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Feasibility of zonal space heating controls in residential buildings in temperate climates: energy and economic potentials in Spain

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ABSTRACT

This paper explores the effects of multi-zone heating systems in residential buildings in different Mediterranean climates. The aim is to evaluate their potential in residential sectors to provide a general basis from the results (from the energy and economic point of view). In addition, if feasible, a further detailed evaluation of this management strategy for optimising the energy use in residential buildings would also be carried out. To do so, the effects of two different zoning controls in different types of apartment, occupancy patterns, building characteristics and locations in Spain, have been assessed. Different combinations of these parameters have resulted in 336 different scenarios that have been dynamically simulated using Design Builder software. The obtained energy results have been analysed in detail. Moreover, an economic analysis of these results has also been carried out to evaluate the economic feasibility of these systems in residential buildings located in temperate climates. This has been calculated by evaluating the maximum investment that can be assumed in each scenario to achieve different payback periods (namely 10 and 20 years). The results obtained show that these systems could be a cost-effective strategy aimed at reducing the energy consumption in residential buildings, not only in cold climates, such as is shown in the literature (the majority of the studies found are located in the UK and northern countries), but also in more temperate climates, such as that of Spain. Savings of around 20% were obtained in the most usual scenarios in Spain (coherent with results obtained in previous studies in the

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UK found in the literature), showing that in several cases, the initial investment in zone-controlled systems could be paid off in less than ten years, especially in large apartments and the coldest weather conditions.

Keywords: *Smart Heating systems; Occupancy prediction; Multi-zone heating; Adaptive behaviour; Occupant behaviour; Multi-family buildings*

1 Introduction

Buildings are currently responsible for 40% of the primary energy consumption in the European Union (EU) and one third of related global greenhouse gas (GHG) emissions [1]. Thus, reducing energy consumption in this sector has become a priority due to the need to meet carbon dioxide emission reduction targets. Moreover, the building operational phase accounts for 80–90% of these emissions [2], space heating being the most important end-use by far in European building stock, mainly in the residential sector (68%). This share is even larger if Mediterranean Countries are not taken into consideration, thus representing 60-80% of the total energy consumption (in the case of Spain, the share of space heating is just below 50%) [3]. Therefore, identifying the most effective strategies aimed at increasing the energy efficiency of buildings and reducing their primary energy consumption has become a key point in facing this challenge.

In this context, the EU has enforced different directives over the last few decades aimed at reducing the energy consumption in both new and existing buildings, such as the Energy Performance in Buildings Directive (EPBD), published in 2002, recast in 2010 [4] and updated with some minor changes in 2018, or the Energy Efficiency Directive (EED) [5] of 2012.

The different strategies to achieve this goal are often classified into 3 main groups: a) measures focused on reducing energy demand by acting on the passive behaviour of buildings (e.g., through higher insulation standards in the envelope or increasing airtightness); b) measures aimed at reducing energy consumption by acting on the active elements (e.g., more efficient heating systems); and c) measures to increase the energy supply from renewable energy sources, so as to minimise the primary energy consumption from fossil fuels and its related GHG emissions.

There is, however, a set of measures which is difficult to classify in one of these three main groups. The fourth group of measures includes those related to the control and management of energy systems. In the last few years, the development of IT-enabled monitoring and control technologies has boosted the use of progressively more complex control systems aimed at adapting the operation of energy systems to the specific environment conditions at every moment, thus optimising the systems' performance and reducing energy waste in different sectors, including buildings [6].

Thus, different studies have shown that facilitating energy system control often brings significant energy savings, which in some cases may even be higher than those resulting from measures on passive or active elements, with lower investment costs. However, as stated by Cockroft et al., despite its potential for reducing energy use, heating controls in general can still be considered a technology with a low presence in residential buildings, as there is a lack of knowledge on which technologies could be applied to obtain the maximum benefit [7].

In this regard, a very comprehensive and detailed review of the evidence of domestic heating controls in terms of energy savings, cost effectiveness and usability has recently been published [8]. This study reviewed over 2400 documents and reported 102 references. Amongst them, it includes 44 research works focused on energy savings, but only 5 present any sort of cost effectiveness analysis. The review establishes three main categories for control types: standard controls (which includes room thermostat and thermostatic radiator valve related studies); advanced heating controls aimed at system efficiency; and advanced space temperature controls (including zone controls, programmable thermostats and smart thermostats).

In practice, as far as residential buildings are concerned, the "on/off control" of the heating system is the most usual control system when a heat generator (usually a boiler) supplies different terminal units. This control is often driven by a thermostat placed in the main room of the apartment. The user selects the set-point temperature, which constitutes the temperature below which the heating system is activated, and provides heat to every terminal unit. An additional control level can be added if thermostatic radiator valve (TRV) heads are installed in some terminal units (e.g., radiators located in bedrooms). More advanced thermostats include the possibility of programming not only set-point temperature, but also allow the definition of more complex profiles, which in some cases can lead to additional savings [7]. Nonetheless, some authors have pointed out that programmable thermostats may often be underused. A. Meier et al. in [9], for instance, showed that almost 90% of respondents to personal interviews in the US reported that they rarely or never adjusted the thermostat to set a weekend or weekday programme.

1.1 Multi-zone heating systems

Developments during the last few years now allow the heat supply in every room to be controlled independently by replacing the TVR head with a wirelessly controlled actuator. As Cockroft et al. state, this can be applied not only in new buildings, but also in many existing homes, where it can be a low cost retrofit option, since no piping work is needed and only some minimal adaptations are required [7].

Beizaee et al. compared two adjacent semi-detached houses in the UK, both with gas combi-boilers and programmable thermostats. One of them had radiators with standard TRVs, whereas in the other one, programmable thermostatic radiator valves (PTRVs) were installed. They reported a reduction of 14.1% of the boiler input in the house with PTRVs (compared to the house with TRVs) during the 49-day wintertime experimental period [10]. This work is also the only one found which provides a reference of the investment cost of these systems: around £1200 (1600€, taking into consideration the currency exchange when that research work was published) for a “luxury system” and £120 (160€) for a basic system. Similar results were obtained by E. Marshall et al., who also evaluated the potential for energy savings of zonal space heating control in a research work based on dynamic simulations run with TRNSYS [11]. The predicted yearly savings were between 10-15%, depending on the occupancy schedules used.

1.2 Smart heating systems and occupancy prediction

Additionally, the emergence and quick development of the so called “smart heating systems” over the last few years can be an opportunity to explore the potential of combining these two strategies and their synergies. As Kleiminger et al. define, *“the difference between a conventional automatic heating system and a “smart” one is that while the former operates according to a pre-defined and typically deterministic schedule, the latter typically adapts its control strategy to the user context”,* and in both cases the heating system is automatically controlled, not requiring explicit human intervention [12].

Thus, the use of the automatic learning of the response times of a given heating system, according to its external conditions (building envelope, weather…), together with the automatic learning of occupancy schedules (as several works of research already explore in this field, such as A. Nacer et al. in [13]) can significantly boost the potential advantages of zonal space heating control, not only in large, tertiary buildings, but also in residential uses. According to a research piece presented by R. J. Meyers et al., the share of total primary residential energy use wasted in heating or cooling unoccupied rooms was estimated at 16% [6]. Then, the combination of these two strategies may bring significant energy savings, without affecting the thermal comfort of indoor environments, by avoiding the heating or cooling of unoccupied rooms.

Finally, the potential of implementing occupancy detection and prediction in these systems has also been evaluated. A zonal space heating control system prototype, which also included occupancy prediction, was studied by Scott et al. [14]. This research study reported savings of around 30% when compared to having the heating system permanently on. The main challenge in this regard is that related to the strategies and methods for detecting and defining occupancy profiles, which have been the object of study in several works over the last few years, such as [15], where occupancy is detected by motion sensors, or [16], where occupancy detection is based on electricity consumption data obtained from digital electricity meters. Z. Chen et al. have recently published a comprehensive review of building occupancy estimation and detection systems, also presenting potential future research lines in this field, taking into consideration the current progress of the technology [17].

So this kind of controls presents a huge potential for development, such as including not only the detection of whether a specific room is occupied, but also more detailed information and more control parameters, such as the exact number of occupants or the energy cost. For instance, W. L. Leow et al. developed a framework and algorithms that would enable a home controller to accomplish occupancy- multi-zone, multi-inhabitant space-conditioning under a demand-driven pricing scheme for electricity [18].

In short, the above-mentioned recently published research works show the potential of this sort of systems for the reduction of heating consumption in the residential sector. They also lay bare the influence that some factors, such as weather conditions, building construction features or occupancy profiles, may have on the energy savings and economic feasibility of these systems.

