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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 50–60 s 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.

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. Che et al. [7] assessed 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. Owrak et al. [9] studied experimentally

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Nomenclature

BAU	business as usual	LTB	low temperature natural gas boiler; high efficiency boiler
BO	best option	LCC	life cycle cost
C	theoretical heating energy consumption (calculated)	NR	non-retrofitted
C_{op}	operating cost	P_{eff}	effective thermal power
C_{en}	current cost of energy	P_{EN442}	nominal thermal power per length (EN-442)
CB	condensing boiler	PLR	part load ration
DHW	domestic hot water	r	discount factor
E	actual energy consumption	RE	rebound effect
e	annual escalation rate of energy	T_{eff}	effective temperature
ESM	energy saving measures	TRV	thermostatic valve
I	current cost of investment		

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] analysed 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. [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 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-Blank 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 50–60 s 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 analysed 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 eco-