTB	Low temperature natural gas boiler; High efficiency boiler
LCC	Life Cycle Cost
NR	Non-retrofitted
P_{eff}	Effective thermal power
P_{EN442}	Nominal thermal power per length (EN-442)
PLR	Part load ration
r	Discount factor
RE	Rebound Effect
T_{eff}	Effective temperature
TRV	Thermostatic valve

1 Introduction

Nowadays, the building sector is responsible of 40% of the overall primary energy consumption in Europe as well as one third of related global greenhouse gas emissions [1]. According to the United Nations Environment Programme, the building operational phase accounts for 80-90% of those emissions, consisting of the energy use for heating, cooling, ventilation, lighting and appliances [2]; therefore, each action directed towards increasing energy efficiency of buildings and reducing their primary energy consumption is of great importance, as it can be inferred from the numerous regulations set up during the last decade [3]. These regulations were originally focused on new construction;

however, the existing building stock is the main challenge for a substantial reduction of the energy consumption. As a result, considerable work has been done throughout the latest years to get a suitable normative framework for facing this challenge [4].

For the specific case of Spain [5], 56% of the 26 million dwellings existing by 2011 were built up before the first Spanish thermal regulation on buildings (NBE-CT 79) came into effect in 1980. Therefore, there is a doubtless requirement for retrofitting in order to meet the European objectives on 20% primary energy consumption reduction [6]. This can be achieved applying energy saving measures (ESM); reducing the energy demand through the improvement of the thermal performance of the building envelope, and/ or implementing more efficient energy systems.

As far as energy systems are concerned, several works have been recently published. Defu Che et al. [7] evaluated the upgrade of a conventional gas boiler into a condensing boiler, focusing on the boiler itself, and leaving out of scope its interaction with the building and its users. Deng et al. [8] evaluated energy supply concepts for zero energy residential buildings in two different climates, by means of simulations. M. Owrak et al. [9] evaluated experimentally and by means of simulations the thermal performance of a room heated with an attached sunspace, which included water tanks with the aim of increasing the heat storage capacity. Focused on thermal installations, Obyn and van Moeseke [10] evaluated for the case of Belgium different heating systems in the renovation of an attached house. They concluded that for highly insulated dwellings, the optimum system is the most simple in terms of composition. Also for Belgium, Vrijders and Delem [11] underlined that condensing gas boilers are the cheapest heating system with low emission level. Tagliabue et al. [12] analyzed three solutions (gas condensing boiler, air source heat pump and ground source heat pump) for a residential building in Milan (Italy). It was proved that heat pumps perform better than gas condensing boilers, being the ground source heat pump the most profitable solution. Anastaselos et al. [13] carried out a comparative analysis between different technologies for a semi-detached house in Germany. Amongst the cases under evaluation, natural gas boilers showed to be the best option from an economical and environmental point of view. Nagy et al. [14] demonstrated that the implementation of a suitable low temperature heating system can be the best solution for existing buildings, even when no ESM is applied to the envelope.

User behaviour is an additional factor to be considered on energy consumption. Its influence can be even larger than the building characteristics or other factors [15-17]. Many studies have pointed out noticeable differences in energy consumption for similar buildings [18, 19] due to the occupants' behaviour. The existing relation between behavioural patterns, user profiles and energy use was demonstrated in [20]. To illustrate this point, the energy use obtained from a field survey in 110 similar dwellings was presented in [21]. The dwelling with the maximum consumption showed an energy use 12 times higher than that dwelling with the minimum. This effect is even greater when the social building sector is analysed, as shown by Brunner et al. in [22].

The rebound effect (RE) [23] is another factor to be taken into account. It is defined as the direct increase on demand for an energy service as a result of improvements in technical efficiency in the use of energy [24, 25]. The so-called backfire occurs when the fuel use actually increases as a result of that fuel efficiency gain. Even though empirical studies suggest that backfire is not usual, many research works prove that actual energy savings in building renovations are hardly ever proportionate to the energy efficiency improvement. Whereas RE focuses on over-consumption after an energy renovation, prebound effect concept is based on the evidence of under-consumption prior to or in the absence of energy renovations [26]. The link between prebound effect and energy savings shortfalls in renovations has been studied in depth by R. Galvin [27-29], while implications of the RE in building renovations have been widely analysed in studies such as [30-32]. In some cases, the rebound effect is recognised as a co-benefit which involves social advantages like healthier conditions [33]; in others, it involves an increase of internal temperatures without occupants demanding it [34]. Despite the difficulties of quantifying these effects, Galvin and Sunikka asserted that it generally lies within the range of 10-35% [26].

Up to now, no work has been found in the literature dealing with the combined analysis of heating system and envelope retrofitting; heating system operation and user behaviour. Thus, the objective of this paper is to evaluate, under a holistic approach, the feasibility of individual natural gas fired boiler-based heating systems in the retrofitting of buildings/dwellings constructed in the 50-60s in Bilbao (northern Spain). This type of building stock has a great energy performance improvement potential, as it has been already shown in other studies [35, 36]. It should be noticed that several of these buildings in northern Spain, especially social housing, have no heating system and the dwellings are usually heated up by individual electrical radiators. Considering the absence of a central heating infrastructure and the wide availability of natural gas networks in the area, individual gas boilers appear as the most feasible option for heating installation upgrade.

The evaluation is carried out over a reference dwelling selected as a case study. This dwelling was presented in a previous paper where the authors analyzed the building envelope ESMs as a first step for energy renovation of buildings at the mentioned location [36]. For that purpose, the dwelling was modelled in TRNSYS and experimentally validated [37]. The work is herein extended, including the upgrade of heating systems and their operation as a second step for energy renovation. Different options will be studied in combination with three envelope options already analysed in [36]. An integral dynamic simulation using a validated TRNSYS model will be used for the purpose. With this aim in mind, the experimentally validated TRNSYS model used in [36] will be adapted and broadened in order to include a detailed heating installation along with the building. The energy and economic results will be evaluated, considering the interrelationship amongst the natural gas boiler technology (low temperature and condensing); its operation (hot water production temperature) and the user behaviour (indoor air set-point temperature). Regarding the latter, the influence of the rebound effect will be also addressed.

The article provides two main significant contributions to the literature published so far. First, the existing lack of studies devoted to heating system upgrades in social housing buildings under mild climates is aimed to be addressed. The study is focused on retrofitting, which can be considered the actual challenge to be faced in the following years. Moreover, the simulations are performed under realistic conditions by means of an existing dwelling and using of a validated dynamic model. Second, the study will be carried out using a holistic approach, where the user behaviour and the (p)rebound effect will be evaluated along with energy and economic aspects. The article will demonstrate that these effects, rarely considered in the related literature, are an essential feature to be taken into account in further studies focused on buildings energy performance.

The remainder of this paper is organized as follows: In Section 2 the methodology and main assumptions adopted and the TRNSYS energy modelling are described. In Section 3, the case study is detailed and the scenarios considered are defined. The evaluation criteria are described in Section 4. Section5 presents the results, while their discussion appears in Section 6. Finally, the main conclusions are addressed in Section 7.