2 Approach and objective

Within the described context, the aim of this study is to explore the possibilities that multi-zone control systems may offer as a way of saving heating energy in existing residential buildings. A few previous studies can be found in this field, such as that carried out by A. Beizaee et al. [10], where a case study in the UK was evaluated and savings of almost 12% were reported as a consequence of using zonal space heating control. The study published in 2017 by Cockroft et al. [7] also deserves special mention, since it presents an interesting study based on computer simulations, where the potential energy savings of multi-zone controls for different occupancy patterns in different house types, locations and ages were assessed.

Additionally, in the previously mentioned review by K. J. Lomas et al. [8], two additional research works focused on zonal space heating control were defined. According to that review, the quality of the evidence for energy savings of zonal space heating control is moderate, i.e., "*further research is likely to have an important impact on the confidence"* of the effects estimated [8]. Moreover, the majority of the cases are focused on the specific conditions and features of the UK (in fact, the great majority of references found are from the UK or the US). However, there is a lack of peer-reviewed information on the potential of multi-zone heating systems in residential buildings in more temperate climates, such as, for instance, Mediterranean climates. Similarly, there are very few references which include an analysis as comprehensive as the one presented in this paper, where the potential of these systems is assessed, not only from an energy point of view, but also considering its economic feasibility.

For that reason, this paper is focused on exploring the potential that multi-zone heating systems (together with a control of occupancy patterns) may have on achieving energy savings in heating consumption for residential buildings in different Mediterranean climates. To do so, a variety of heating zoning controls have been evaluated in two different types of apartment, occupancy patterns, building characteristics and locations in Spain. Furthermore, according to the results obtained, an economic feasibility has been carried out to get a first insight into what the maximum, affordable investment cost would be to achieve different payback periods.

Moreover, the conditions evaluated in this paper are especially interesting since, in general, heating demands will be lower than those considered in the previously mentioned studies. This fact is mainly due to two factors: on the one hand, Spain presents, a priori, lower winter severity than the UK; on the other hand, multi-family buildings, in general, have a lower exposed envelope-to-useful area ratio than detached houses, the heat losses per square metre thus being lower. This point is significant because in Spain, unlike in other northern European countries, multi-family buildings are the most usual typology in the residential sector: in 2018, 65% of the Spanish population lived in a flat; whereas, in the EU-28, the average is 42% and in the UK, where the majority of the previously referenced studies have been conducted, the population rate that lives in a flat is less than 15% [19].

The remainder of this paper is organized as follows: a detailed description of the methods followed, including the model definition, scenarios assumed and data processing methods are described in Section 3. Section 4 presents the obtained results together with their discussion. Finally, the main conclusions are summed up in Section 5.

3 Materials and methods

The study presented in this paper was carried out using data obtained from 336 dynamic simulations run with the Energy Plus simulation engine, using the Design Builder software interface. Two different building typologies were modelled and simulated, generating a set of simulation cases by combining different scenarios related to occupancy profiles, thermal envelope characteristics, zonal space heating definitions and climates. The results obtained were evaluated taking into consideration both energy and economic issues. Thus, in the following sections, a detailed description of the methods is presented.

3.1 Parameters and hypotheses assumed

Some common hypotheses for every scenario evaluated were assumed in this study. First, regarding set-point temperature, two different set-points were assumed for a day: 20 ºC from 7 a.m. to 11 p.m. and 17 ºC for the night-time (11 p.m. to 7 a.m.), as recommended in [20]. Secondly, the airflow rate through internal doors may slightly affect energy consumption in a no-zoned house, but it can play a very important role in the case of zoned houses. However, this rate depends on several parameters (such as wind, geometrical features of the given house…) and the definition of accurate models would require CFD simulations, which are beyond the scope of this paper. For this reason, a fixed airflow rate per opening area was assumed, considering the value suggested by Design Builder, i.e., 0.1 $m^3/s\text{-}m^2$. In order to take into consideration the effect that this parameter has on the final results, two extreme scenarios were considered in every scenario evaluated: (i) internal doors are open during the whole day (thus having the maximum amount of mixing airflow between rooms) and (ii) internal doors are totally closed during the whole day (thus having the lowest limit where there is no airflow mix between connected rooms). This issue is described in more detail in section 3.3.4.

3.2 Case Studies

As previously discussed, two different apartment typologies were defined (three bedroom apartments of different size) in order to evaluate the effect of the proposed system in different apartment areas: one is a 52 m^2 apartment and the other has 103 m^2. As far as typologies are concerned, geometries were defined in both cases based on existing apartments located in Bilbao (Northern Spain). Using these typologies as a base, different thermal envelope features were assumed, while the same heating system (natural gas boiler with hot water radiators) was considered for both typologies, as later detailed in section 3.4.

3.2.1 Case study 1

This case study is based on an existing social apartment located in Otxarkoaga District in Bilbao, Spain (latitude: 43ºN, longitude 2.9ºW). This first typology was selected taking into consideration its representativeness, according to the analysis of the residential building stock of this region carried out by the authors [21]. Moreover, the multi-family building where this apartment is located has previously been assessed in detail as a case study in other research works [22-24].

The indoor height of the apartment is 2.7 m. The external walls are composed of two layers of hollow bricks separated by an air gap and 2 cm of fibreglass, with a resulting U-Value of 0.74 W/m2.K. The indoor surfaces of the walls consist of plaster over gypsum. Regarding the window features, they are double-glazed with aluminium frames without thermal break. These general characteristics were used to define the base case (Scenario 0 of the thermal envelope), as later presented in Section 0. A layout of the apartment is presented in Fig. 1 (left). A more detailed description of the apartment can be found in [25].

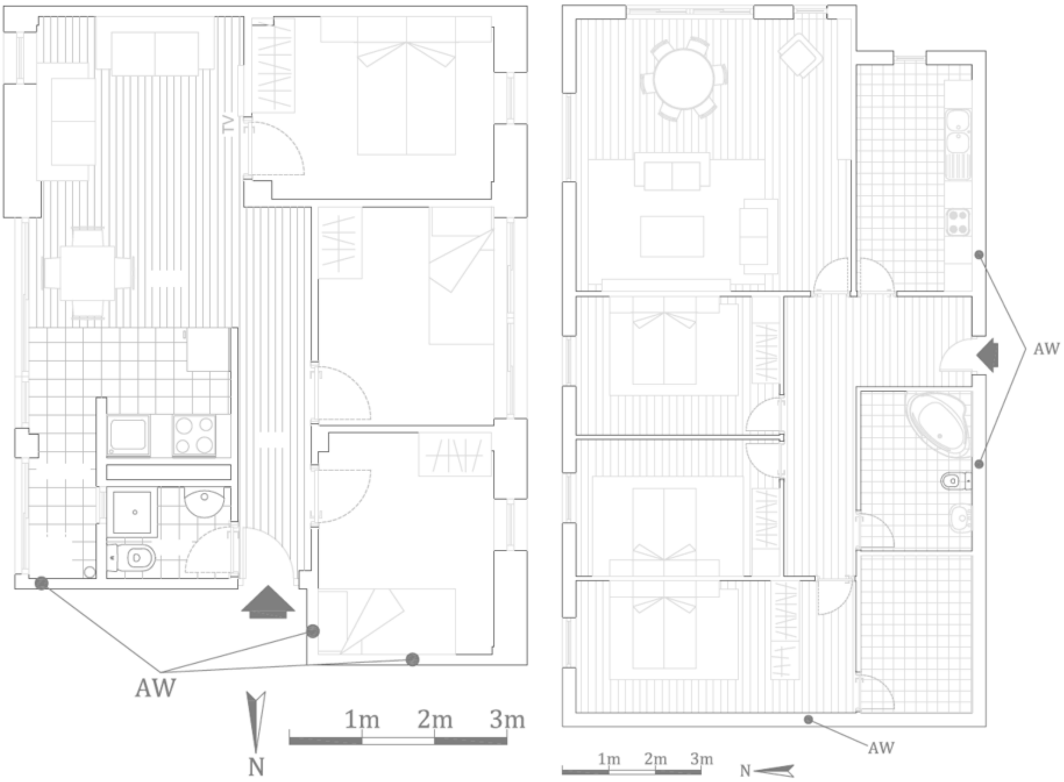

Fig. 1. Layouts of the case-studies evaluated (1st case study on the left, 2nd case study on the right).

3.2.2 Case study 2

The second case study evaluated is also based on a 103 m2 apartment located in a multi-family building in Bilbao. As far as the general features are concerned, the same values as in the previous case study have been assumed to define the base scenario: an indoor height of 2.7 m, a U-value of the façade of 0.74 W/m2.K, and double-glazed windows with aluminium frames without thermal break. A layout of the dwelling is also presented in Fig. 1 (right).