2 Modelling approach

The energy renovation in a building or dwelling generally consists of the energy demand reduction by improving the thermal performance of the envelope and, subsequently, the production of such demand by more efficient energy supply systems. While the envelope retrofitting was covered in [36], in this paper the heat production systems upgrade is faced. Every heating system consists normally of the following elements: (1) heat production unit; (2) terminal units and (3) control system. The integration of these three elements makes up the heating installation. The characteristics of each of the elements for the system involved are detailed next.

2.1 Heat production unit

Considering that the building stock in northern Spain is mostly comprised by individual electrical heating systems [35], only individual systems are taken into consideration in this paper. Amongst the different individual heating systems available, natural gas boilers are selected, owing to the wide natural gas network existing in the region.

Natural gas boilers can be nowadays divided into two categories: high efficiency boilers (LTB) or condensing boilers (CB). Both technologies have a common operation basis, being the difference that condensing boilers recover part of the latent heat content of the exhaust by condensing their vapour water content through heat exchange with the water returning from the load side. Accordingly, the lower the temperature of the returning water, the higher the condensing level and the efficiency [38]. Besides, in boilers with modulating burners, the lower the part load operation, the higher the efficiency, since the lower flow rate of fumes implies a better heat recovery rate. This trend is maintained until a limit PLR (Part Load Ration) is reached (namely 10-15%). Below that point, the efficiency suddenly drops and thus, this condition is usually prevented by the boiler burner control. The dependency between the thermal efficiency and the return temperature and PLR can be found in Fig. 1.

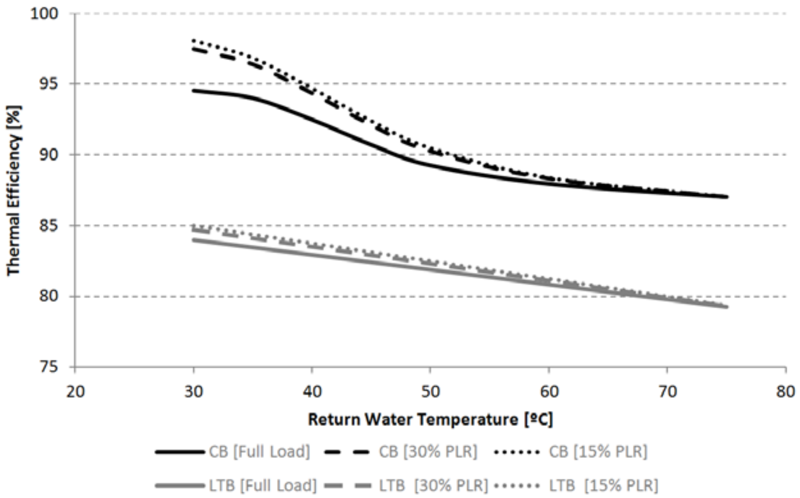

Fig. 1. Thermal efficiency relationship for high efficiency boilers (LTB) and condensing boilers (CB); adapted from [39]

As it can be seen, condensing boilers perform better than non-condensing ones, especially when the return temperature is lowered below the condensing temperature (around 50°C-55°C for natural gas) and when part load operation is boosted. This is closely related to the selection of the terminal unit and the control of the whole installation, which are subsequently discussed.

2.2 Terminal unit

Radiator networks are chosen as terminal units, because they are the most common option in natural gas boiler installations. These units were originally sized for a high temperature operation; however, their design has been updated for operation at lower temperature levels with inlet temperatures around 55-60°C, being the return temperature a function of the thermal load and the radiator thermal efficiency. Their effective thermal power can be related to the design performance by Eq. 1 [40], where *n* is a coefficient considered equal to 1.3 for natural convection.

Eq. 1

The performance values are given by the manufacturers following the EN442 for a 50K temperature difference between the water average temperature and the room temperature (being commonly 70°C and 20°C, respectively) [40]. Accordingly, an average temperature of the radiator of 50°C would give a 30K temperature difference, which results in a 50% reduction of the nominal power of the units. This makes necessary to increase the radiator length in order to lower the operation temperature when condensing boilers are used. Therefore, a relation between the radiator length increase and the operation temperatures is required. This is presented in Fig. 2, being the flow rate assumed constant.

Fig. 2. Relationship between radiator average temperature and radiator length increment

The shadowed area of the plot remarks the operation points where condensing occurs (when the return temperature (T_{outlet}) is below 55°C according to Fig. 1). As it can be seen, it requires longer radiator (Δl_{rad}) units, which increase exponentially as the operation temperature drops. This means a bigger investment for the heating systems renovation which will affect the economic feasibility.

Another alternative for reaching low return temperatures is to employ the radiant floor technology as terminal unit. This system works at a lower temperature, being the inlet water temperature around 40°C. This fact ensures the condensing effect, but it also presents a higher initial investment and technical complexity. For that reason, this option is not very common on retrofitting works of social household in Spain, and thus, it has been considered out of the scope of this study.

2.3 Control system

Heating systems can be controlled acting over one of the following variables: (1) On/Off control of the heating system; (2) control over the water delivery temperature; and (3) control over the water mass flow rate.

The On/Off control is usually made by a thermostat, which is usually placed in the living room. The user specifies the temperature below which the heating system is activated. The control presents certain hysteresis in order to avoid too fast On/Off sequences. This hysteresis cycle is around 1°C downward.

The control over the water delivery temperature is regulated by the boiler. Modern boilers allow part load operation with the aim of meeting a given set-point temperature. This temperature can be modified by the user separately for space heating and DHW. Therefore, from a practical point of view, the hot water supply temperature can be considered as constant in individual boiler systems and then, the burner is regulated in order to meet it.

Regarding the control over the water mass flow rate, this possibility presents two options: acting directly over the flow rate by the use of variable speed pumps, or acting over the pressure drop of the heating loop by the use of valves. However, none of these options are included in this paper since individual boilers integrate their own single speed pump and the pressure drop-based control could imply noise and higher pump head, and therefore, higher pumping costs.

Additionally, the flow rate of the water that flows through each terminal unit can be controlled by a three way valve, bypassing part of the flow. This can act over the heat delivered by the terminal units, but is not useful for reducing the temperature of the return water, since the bypassed flow is mixed with the water exiting from the terminal units.

2.4 TRNSYS energy modelling

The dwelling, along with the heating system, is simulated with TRNSYS simulation software. The main features of the dwelling will be presented in Section 3. The model and its experimental validation were already detailed in [36]. In the current work, the heating system model is integrated into it. The analysis performed evaluates the performance of different systems made up from the combination of: high efficiency and condensing natural gas boilers as heat production units; radiators as terminal units; and different water supply temperatures and indoor air set-point temperatures.

The natural gas fired boiler is simulated using the Type 700 simple boiler model developed by TESS [41]. A thermal power of 24 kW is considered as typical for this kind of boilers. The thermal efficiency for both high efficiency and condensing boilers are obtained from Cockroft et al. [39]. The On/Off operation of the boiler is controlled by Type 2b that switches it off when the air temperature of the reference room (living room) is reached. A hysteresis of ±0.5°C is included in order to guarantee a smoother operation. The pump is integrated in the boiler and modelled within it, being controlled by the room thermostat. In the simulations, only the thermal production for space heating is considered, neglecting the operation of the DHW. The energy consumption for DHW production is added *a posteriori* for the economic evaluation, as detailed in Section 4. This assumption does not have significant influence on the results, since the model does not take into account the thermal mass of the boiler.