3.3 Evaluated scenarios

Using the case studies described in the previous section as the base, the scenarios to be evaluated were defined as a result of combining different assumptions on occupancy profiles, thermal envelope features, heating zoning criteria and climatic conditions. As a consequence, a set of 336 simulations were run and evaluated. In the following, a detailed description of the scenarios assumed is presented.

3.3.1 Occupancy profiles

As discussed in the previous section, occupancy is one of the parameters which plays a key role in the final energy consumption of buildings, in so far as it affects the heating system operation. With the aim of taking this effect on the analysis into consideration and then to define (in section 3.3.2) several scenarios for the heating operation, two different occupancy scenarios are considered. These occupancy scenarios were defined based on the proposal of Jazaeri et al. [26]. Two of their scenarios, defined as *"common occupancy scenarios in Australia"*, were used as a reference and adapted to Spanish conditions, additionally including the number of occupants and the room(s) occupied during each hour.

Thus, the first assumed scenario O1 (based on Scenario 1 in [26]) consists of a 4-person apartment, where all occupants have full-time job schedules (e.g., a family with two children that go to school). The second scenario O2 (based on scenario 3 in [26]) corresponds to a 2-person apartment where the occupants spend a couple of hours in the evening outside the apartment (e.g., a retired couple with no child at home). Based on these descriptions, the occupancy profiles per room are depicted in Fig. 2.

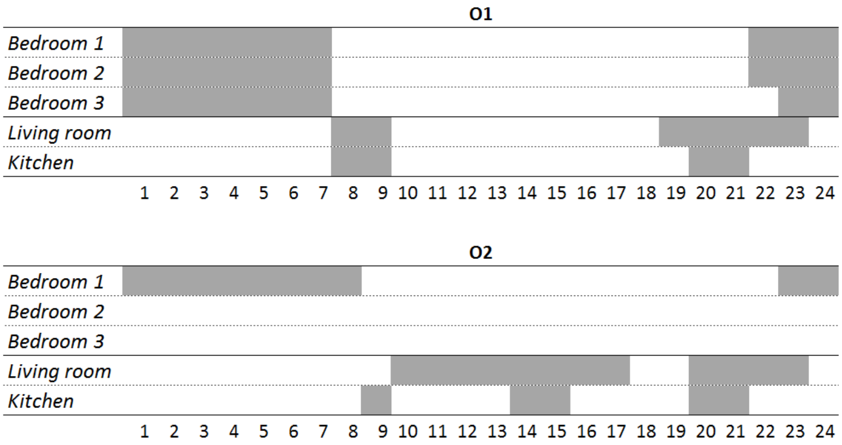

Fig. 2. Occupancy scenarios assumed per room (in each hour of a typical day)

These scenarios are representative of two opposite occupancy profiles: O1 represents a profile where the apartment is empty during most of the day; whereas O2 represents a profile where the apartment is occupied during almost all the day. For the sake of clarity, no difference between working days and holidays was assumed.

3.3.2 Zonal space heating and operation criteria

Concerning zonal heating, three scenarios were evaluated in this study. The simplest one, Z1, has a central heating control in the apartment (i.e., just one thermal zone is defined for the entire apartment). The second scenario, z2, consists of two different zones, one including all “day-time rooms” (i.e., living-room and kitchen), and the other including “night-time rooms” (i.e., bedrooms). For the third scenario, Z3, a zoned control for each individual room is proposed.

Based on these heating zoning scenarios and the occupancy profiles defined in the previous section, the heating operation was defined. The combination of the two occupancy profiles and 3 heating zoning scenarios gave rise to six heating operation cases for each apartment resulting from the combination of the two occupancy scenarios and 3 heating zoning scenarios. Additionally, a seventh one was defined, where the heating system is working all day long, according to the criteria defined by IDAE for performing energy simulations in buildings [20].

According to these criteria, the heating operation scenarios evaluated in this research work are those depicted in Fig. 3. In this figure, dark grey represents the hours when the set-point temperature is 20°C; whereas light grey represents the hours when the set-point temperature is 17°C.

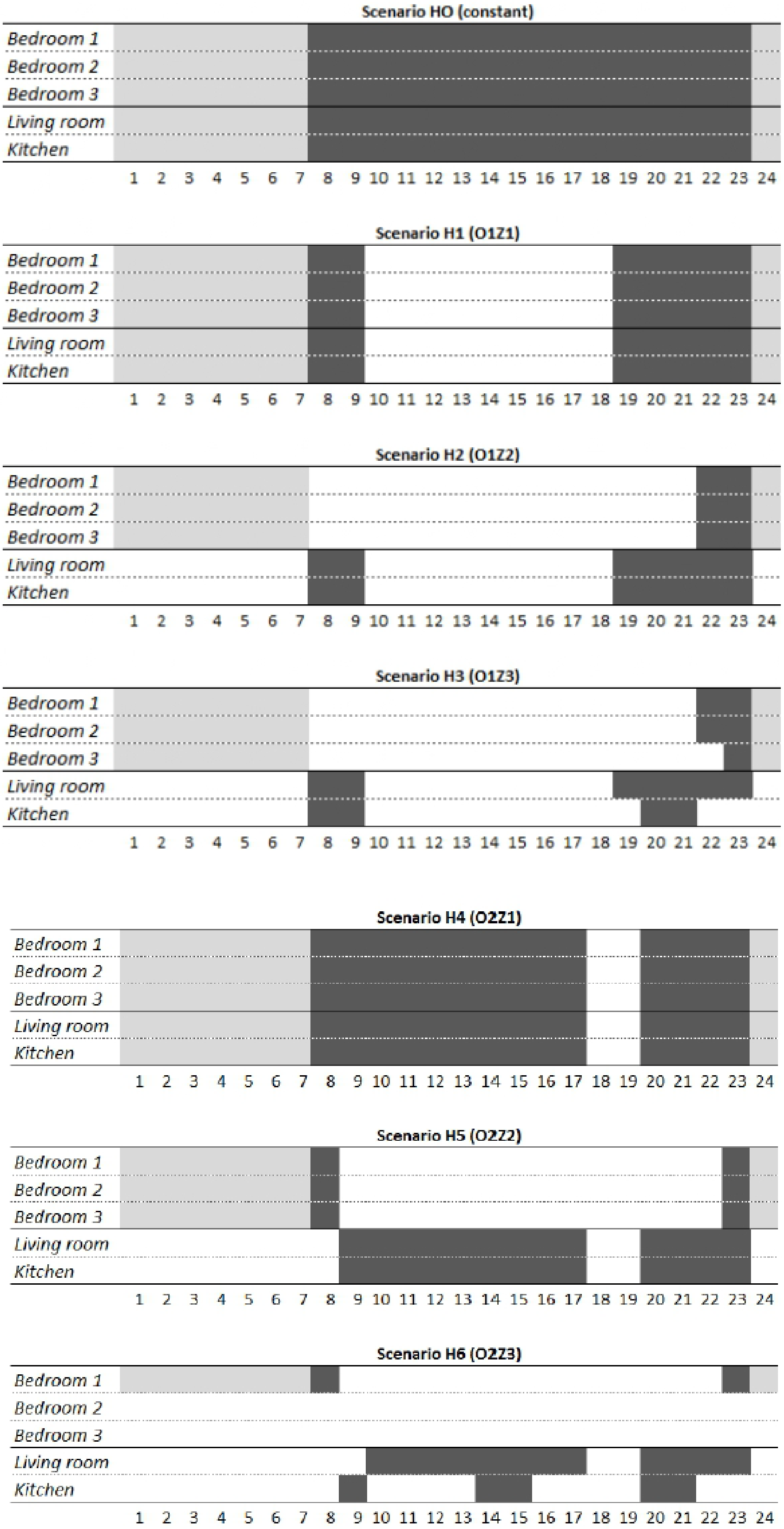

Fig. 3. Heating operation scenarios resulting from occupancy and zonal criteria assumed

3.3.3 Thermal envelope features

With the aim of evaluating the effect of the thermal envelope on the results, 4 different windows and levels of thermal insulation in the façade were evaluated. These scenarios were defined using a previously published work [23] as a reference, where 64 different energy saving measures were proposed and evaluated. The selected ones were considered as representative of the existing (as well as the expected) building stock, taking into consideration levels of thermal insulation in the façade and the thermal quality of the windows. Thus, scenario 1 (previously defined as the base scenario) may be representative of existing buildings where no renovation has yet been carried out; scenario 2 of existing buildings where a sort of energy retrofit has been carried out; scenario 3 of new buildings which meet the thermal requirements set in the current Spanish regulations; and scenario 4 of new buildings built under nZEB standards. The main features of the four scenarios are summarised in Table 1.