Radiators are modelled by a self-tailored type, implemented as Type 211. The model consists of a lumped capacity model which is based on a first-order differential equation that accounts for the thermal inertia of the radiator. The heat delivered at any instant by the radiator at different operation conditions is obtained by applying Eq. (1). The heat released by each radiator is introduced as heat gains to each zone, a typical convective/radiative ratio of 80/20 can be considered.

Piping from the boiler to the terminal units acts as heat emitters (thermal losses are released to the ambient) and adds thermal inertia to the heating installation. They are modelled by Type 31, a single-node pipe model. Radiator networks in dwellings are better arranged by double pipe configuration; thus, water enters radiators at the same temperature and thermal unbalance is avoided. A water flow rate of 10 l/min is considered and distributed to the different rooms according to the nominal power of the radiators. Each radiator has a thermostatic valve (TRV) that bypasses the hot water when the indoor air temperature set-point is reached; this is modelled by Type 2b.

The TRNSYS model scheme is presented in Fig. 3, where the different information flows are represented by different colours, showing the main components and connections. For the sake of clarity, only 2 rooms have been presented. Simulations are run using a 6 minute-time-step, in order to include the dynamic effects of the different elements of the plant.

Fig. 3. Scheme of the TRNSYS model for the radiator based heating system

3 Case study

A building case study located in Bilbao, Spain (latitude: 43 ° N, longitude 2.9 ° W) and presented in [36] is used in this paper (see Fig. 4). The climate for the studied area is oceanic, with temperate summer and winters and low intensity thermal oscillations. The average maximum temperature is nearby 25 °C during summer, while the average minimum in winter is around 6 °C. A 60 m^2 dwelling of the building was selected for the purpose. It was previously monitored in [37] and used as reference to validate the TRNSYS model of the building.

Fig. 4. General view of the building case study, where the selected dwelling is marked by a red rectangle

The operating conditions assumed in the model are those presented in [36], with the only exception of the indoor set-point. In this case, in order to evaluate the influence of this parameter on the energy behaviour of the system, three different constant values have been assumed: 19, 20 and 21 °C.

Three of the ESMs analysed in [36] have been herein considered. The NR (non retrofitted)* scenario presents 2 cm of thermal insulation in façade, no thermal insulation in the roof and double glazed windows with PVC frame. The BAU (business as usual) option is an intermediate and usual level of energy renovation of the thermal envelope, with 6 cm of thermal insulation in façade, 6 cm of thermal insulation in roof and the same double glazed windows with PVC frame used in NR. Finally, the BO (best option) scenario is a high level renovation choice which presents 14 cm of thermal insulation in façade, 20 cm of thermal insulation in roof and triple glazed windows with PVC frame. These three options are combined with the two heating options presented in Section 2.2. Table 1 summarizes the main characteristics of the selected envelope scenarios, where the investment is made in relation to the NR scenario.

	U-Value [W/m²·K]			UA [W/ K]	Building heating Dem. [kWh/m²·year]	Investment
MODEL	Façade	Roof	Windows			
NR (non retrofitted)	0.74	2.7	2.76	80.28	39.67	-
BAU (Business As Usual)	0.43	0.53	2.76	59.95	29.84	529.75 € (8.83€/m²)
BO (Best Option)	0.24	0.19	1.15	32.99	15.43	6545.22 € (109.09 €/m²)

Table 1. Summary of the thermal properties of the building after applying the envelope ESM, and the investment cost of each retrofit proposal.

*For the sake of clarity, the nomenclature used to define each scenario in the present paper has been modified in relation to Ref. [36]. The options herein termed as NR, BAU and BO correspond to the former scenarios 0.0.1; 1.1.1 and 3.3.3, respectively.

The effective UA is calculated using the U values presented in Table 1 and taking into account the thermal envelope area of the dwelling case study. The building heating demands are those obtained in [36]. The envelope upgrade cost (investment) is calculated in relation to the NR scenario and is based on the data presented in [36]. In the case of the façade, it is calculated taking into account the façade area corresponding to the household and the cost per m^2. In the case of the roof, considering the cost per m^2, the renovation cost is shared equally amongst the households of the building (36 dwellings, in this case). Only the specific cost of the addition of thermal insulation (both material and labour costs) is considered, since these actions are usually carried out when general maintenance of the façade is necessary and very rarely due to exclusively thermal demand reduction. Finally, the cost of replacing windows (only under BO scenario) is calculated following the methodology proposed in [42]. Every price values proposed include VAT and labour costs. However, they do not include any renovation subsides.

In Fig.5, the floor plant of the dwelling is presented, where the general scheme of the heating system has been depicted. The main characteristics of the radiators are presented in Table 2. They are sized using the ASHRAE method for heat losses determination of each room [43] and considering the length increment arising from reducing the supply temperature in relation to the nominal conditions (Eq. (1)). A security factor of 1.2 is applied to the resulting size. The lengths of the radiators for each configuration are presented in Table 3.

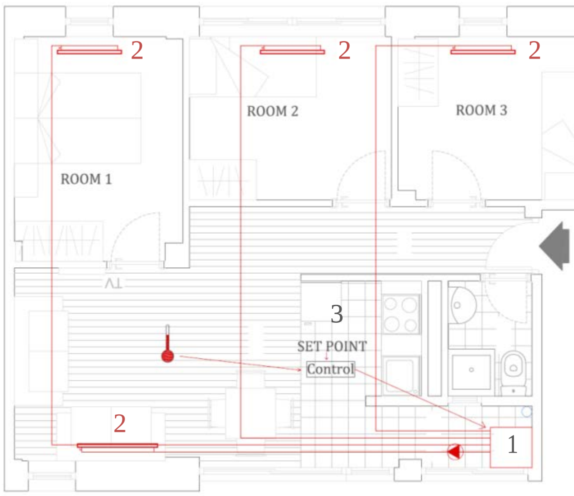

Fig.5. Heating system considered in this assessment (1: boiler; 2: Terminal units; 3: control system)

Nominal thermal power per length (P_{EN442}/l)*	1778 W/m
Thermal capacity	1142 J/kg·K
Height of the radiator	1.5 m/0.6 m **

**Nominal for 75 °C inlet temperature, 65 °C outlet temperature and comfort temperature of 20 °C*
*** In the BAU case, to supply 2225W in the living room and 890W in each bedroom, calculated considering a comfort temperature of 20 °C.*

Table 2. Main characteristics of the radiator

Heat production set-point Temp.	60	55	50
(P_{EN442}/l) [W/m]	1330.3	1118.3	915.2
[NR] Radiator length (living room) [m]	2.5	3	3.7
[NR] Radiator length (bedrooms) [m]	0.9	1.1	1.3
[BAU] Radiator length (living room) [m]	2.0	2.4	2.9
[BAU] Radiator length (bedrooms) [m]	0.8	1.0	1.2
[BO] Radiator length (living room) [m]	1.1	1.3	1.6
[BO] Radiator length (bedrooms) [m]	0.45	0.55	0.65

Table 3. Size of the radiators for the different spaces and different heat production set-points

The evaluation is made parametrically using the design variables summarized in Table 4. Each heating system parameter combination (18 possible combinations) is applied assuming the three different envelope scenarios presented in Table 1 (NR, BAU and BO) making up a total of 54 scenarios. Regarding nomenclature, scenario NR.LTB.55.21 corresponds to a non-retrofitted dwelling with a low temperature natural gas boiler connected to radiators, being the heat production set-point and the air temperature set-point, respectively, 55 and 21°C. This format will be used from now on in the paper.