Table 1. Summary of data assumed in each envelope scenario

		Scenario E1	**Scenario E2**	**Scenario E3**	**Scenario E4**
WINDOWS	Frame (30%)	Al without TB (U=5,7 W/m^2.K)	PVC (U=2,2 W/m^2.K)	PVC (U=2,2 W/m^2.K)	PVC (U=2,2 W/m^2.K)
	Glass (70%)	4/6/4 (U=3,44 W/m^2.K)	6/12/6 (U=3,00 W/m^2.K)	3/12/3 Low-E (U=1,76 W/m^2.K)	4/16/4/16/4 (U=0,7 W/m^2.K)
	U_{window}	**4,12 W/m^2.K**	**2,76 W/m^2.K**	**1,89 W/m^2.K**	**1,15 W/m^2.K**
FAÇ.	Insul. thickness	2 cm	6 cm	8 cm	14 cm
	$U_{façade}$	**0,74 W/m^2.K**	**0,43 W/m^2.K**	**0,36 W/m^2.K**	**0,24 W/m^2.K**
Correspondence in [23]		0.0.0.	1.1.1.	2.2.2.	3.3.3.
Representative of…		Existing buildings with no renovation	Existing renovated buildings	New buildings (current reg)	New buildings (nZEB)

3.3.4 Air exchange between adjacent indoor zones

In order to assess the effect of air exchange between zones, which is an important factor affecting energy consumption in a zoned apartment, two constant door-opening levels were considered: an average door opening time and area of 0% and an average door opening time and area of 100%. In order to calculate the mixing flow, the software uses an approximate empirical relationship, as presented in Eq. 1.

$$Flow\ \left[{}^{m^3}/_{s}\right] = Door\ area\ [m^2] \cdot \%Area\ doors\ opens \cdot \%time\ door\ is\ open \cdot FlowRate \qquad \text{Eq. 1}$$

The size of internal doors were assumed to be standard (2 m x 0.9 m), and the opening percentage area of open doors was set at 100%; while a fixed flow rate per opening area, as previously mentioned, of 0.1 $m^3/s\text{-}m^2$ has been assumed in every scenario evaluated. Then, the two assumptions considered for average door opening times, 0% and 100%, involve a constant flow rate through internal doors of 0 m^3/s and 0.18 m^3/s, respectively.

3.3.5 Climatic conditions

The Spanish Technical Building Code identifies 6 levels of winter severity in Spain, as depicted in Fig. 4: the mildest winter is represented by the letter "A" and the coldest by the letter "E" (there is also a sixth letter, α, to represent the winter severity in the Canary Islands) [27]. To represent the whole range of winter severity in Spain, three different climatic zones were considered in this study: the climates of Almería (A), Bilbao (C) and Burgos (E). Taking the HDD15/15 [28] as reference, Almería, located in the south of the country, has 313 HDD and the heating season goes from December to February; Bilbao (Northern Spain, close to the sea) has 970 HDD and its heating season usually covers from November-December to March-April; and Burgos (Northern Spain, inland) has 2005 HDD and it's heating season lasts from October-November to April-May.

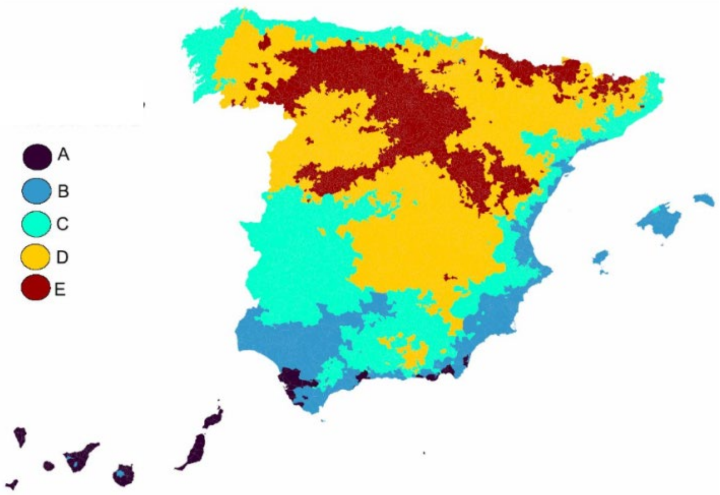

Fig. 4. Map of winter severity in Spain (Taken from [29])

3.3.6 Summary of the evaluated scenarios

As a result of the combination of the previously defined scenarios, a set of 336 simulations were performed. A summary of the considered scenarios, as well as a short description of each one and a reference to the section of the paper where it is mentioned, is presented in Table 2.

Table 2. Summary of the evaluated scenarios

Building typology [See section 3.2]	**T1** *(55 m^2)*				**T2** *(103 m^2)*		
Occupancy [See section 3.3.1]	O1 *(4 people, full time job)*			O2 *(2 people, retired)*			
Heating zoning [See section 3.3.2]	Z1 *(no zoning)*			Z2 *(day-night)*		Z3 *(individual rooms)*	
Heating Operation [See section 3.3.2]	**H1** *(O1Z1)*	**H2** *(O1Z2)*	**H3** *(O1Z3)*	**H4** *(O2Z1)*	**H5** *(O2Z2)*	**H6** *(O2Z3)*	**H0** *(constant)*
Envelope [See section 3.3.3]	**E1** *(existing building)*		**E2** *(renovated building)*		**E3** *(new building)*		**E4** *(nZEB)*
Door opening area [See section 3.3.4]	**D1** *(Door opening area of 100%)*				**D2** *(Door opening area of 0%)*		
Climate [See section 3.3.5]	**A** *(Almería)*			**C** *(Bilbao)*		**E** *(Burgos)*	

Regarding nomenclature, scenario T1-H1-E2-D2-C corresponds to the 55 m^2 apartment in a renovated building, with 4 occupants with a full-time job schedule and no heating zoning, considering a door opening area of 0% and located in Bilbao. This format will be used from now on in this paper.

3.4 Model Definition

The 336 resulting simulations were run using Design Builder energy simulation software (Energy Plus). Indoor partitions in both typologies (i.e., ceiling, floor and indoor partitions to adjacent apartments) were defined as adiabatic (walls identified as AW in Fig. 1). Each room of the apartment was defined as an independent thermal zone.

A standard heating system, which consists of a gas-fired condensing boiler for heating and DHW supply with a seasonal performance of 85%, was defined for both typologies. However, the analysis presented in this paper does not consider DHW, focusing solely on heating consumption. As far as terminal units are concerned, a hot water radiator network coupled to this boiler was considered, locating one radiator in each room of the apartment. An average nominal supply temperature of 75 °C was assumed, and a convective/radiative ratio of 90/10 was considered. Radiator sizing was auto-sized by Design Builder, so the programme calculates the nominal heating design capacity for each room and each scenario based on a winter design day. The operation of these radiators in each scenario was programmed according to the occupancy and zoning criteria discussed in sections 3.3.1 and 3.3.2. Additionally, the thermal inertia added by the piping from the boiler to the terminal units was also considered.

Internal gains considered in the models were those related to occupancy and lighting and other appliances. With respect to occupancy, a value of 0.9 Met per person was assumed (i.e., 100W/person), modelling the gains of each scenario according to the values presented in section 3.3.1. Meanwhile, the gains related to lighting and other appliances were rated at 5 W/m^2, from 7:00h to 10:00h and from 19:00h to 23:00h for weekdays, and from 7:00h to 24:00h during weekends. No additional internal gains were considered. Finally, regarding the thermal envelope, U-values presented in section 3.3.3 were used for modelling each scenario.

For performing the simulations of each apartment, standard heating controls were considered for scenario Z1 (temperature control in each room, but a single time programme for the whole apartment); whilst a zoned heating control system with independent time and temperature control in each room was used in scenario Z3 (similar to Cockroft et al. [7]). For its part, scenario Z2 was also performed in this latter way, but in this case, the rooms (thermal zones) were grouped into two different zones: kitchen and living room on the one hand, and bedrooms on the other. Meanwhile, the heating schedules of both the bathroom and the hall follow that of the living room.

As far as infiltration and ventilation rates are concerned, a constant flow rate of 0.6 ACH was assumed in the apartments for scenario E1 (Existing building). Even though there is no single standard value defined for the infiltration rate, the considered ratio is within the commonly used range for existing buildings [30]. This value was rated at 0.3 ACH for scenarios that represent renovated or new buildings (i.e., E2, E3 and E4).

Finally, the effects of air exchange between zones were also considered by modelling two levels of door opening, corresponding to average door opening areas of 0% and 100% of full open area, as previously discussed in section 3.3.4. This value was applied to the whole opening area of each room in each apartment.