Heat Production Boiler	Terminal Unit	Heat production set-point	Comfort temperature set-point (*)
Low temperature natural gas boiler (LTB) Condensing natural gas boiler (CB)	High efficiency radiators (R)	Low (L): 60°C Medium (M): 55°C High (H): 50°C	Low (L): 19°C Medium (M): 20°C High (H): 21°C

Table 4. Design variables for the heating system design

4 Evaluation criteria

The analysis of the results of each combination is based on energy and economic results. The implications of the user behaviour and rebound effect were also considered. Additionally, indoor comfort has been analyzed through the room air temperature, in order to check that the different scenarios guarantee similar comfort conditions. All these criteria are described next.

4.1 Energy analysis

The different renovation scenarios are compared to a reference case corresponding to the not-retrofitted envelope (NR), where heating and DHW demands are supplied by electrical systems, and considering the energy demand needed to meet the same air temperature set-point that of the case it is compared with.

The heating energy consumption for each scenario is obtained by the model defined in Section 3. The energy consumption for DHW production is calculated from the DHW demand and taking into account the seasonal energy performance of each system. An average value of three occupants and a water consumption of 30 l at 60 °C per day and person is considered, which gives a demand of 90 l/day. This value is in accordance with the literature [10, 44-47]. The water is assumed to be heated up from the water supply monthly mean temperature to the DHW temperature set-point (60°C). As result, the calculated DHW energy demand is 1800 kWh/year. Considering this value, different energy efficiencies have been assumed for each energy system in order to calculate the energy consumption for DHW: 100% for the electric boiler of the reference case; a 95% for the LTB case; and a 85 % for CB. The efficiencies for both LTB and CB cases were estimated based on the thermal efficiency for low temperature at a high PLR (Fig. 1.).

The corresponding annual consumption of primary energy is calculated by means of conversion factors, calculated for the electricity mix and gas supply conditions of Spain: 1.195 kWh_{prim}/kWh for natural gas and 2.368 kWh_{prim}/kWh for electricity [48].

4.2 Economic analysis

Economic results include both investment and operating costs. Two different evaluation criteria are adopted, depending on how the investment is considered. Approach (A) calculates the investment cost as the addition of the investment of the energy system and the envelope upgrade. The starting point is the NR scenario with electric boiler and every retrofit work is evaluated regarding that reference scenario. Approach (B) consists of focusing just on the energy system; that is, to evaluate the economic issues of the energy system in regard to three different levels of "envelope thermal efficiency". Thus, the reference scenarios are: NR with electrical system, BAU with electrical system and BO with electrical system.

In order to evaluate the economic feasibility of each scenario, the life cycle cost is estimated according to Eq. 2. There I represents the investment cost (€), and C_{op} is the operating cost of the system (€), both calculated for the lifespan of the system (30 years). The procedures to estimate these two factors are detailed next.

$$LCC = I + C_{op} \quad \text{Eq. 2}$$

4.2.1 Investment cost

The investment cost is calculated from the addition of the individual cost of the elements that comprise the system, i.e.: the boiler selected; radiators (whose cost will depend on their length); piping installation and connection to the natural gas distribution system (these last costs are equal for all scenarios). The exhaust exit cost is assumed to be negligible since it is straight to the façade. The indoor temperature set-point temperature is user-dependent and is not considered in the sizing of the system, where a standard temperature of 20°C is generally considered.

The calculated investment costs for each scenario are summarized in Table 5. They were derived from Spanish market prices and, while they include VAT and labour costs, no renovation subside is included. As observed in Table 5, the deeper envelope retrofit (NR-BAU-BO) is, the less energy losses through the envelope will be. This results in smaller and thus more economical radiators. At the same time, and as shown in Fig. 2, the lower the heat production temperature is, the longer the radiators, which increases the investment cost will be.

	LTB.60	LTB.55	LTB.50	CB.60	CB.55	CB.50
NR	3728 €	4000 €	4238 €	4128 €	4400 €	4638 €
BAU	3575 €	3813 €	4017 €	3975 €	4213 €	4417 €
BO	3184 €	3269 €	3388 €	3584 €	3669 €	3788 €

Table 5. Summary of the investment cost of the energy system according to each scenario

4.2.2 Operating cost of the system

The operating costs of each scenario are calculated by assessing the cost of the annual energy consumption related to the heating and DHW production by means of Eq. 3. There C_{en} accounts for the current cost of energy (€); e represents the annual escalation rate of energy less general inflation (%) and r is the discount factor (%).These two last factors allow including the future energy and economic scenarios.

$$C_{op} = \sum_{n=1}^{LS} C_{en} \cdot \left(\frac{1+e}{1+r}\right)^{n} \qquad \text{Eq. 3}$$

The values for the cost of energy for Spain are obtained from the Eurostat [49]: 0,2309 €/kWh for electricity and 0,073152 €/kWh for natural gas. An increment of 4% in the energy cost and a discount rate of 4% have been assumed as a basis, according to the criteria presented in [36]. Maintenance costs are neglected since it is common ground for all the options under analysis.

4.3 (P)rebound effect analysis

With the aim of evaluating the consequences of a potential indoor temperature increase after renovation works as a result of a higher efficiency in the use of energy, the (p)rebound effect (*P)* is quantified.

Amongst the different forms of rebound effect existing in the literature [50], only direct effects are considered in this paper. They are calculated by Eq. 4 [26].

$$P = \frac{C - E}{C} \qquad \text{Eq. 4}$$

There, C is the theoretical heating energy consumption (calculated), which is obtained considering that the indoor temperature set-point after retrofitting is the same to that it was before. E is the actual energy consumption, and is determined assuming a given increment of the indoor temperature set-point after energy efficiency upgrades. Two increment values are considered: 1 and 2 °C. In both cases, the assumed indoor temperature set-point before the energy efficiency upgrades is 19°C [35]; thus, the set-point temperature after the energy efficiency upgrades is considered to be 20°C and 21°C.

5 Results

The general results of the 54 scenarios are herein presented and discussed. Prior to the evaluation, the comfort conditions were analyzed for all the cases in order to check the actual behaviour of each installation in relation to the theoretical design. The actual air temperature was qualitatively compared to the set-point, showing good agreement. A simple analysis of the comfort was made by considering the number of hours in which indoor temperature is below 18 °C. Similar conditions were obtained for all the scenarios, where the number of hours below 18°C ranged between 0 and a maximum value of 37 hours, depending on the indoor temperature set-point. Thus, it can be stated that all the selected designs were adequate.