3.5 Analysis of results

Energy assessment was carried out by evaluating the yearly results for each scenario. Thus, the energy savings attributed to the implementation of multi-zone heating systems could be obtained as the difference between the energy consumption of that scenario and the energy consumption obtained in the same scenario with no zonal control (Z1, according to Table 2). For instance, in the case of T1-H3-E2-D2-C, the energy savings resulting from the implementation of multi-zonal space heating control will be obtained by comparing the energy consumption of this scenario to that of T1-H1-E2-D2-C (its corresponding "base scenario", where every parameter remains the same, except the multi-zonal space heating control, which is Z1).

Once the energy results had been evaluated, an economic approach was applied. This sort of assessment is often based on calculations of the payback periods of a given installation according to the energy savings obtained. However, in this case, different system configurations can be assumed (so the investment costs may change significantly, in particular, depending on the specific features of a given apartment) while, on the other hand, as a relatively new technology, it is expected that the costs of zonal space heating control heating systems can vary over the next few years. For this reason, in order to provide a more consistent reference in the near future and avoid the aforementioned uncertainties, a different approach is proposed in this paper. The said approach is one where the maximum investment to obtain two different payback periods (10 and 20 years) has been calculated for each scenario, considering the energy savings achieved. In any case, as presented later in detail, some reference values related to the implementation costs of these systems are provided in order to make the analysis of the results presented in this paper easier to the reader.

In order to take into account the effect of a discount rate value, as well as possible variations in energy costs over the next few years, the gradient present worth (GPW) has been calculated for each scenario [31]. This factor can be used to estimate the present amount of money P (in this case, investment cost) that can be paid by annual amounts A' (in this case, economic savings corresponding to energy savings which escalate at e percent (increase of energy cost), at i percent interest (discount rate), for n years. This indicator has been calculated for each scenario using Eq. 2.

$$P = A' \times \frac{\frac{1+e}{1+i}\left[1-\left(\frac{1+e}{1+i}\right)^{n}\right]}{1-\frac{1+e}{1+i}} \qquad \text{Eq. 2}$$

To calculate the economic impact of energy savings, a natural gas cost of 8.75 c€/kWh has been assumed, according to data concerning gas prices for household consumers in Spain for the second half of 2018, provided by Eurostat [32]. On the other hand, a discount rate (i) of 3% has been assumed (following the criteria used in [33]) and, even though in the literature some fixed values for the growth rate of natural gas can be found (e.g. 3.5 %, in [34]), due to its uncertainty, two different extreme rates of increase in energy costs (*e*) have been considered: 0% and 8% per year, so as to evaluate two extreme scenarios. As previously mentioned, the calculations have been carried out for periods of 10 and 20 years (*n*).

4 Results and discussion

According to the methodology described in detail in the previous section, the resulting yearly heating consumption in the 336 scenarios was obtained. In this section, these results are presented and discussed by means of an energy and economic assessment. Firstly, yearly energy consumption results are presented and discussed; then energy savings are calculated, following the procedure and criteria presented in section 3.5. Afterwards, these energy savings are turned into economic savings and finally, based on these economic savings, the economic feasibility of zonal space heating control systems are evaluated by means of the GPW described in section 3.5.

4.1 Energy results

The calculated yearly heating consumption results, for the three climatic conditions evaluated, are depicted in Fig. 5. For the sake of clarity, a two-colour code has been used: grey bars represent the scenarios corresponding to a 0% of average opening time (Scenarios D1); whereas black bars represent the scenarios where the maximum air exchange between adjacent indoor rooms was assumed (Scenarios D2). Moreover, the results are grouped together by typology (the first 56 bars correspond to the smaller apartment (T1) and the other 56 bars represent the energy consumption of the larger apartment). Additionally, another subdivision has been applied, according to the level of thermal insulation of the envelope (from E1 to E4).

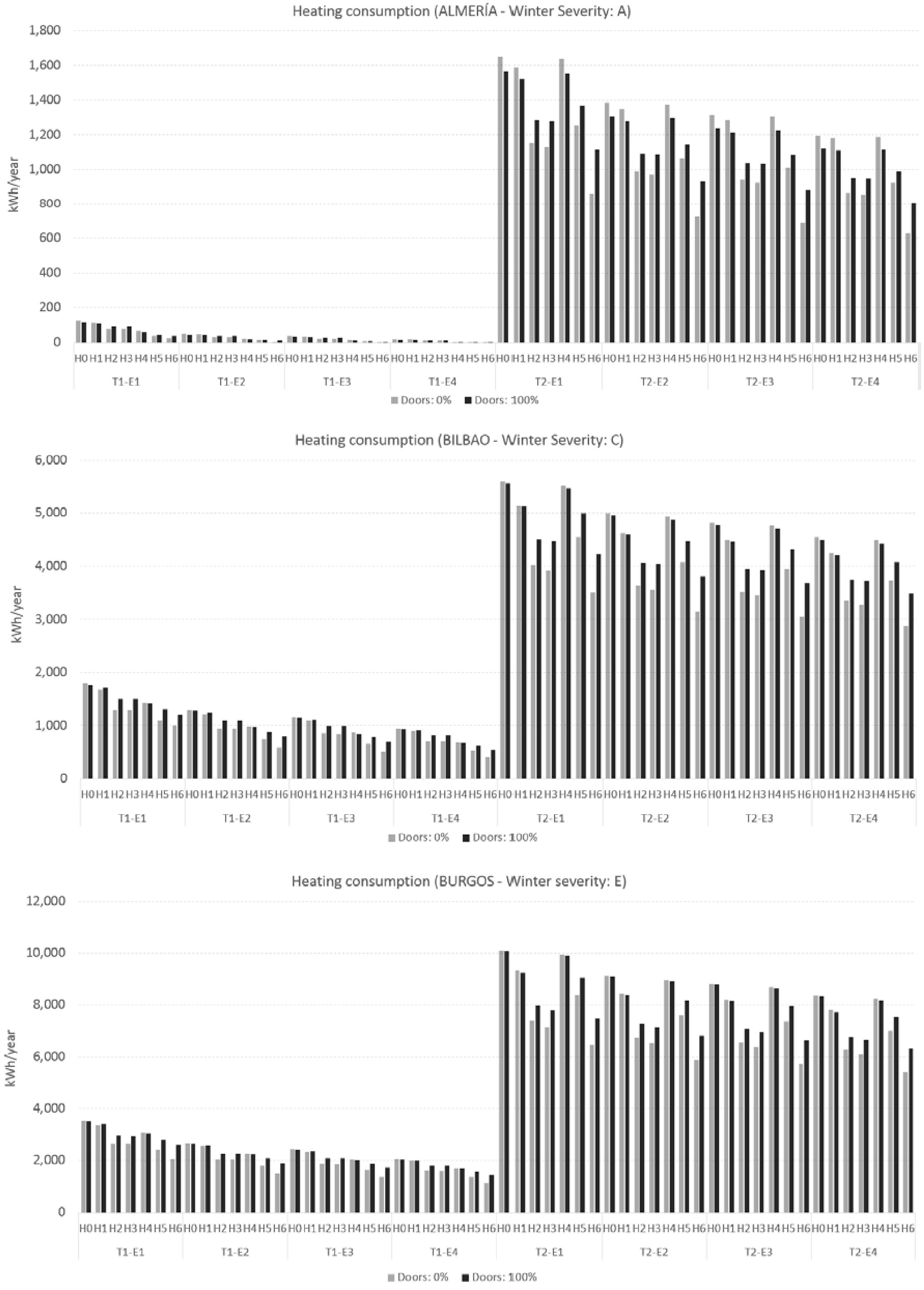

Fig. 5. Yearly heating consumption in the 336 scenarios evaluated, gathered by location

Some general trends can be identified in these data. At first sight, the differences in the heating consumption between both typologies are clear, the consumption in T2 being about 3-4 times higher than that obtained for T1 (except in the scenarios located in Almeria, where the ratio changes significantly due to the low energy consumption values). These differences are reduced when the energy consumption per square meter is analysed, but they are still significant (in general between 1.5-2 times higher in T2 than in T1).

In addition, several tendencies can also be identified when focusing on the different scenarios assumed for the heating operation (H) in all locations evaluated. As expected, H0 (heating system activated the whole day, according to set-point temperatures defined) presents the highest consumptions in all cases, followed by H1 and H4 (both scenarios with a central heating control in the apartment). Regarding this issue, the trend differs when typologies T1 and T2 are compared to each other: while scenarios H4 present higher consumption than scenarios H1 in T2 (due to the fact that the heating system is on for longer in H4), this trend, counter intuitively, does not occur in T1. This is because of the occupancy gains (higher in H1) which, being the same in both typologies in absolute values, their specific weight is more significant in T1, where the demand is lower. As a consequence, the occupancy gains in this typology compensate the fact that the heating system is operating for longer.