5.1 Energy results

Heating consumption for each scenario is depicted in Fig. 6. Data are distributed by the different envelope retrofitting options, energy supply systems and hot water production temperatures. Additionally the effect of the indoor air temperature set-point can be seen for each case.

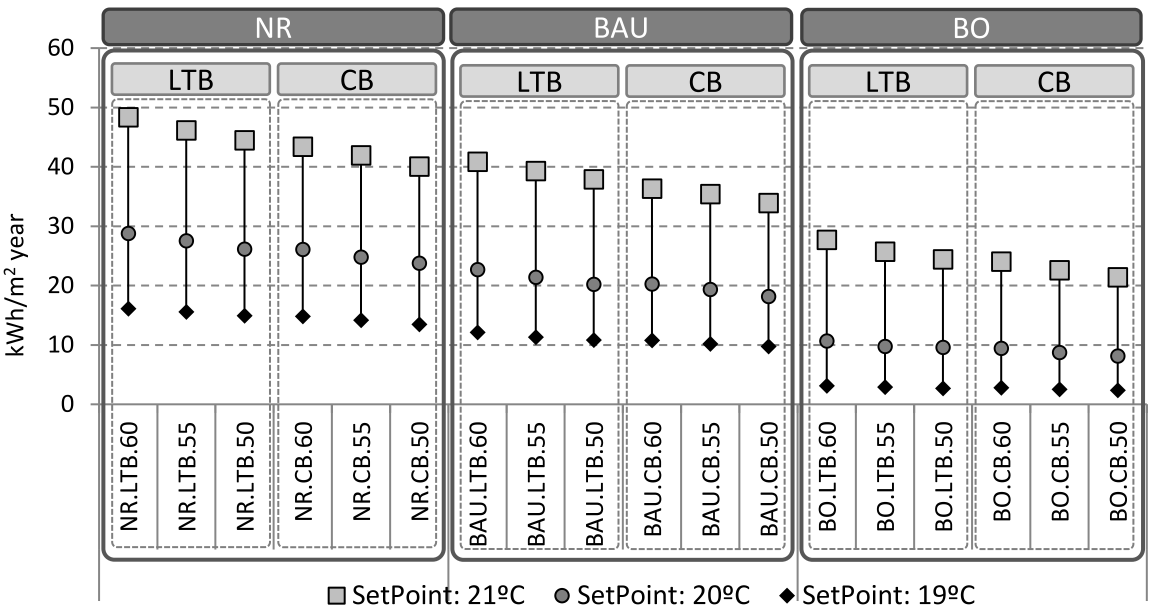

Fig. 6. Final energy consumption (for heating) per year

As expected, the envelope retrofitting option has a significant effect on the energy consumption of the dwelling. BAU scenario shows, in comparison to NR, average energy savings between 15% (6.5 - 7.5 kWh/m^2; 21°C set-point) to 27% (3.5 - 4 kWh/m^2; 19°C set-point). When NR and BO scenarios are compared, average savings from 45% (19 - 20 kWh/m^2; 21°C set-point) to 80% (11 - 13 kWh/m^2; 19°C set-point) are achieved. The final energy consumption values could be partially deduced from the demand results in [36], but here the effect of the seasonal heating system performance is also considered (which ranges for supplying the heating demand between 0.71 in the case of LTB and a set-point temperature of 21 °C to 0.87 in the case of CB and a set-point temperature of 19 °C) in the evaluation.

The greatest impact on the energy consumption is closely related to the occupants' behaviour, i.e. the indoor temperature set-point. A non-linear relation between the temperature set-point and the energy consumption reduction can be clearly observed. Thus, a significantly higher reduction in the consumption is appreciated when changing from a temperature set-point of 21°C to 20°C. This reduction is also significant when changing from 20 to 19°C. This influence is quantitatively presented in Table 6. It can be observed that, whereas energy savings in absolute values decrease when the envelope efficiency is higher, the impact in terms of relative values becomes the biggest in the BO scenario. This demonstrates that the user interaction plays a role more important than other design aspects, and accordingly it must be taken into account in this kind of analysis. This trend is maintained for all the cases evaluated; thus, for the sake of clarity, a set-point of 20°C is considered as the basis for the analysis for the rest of the paper.

	NR	**BAU**	**BO**
21 °C →20 °C	17.86 (40.5%)	16.95 (45.5%)	14.93 (61.4%)
21 °C →19 °C	29.21 (66.3%)	26.45 (70.9%)	21.6 (88.7%)

Table 6. Summary of energy savings in kWh/m^2.year related to set-point temperature (in brackets, percentage of the saving in relation to energy consumption with a 21 °C set-point)

Regarding hot water production temperature, a lower production temperature means a lower return temperature and, therefore, a higher efficiency. The energy consumption reduction is of 4-5% (from 60°C to 55°C) and of 9% (from 60°C to 50°C) for the NR and BAU scenarios. Energy savings are higher in the BO scenarios, 8% (from 60°C to 55°C) and 12% (from 60°C to 50°C). This is explained by the fact that the BAU case presents slightly lower demand and, therefore, for a given boiler nominal power, the part load ration is lower, meaning a higher efficiency (Fig. 1). The same trend is get regardless of the boiler type. In the case of the heating system supply, differences between LTB and CB performance are hardly found, which is owed to two main reasons: both options present the same mean return temperature of 37.6 (60°C), 33.1 (55°C) and 28.9°C (50°C), and the energy efficiency percentage variation between these return temperatures is practically the same for both boilers, around 8-9% (Fig. 1).

The results of the primary energy consumption, which are obtained adding the DHW consumption to the heating consumption, are presented in Fig. 7. The values are gathered in two groups for the sake of clarity: those related to LTB and those related to CB. The results shown reinforce the aforementioned influence of the set-point temperature and, to a lesser extent, the effect of reducing the hot water production temperature.

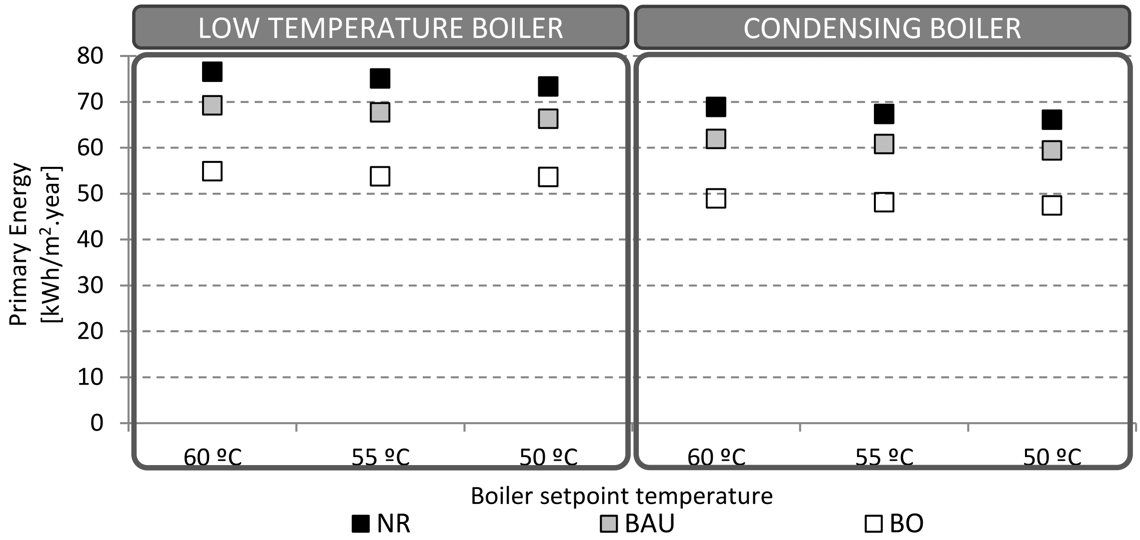

Fig. 7. Operating Primary Energy consumption per year (indoor air temperature set-point: 20 ºC)

5.2 Economic results

Results corresponding to the evaluation Approach (A) are summarized in Fig. 8. In the graph, annual costs are presented, considering them as the sum of the investment amortization and the yearly average operating cost of the system.

Each envelope renovation option (BAU and BO) presents the investment (in dark gray), prorated according to the system lifespan assumed. Additional costs are related to the heating system upgrade: annual investment and fuel costs. The overinvestment needed for the condensing boiler in relation to the low-temperature one can be observed, as well as that required for lower hot water production temperature, i.e. larger radiators according to the sizing method (Table 3). Thus, under Approach (A), the joint renovation action consisting of BAU envelope and condensing boiler brings the best economic results. Amongst the different hot-water production set-points, no significant differences are observed, but the economics are better when the boiler operates at 60°C. This means that the additional investment for operating at a lower temperature does not compensate the economic savings for a fuel usage reduction.

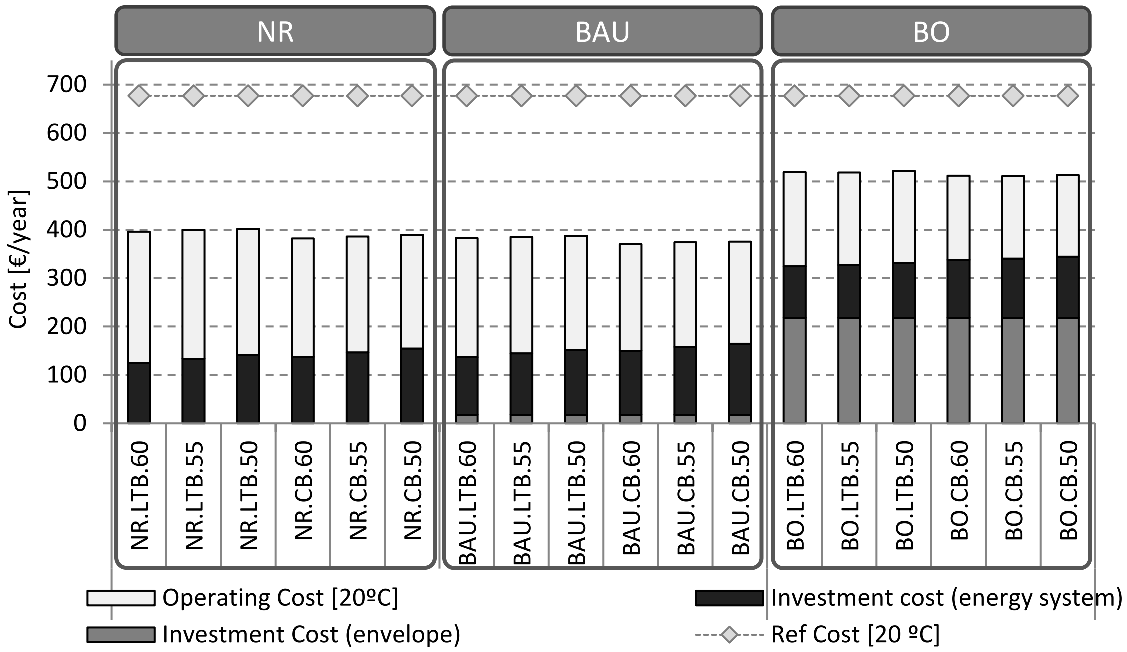

Fig. 8. Economic results. Approach A. Annual cost for each scenario (amortization of investment + operating cost) considering as reference case the NR scenario with electric system.

Results corresponding to Approach (B) are depicted in Fig. 9. The difference with respect to Approach (A) is that, for each case, the envelope retrofitting is assumed to be made by the user prior to the heating system upgrade. Thus, the NR scenario is the same that the one presented before in Fig. 8. For the BAU and BO scenarios, both annual costs and savings in relation to the reference case are lower.

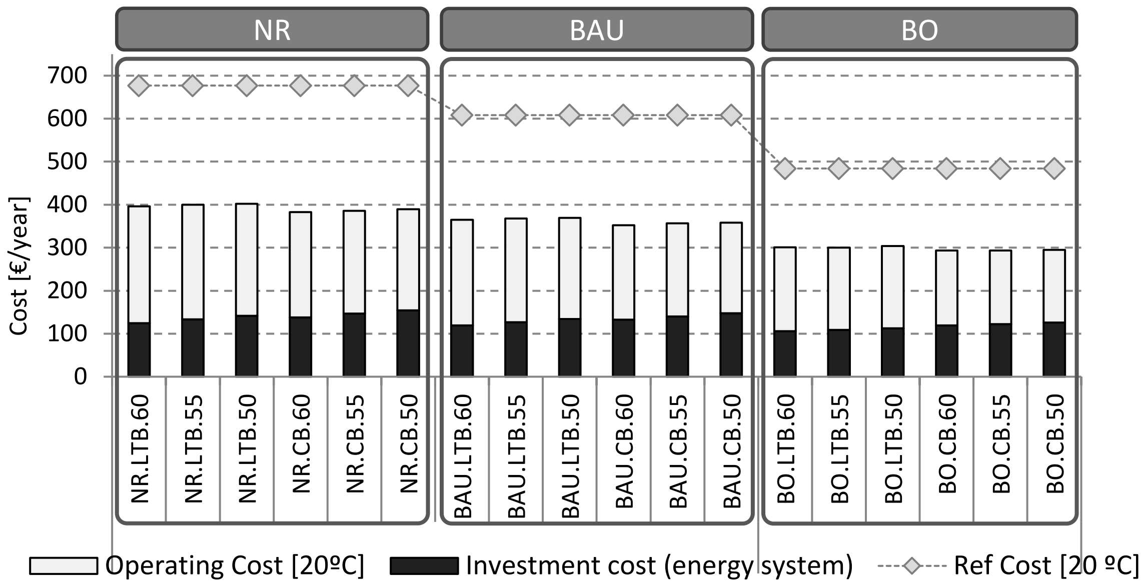

Fig. 9. Economic results. Approach B. Annual cost for each scenario (amortization of investment + operating cost) considering as reference cases the NR, BAU and BO scenarios with electrical systems

The simple payback results under both approaches A and B are presented in Fig. 10. Payback periods in NR and BAU scenarios are similar regardless the renovation approach, ranging between 8 and 11 years.