The last consideration in this first analysis of the energy consumption values is related to the "door opening" scenarios (D). As expected, the assumed value of air exchange between adjacent indoor zones hardly affects the yearly consumption in those scenarios where no zonal heating control is assumed (H0, H1 and H4). In these cases, the energy consumption is virtually the same for D1 and D2 (or even slightly higher in D1 scenarios, as the graph in Fig. 1 clearly shows, where the heating consumption values in Almería are depicted). The differences between the two extreme scenarios related to air exchange are clearly shown in those scenarios where a zonal heating control system was assumed (Z2 and Z3, i.e., H2, H3, H5 and H6). The influence of this parameter (the lower air exchange between adjacent rooms is, the lower the energy consumption will be) can be clearly appreciated in the results of typology T2, but it can also be observed in the smaller apartment (T1). The effect is especially noticeable in H6 (mainly in the larger apartment).

After this first analysis, the effects of the zonal heating control systems were evaluated. To do so, the energy savings for each scenario were first evaluated. Thus, the energy savings calculated (in %) for each zonal heating control scenario for the three locations evaluated are depicted in Fig. 6.

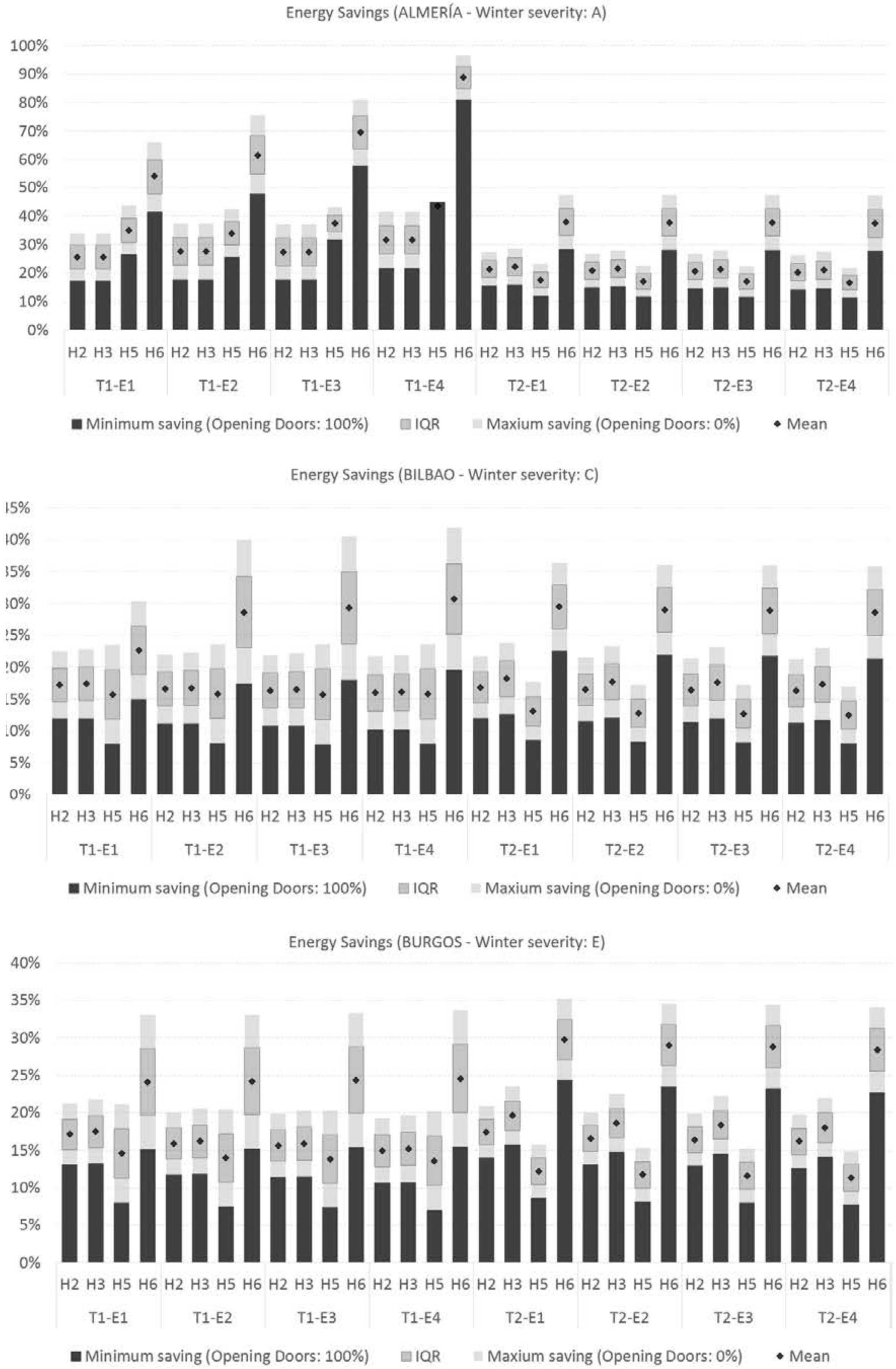

Fig. 6. Yearly energy savings in the 336 scenarios evaluated, gathered by location

The dark grey bars represent energy savings assuming the maximum air exchange between indoor adjacent zones (that is, minimum energy saving values); whereas the light grey bars represent the range of energy savings depending on the level of air exchange between adjacent rooms. The light grey bars, then, present the uncertainty associated to the effect door opening has on the evaluation of zonal space heating control systems, especially in residential buildings. In order to perform a more adjusted analysis, the graph highlights the middle values (the darkest part of the light grey bars) more than the extreme ones (those located in the upper and lower quartiles of the light grey bars, highly unusual) by focusing on the interquartile range (IQR) of each scenario (the middle 50%, IQR in Fig. 6, represented as a darker grey part inside the light grey bars). Additionally, the mean value of that range has also been represented in each bar by means of a black dot.

Similar trends can be identified when values obtained for Bilbao and Burgos are compared. Comparable energy savings in percentage can be observed for H2 and H3 (those corresponding to the 4-person occupation, O1) in the smallest apartment: the values range between 15 and 20%, with mean values around 17% in all cases. An analogous trend is also identified in the large apartment (T2), when the same occupancy profile is evaluated, even though in this case a slight difference (about one percentage unit in the case of Bilbao, from values around 16.5% in H2 to values around 17.5% in H3, and two points in the case of Burgos) can be found. This point shows that no significant additional benefits (in terms of energy savings) are achieved when zoned control for each individual room is applied when compared to a simpler zoned control based on day-time and night-time rooms in apartments with this kind of occupancy profile.

However, zoned control criteria involve meaningful effects on energy savings when they are evaluated for the 2-people occupancy profile in both locations, regardless of the typology (T1 or T2) assumed. Whereas H5 shows similar energy savings to H2 and H3 (with values that range from 15% to 20% in typology T1 -similar values to those concluded by Cockroft et al. in [7]-, and slightly lower in typology T2), H6 reaches values that range from 25% to 35% and mean values in Bilbao around 30% in all cases, with the exception of the first typology with lower thermal performance (T1-E1). In this latter case, the values range from 19% to almost 27%, with a mean value of 22.7%. In the case of Burgos, the mean values are close to 25% when typology 1 is considered. In the case of Almería, taking into consideration the low heating necessities, the percentage of energy savings for each scenario should be analysed with caution and, in any case, absolute values in terms of economic savings (which are presented in the next section) are more representative and useful for their evaluation.

To complete this part of the analysis, the energy savings obtained were compared to those presented by Cockroft et al. [7], to evaluate the concordance of the obtained results with other previous works in the same field. In that study, two profiles of the four evaluated were a "young family" (YF) and "Elderly Couple" (EC), which are closely related to O1 and O2 assumed in this paper. Similarly, two different typologies were evaluated (Bungalow and Semi-Detached) which, in terms of size, could be similar to typologies T1 and T2, respectively. Based on this correspondence, the comparison between the energy savings obtained in the three locations assumed in this paper and those obtained by Cockroft are presented in Table 3. In this table, the average values of energy savings obtained are summarised by occupancy profile and typology for each location. The difference with the analogous value obtained in [7] is also included in brackets below each value. It can be observed that, with the exception of Almería (where heating consumption values are uncommonly low), energy savings obtained in Bilbao and Burgos are quite coherent with those obtained in [7]).

Table 3. Comparison between energy savings obtained in this study and those obtained in [7] (%).