In BO scenarios, the renovation approach is of great importance, especially due to the relatively higher investment that it requires (i.e. windows replacement). Thus, payback ranges from 19 to 20 years for approach A and from 10 to 12 years for approach B.

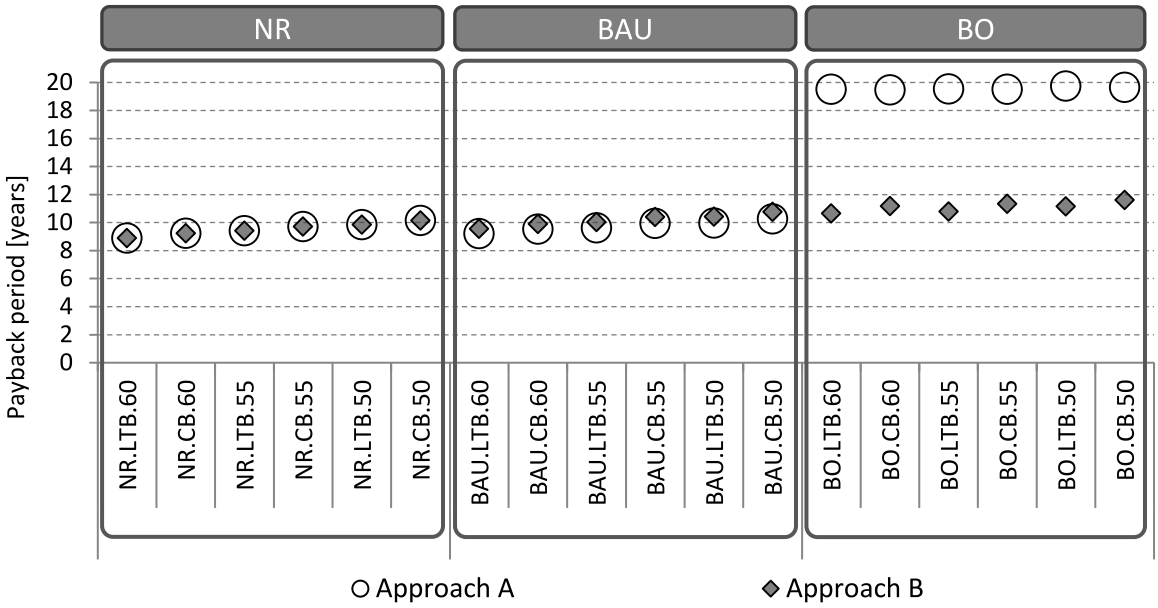

Fig. 10. Simple payback for each scenario for Approach A and B (indoor air set-point temperature: 20ºC)

5.3 User behaviour

The occupant behaviour was partially evaluated in Section 5.1 by means of the analysis of different set-point temperatures (Fig. 6); however, the same set-point was assumed before and after renovation. For a deeper discussion, the evaluation of the (p)rebound effect is carried out. The results obtained are presented in Table 7, where the percentages shown are the ratio between theoretical and actual savings.

Set-point temperature prior to upgrades	Set-point temperature after upgrades	NR	BAU	BO
19 °C	**20 °C**	29.9%	31.5%	34.8%
19 °C	**21 °C**	60.5%	59.7%	59.5%

Table 7. Rebound effect in each scenario, considering a temperature increment of 1 and 2 °C

As observed, an increment of 1°C (from 19 to 20°C) involves rebound effect values around 30-35%. These results agree with previous publications [26]. An increment of 2 °C from 19 °C to 21 °C involves a rebound effect around 60%. Note that this study deals with social housings, where electric heaters are usually employed. These systems are expensive to operate for low-income households, and they create temperature gradients of the indoor air that make the actual room temperature significantly lower than the set-point of the system. Accordingly, increments of 2°C are considered feasible.

The yearly savings on primary energy consumption and payback period values considering the aftermath of the rebound effect are depicted in Fig. 11 and Fig. 12. The dark grey rhombus represent the theoretical values with no rebound effect (set-point temperature of 19 °C), while the white rectangle represents the range of depicted values when the increase of set-point temperature ranges from 1 to 2°C.

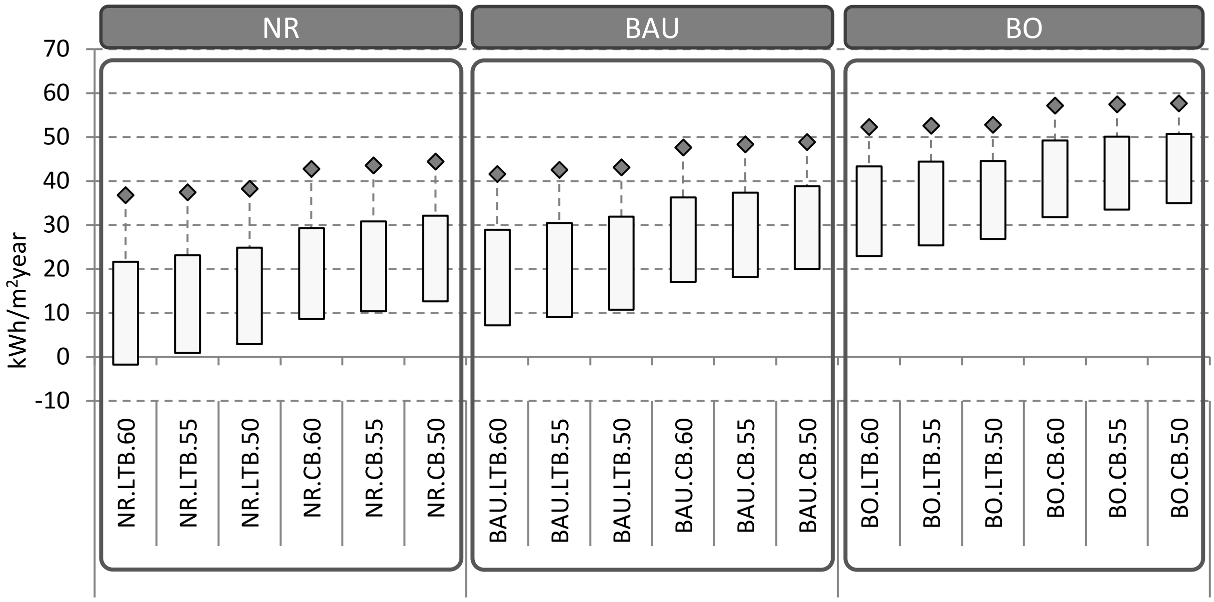

Fig. 11. Range of primary energy savings values considering the rebound effect

It can be appreciated that ranges are wider in those case where a less intensive energy efficiency upgrade is carried out, and even the aforementioned backfire effect is reached in the NR.LTB.60, where negative energy savings (higher energy consumption) are found when set-point temperature increases close to 2°C.

Analogously, payback period values can be analyzed using a similar methodology. In this case, as a way of example, payback period values under approach (A) are presented considering the consequences of the (p)rebound effect. Mentioned values range between 10,5 and 12,5 years in NR and BAU scenarios when no rebound effect is considered (dark grey rhombus), increasing the payback period up to 17-18 years under some cases when the rebound effect is considered. Similar consequences are found in BO scenario; whilst payback period values are in all cases close to 24 years when no rebound effect is considered, values higher than 30 years are get in some cases, values that are higher that the considered lifespan of the system, thus compromising the feasibility of the renovation.

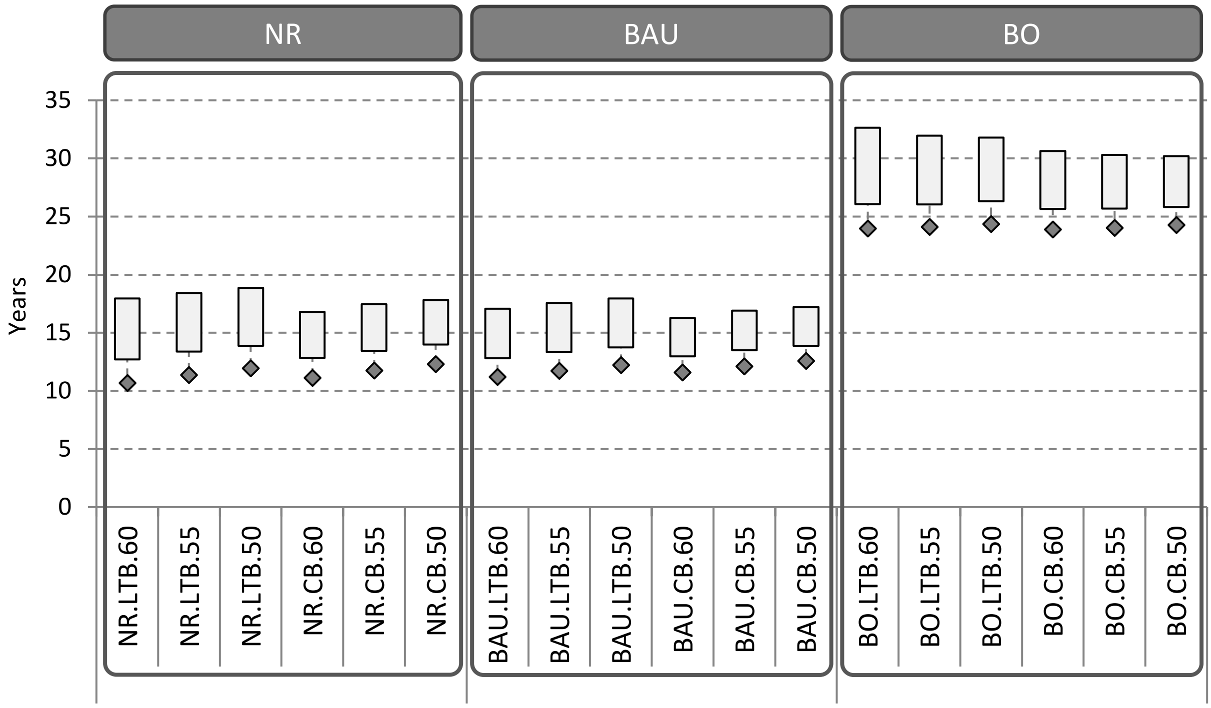

Fig. 12. Range of the payback period values considering the rebound effect (Approach A)

6 Discussion

The obtained results have significant relevance on the planning of energy retrofitting of buildings. First, it is observed that, from the analysed issues, reducing the temperature set-point has the greatest effect on the energy consumption reduction with no additional expense, showing a saving potential of up to 80%. This makes it the measure that more effectively addresses the energy consumption reduction sought but current energy policies. Addressing this issue requires checking the concept of how the required comfort levels are reached and to emphasize the role of clothing in buildings. This need is especially remarkable in mild climates as it is the case under evaluation.

The use of more efficient heating systems, such as condensing boilers, involves savings over conventional low-temperature ones, but these savings are in the order of 1-2 kWh/m^2. Similar savings are got from reducing the hot water production temperature, since it allows a higher efficiency, but this could lead to problems in meeting the comfort requirements. To avoid that, in this paper the sizing of the radiators was performed according to that operating temperature. However, the sizing of radiators is usually made regardless of these issues, and problems could arise when trying to meet the set-point temperatures when reducing the hot water production temperature. Finally, the energy consumption reduction is similar in percentage terms for all the envelope retrofitting scenarios, which makes it more desirable in terms of energy intensity reduction when the envelope is less efficient.

With the exception of the temperature set-point, the different aspects evaluated before imply different levels of investment. For example, a condensing boiler implies an overinvestment in relation to a low-temperature one, while a lower hot water production water implies a higher radiator surface and therefore, investment. From the economic analysis, the BAU envelope with condensing boiler option and hot water production at 60°C offers the lowest annual costs. The additional investment needed for bigger radiators when reducing the hot water temperature does not compensate the fuel consumption reduction in any case. BO envelope option needs for significantly higher investment that reduces the economic feasibility. This is mainly due to the windows replacement, which makes the investment orders of magnitudes higher than the insulation addition. However, windows replacement offers other benefits that cannot be analysed from a purely economic point of view: comfort, acoustics, etc. These results are different if the investment for the envelope retrofitting is already done when the heating system upgrade is faced (approach B). In this case, a better envelope reduces the annual costs, but also the reduction according to the reference case. In general, results have addressed the interest of integrated energy renovations, with packages that include energy savings measures with short payback periods and other measures with higher payback periods.

Normally the same operating and comfort conditions are considered before and after the renovation. However, the so-called rebound effect usually occurs, meaning that energy efficiency measures lead to changes in the user that could imply a higher specific use of energy. From the results, it is observed that rebound effect can play a very important role, especially considering the low performance of the reference heating system, under which the comfort conditions were hard and expensive to meet. Thus, under a potential increase of the set-point temperature of 2°C, some scenarios could lead to no energy savings and some retrofitting options could be directly economically unfeasible.

7 Conclusions

A holistic methodology based on TRNSYS simulation has been presented for the evaluation of individual heating systems in the energy retrofitting of domestic buildings. It has been subsequently applied to a social housing building located in northern Spain, for which an already validated model is available.

Different retrofitting scenarios and options have been analysed. From all of them, the temperature set-point has resulted in the most effective to reduce the energy consumption which underlines the role played by the building user. The nature and operation of heating systems plays a significant role. Condensing boiler offer higher savings than conventional boilers but the benefits from the reduction of the operating temperature do not compensate the need for the higher investment of larger radiators. The eventual effects of the (p)rebound effect have been demonstrated very significant and it should be analysed whether this increase is a benefit or a feature not-demanded by the occupants

The fact that the user interaction plays the most important role for getting significant energy savings reinforces the need of exploring new ways to achieve thermal comfort. This can be regarded as a key factor to reduce energy consumption in buildings and should be considered in further works.

8 Acknowledgements

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