	Door Opening	**ALMERÍA**		**BILBAO**		**BURGOS**		**Cockroft et al. [7]**	
		YF	**EC**	**YF**	**EC**	**YF**	**EC**	**YF**	**EC**
T1	**0 %**	37.45 % *(+14.45)*	61.27 % *(+33.97)*	22.20 % *(-0.8)*	30.87 % *(+3.57)*	20.34 % *(-2.66)*	26.91 % *(-0.39)*	23.0 %	27.3 %
	100 %	18.54 % *(+7.34)*	44.56 % *(+31.96)*	11.04 % *(-0.12)*	12.74 % *(+0.14)*	11.78 % *(+0.58)*	11.39 % *(+1.21)*	11.2 %	12.6 %
T2	**0 %**	27.38 % *(+5.48)*	34.91 % *(+9.11)*	22.42 % *(+0.52)*	26.69 % *(+0.89)*	21.37 % *(-0.53)*	24.94 % *(-0.86)*	21.9 %	25.8 %
	100 %	14.96 % *(+1.76)*	19.85 % *(+4.05)*	11.82 % *(-1.38)*	15.08 % *(-0.72)*	13.96 % *(+0.76)*	15.78 % *(-0.02)*	13.2 %	15.8 %

4.2 Economic results

Having calculated energy savings and shown the coherence of the obtained results, these energy savings were turned into economic savings according to the criteria presented in section 3.5, so as to have a first approach to the feasibility of this kind of system. Thus, the obtained ranges of yearly economic savings for each location are depicted in the box plots presented in Fig. 7. The ranges presented in this graph were calculated defining the maximum (energy savings corresponding to 0% of opening doors) and minimum (energy savings corresponding to 100% of opening doors) Values. Also, as described for the energy savings in Fig. 6, this graph highlights the interquartile range of each scenario, which includes the most probable results within the whole range in order to focus on a more reduced range. In this case, the IQR is represented with grey bars, with the maximum and minimum value of each scenario depicted by a dark grey point and a black point, respectively. It can be appreciated that it follows a similar pattern to those identified in the energy savings in Fig. 6. The only change is related to the fact that, in this case, the results are not relative (as in Fig. 6, in %) and, consequently, the differences between the savings of the large (T2) and small (T1) apartments are clearly shown in the graph. It should also be remarked that the economic savings in the case of Almería are almost negligible in all scenarios where typology 1 is considered.

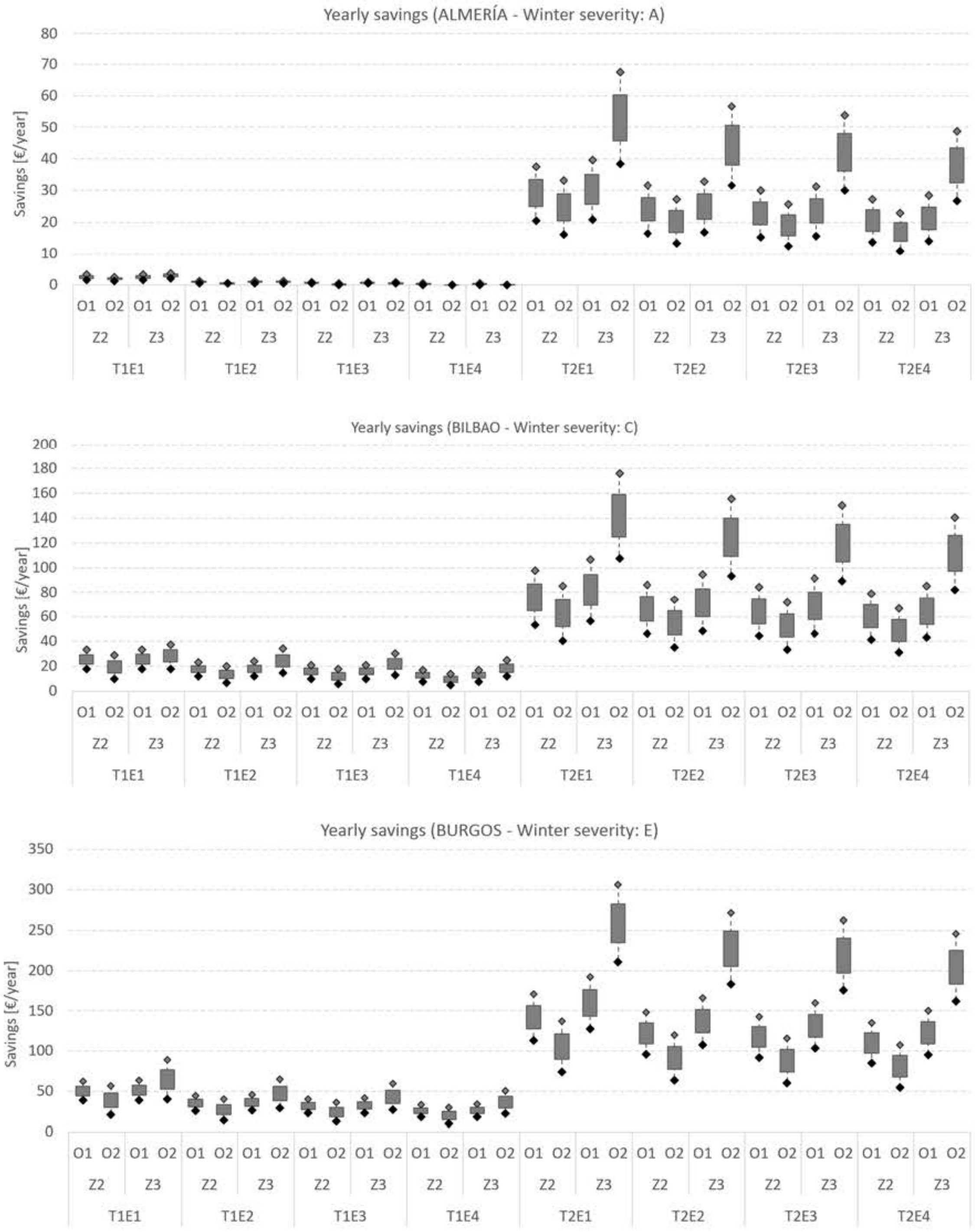

Fig. 7. Ranges of yearly economic savings in the 336 scenarios evaluated, gathered by location

Finally, these savings are transformed into GPW in order to calculate the maximum investment if payback periods no longer than 10 years and 20 years are to be assumed. To do so, based on a discount factor of 3.5% and the two possible scenarios of energy cost variation (0% and 8%) discussed in section 3.5, the GPW values obtained for each scenario in the three different locations are depicted in Fig. 8 (assuming a 10-year period) and Fig. 9 (assuming a 20-year period). In these graphs, the light grey squares and dots represent the values for each scenario corresponding to the assumption of e=0% (considering doors totally open and totally closed, respectively); while black squares and dots represent the values corresponding to the assumption of e=8%.

Before starting analysing the results presented in those graphs, it should be noted that very few academic works giving reference values of the investment costs of these systems have been found in the literature. One of them is the aforementioned study presented by A. Baizaee et al. in [10]. Since it was published in 2015 and costs may have changed since then, updated costs of implementing this kind of systems have also been explored. It should be taken into consideration, however, that, due to the variability of these costs (mentioned in section 3.5), they are presented just with the aim of providing an additional reference for interpreting the results. As a way of example, in Table 4 some current investment costs (checked in February 2020) for different systems are presented, as well as a short description of each one. The cost referenced in the table for the high quality system also includes a device for integrating the heating control with other automated systems of the apartment (such as lights control or blind control, for example) in a unique interface. The table also includes the cost presented by Baizaee et al. in [10].

Table 4. Investment cost of different systems for implementing zonal space heating controls

	Description	**Cost (Feb. 2020)***	**Cost based on [10]**
Basic system	Single TRVs (x4)	70 €	160 €
Medium system	Smart TRVs (x4) + Smart Thermostat *(It allows more flexible schedules and WiFi connection)*	350€	-
High Quality system	Smart TRVs (x4) + Smart Thermostat + Automation system *(It also includes a remote control and additional features such as "self-learning mode" (valves learn how long it takes to heat up a room) or the "Open Window feature", which allows the valve to detect possible windows openings (by means of sudden drops in temperature) in order to turn heating down)*	850€	1600 €

**The costs of this column do not include the installation nor possible modifications of the heating system configuration*

It should be noted that updated costs (February 2020) do not include the installation and they consider that the existing system is fully compatible with the new TRVs, so consequently, that no changes in the heating system configuration are required. Otherwise, investment costs would also have to include the mentioned extra charges. Considering this issue, it can be observed that these values are in coherence with those presented in [10]. Thus, in order to consider conservative values, the reference values presented by Baizaee et al. are considered as adequate as limits of the cost-values range, and they are consequently represented in Fig. 8 and Fig. 9, by means of two dotted red lines (160 € and 1600 €). In any case, any of the cost including in Table 4 can be employed when interpreting the results, according to the specificities of the case study evaluated.

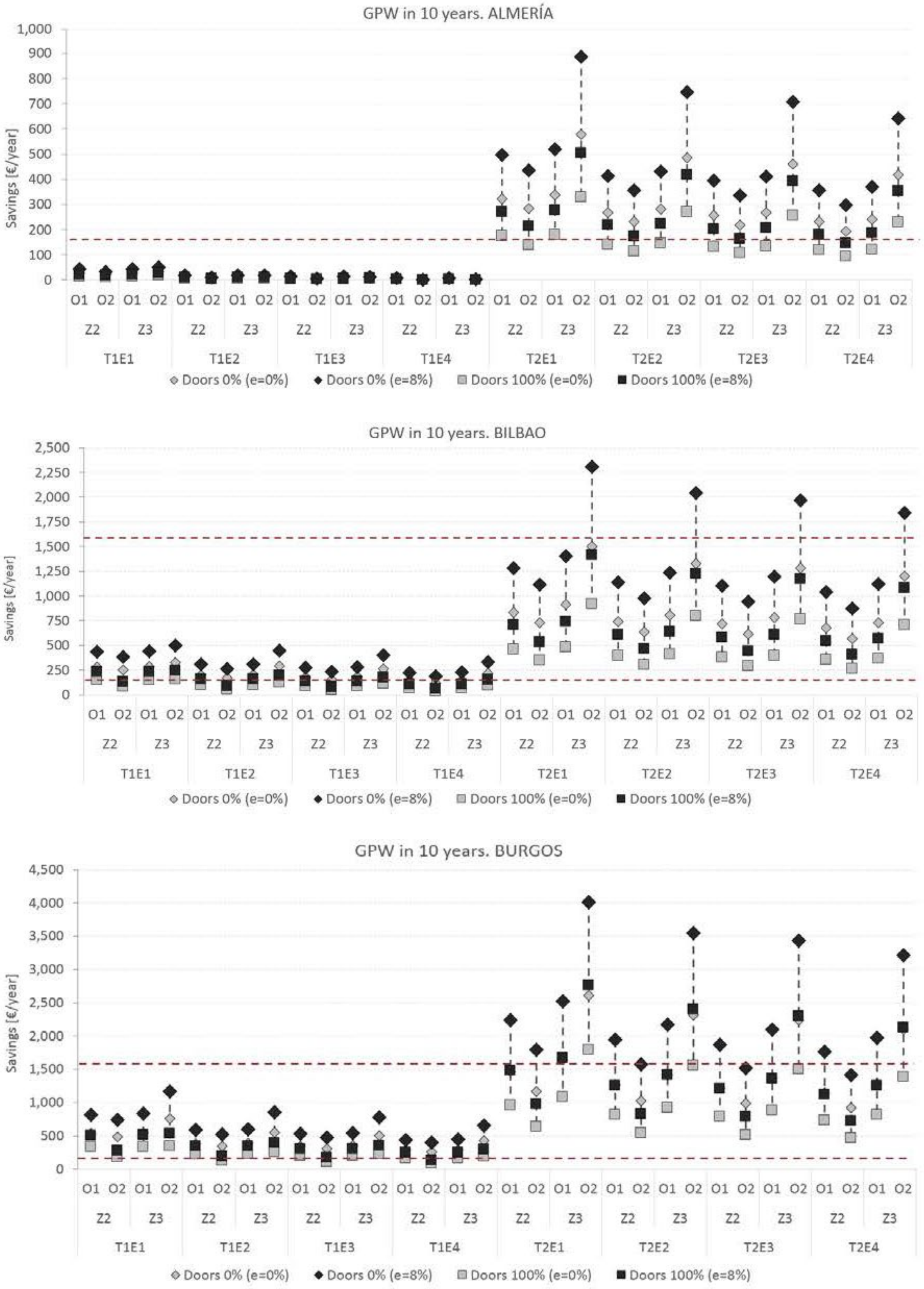

Fig. 8. GPW values assuming a 10-year period

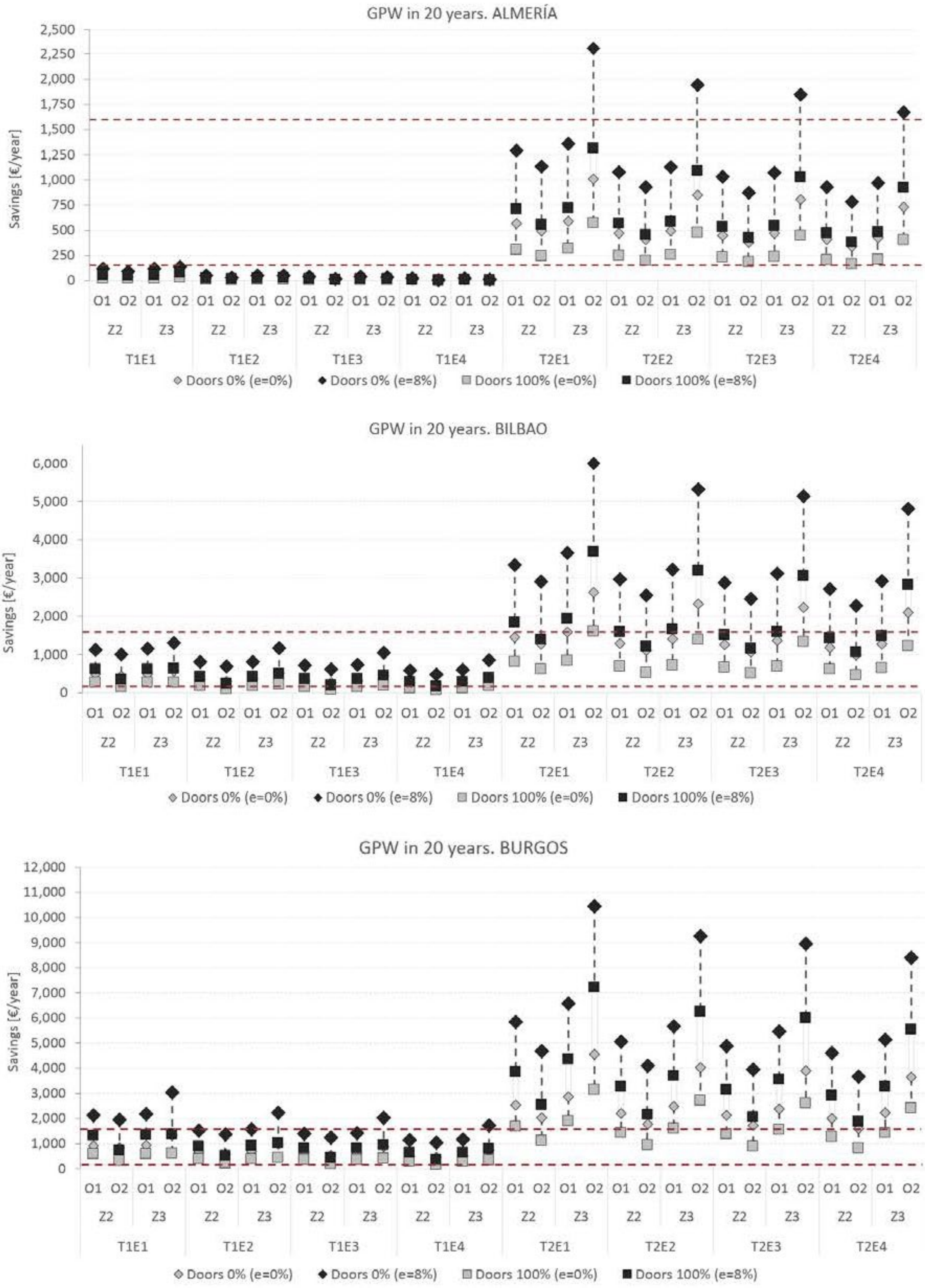

Fig. 9. GPW values assuming a 20-year period

When a 10-year period is targeted, it can be seen that, in the case of Bilbao, a luxury system could only be economically justified in the large apartment, in H6 scenarios, and if energy costs increase significantly in the next years (4 out 128 of the evaluated scenarios, 3.13%). Its potential increases a little if a 20-year period is considered. In this case, the amount of evaluated scenarios which present GPW values higher than the considered cost for the luxury system (1600€) is 28 - all of them in Typology 2 -, 21% of the scenarios evaluated. In this climatic zone, the results show that a basic system could be a cost-effective solution regardless of the typology: only 8 scenarios present lower GPW-20 values than the cost of a basic system (160€), and more than 75% present a payback period lower than 10 years (97 out 128 of the evaluated scenarios).

In the case of Burgos (the coldest winter conditions), the basic system presents payback periods lower than 10 years in almost every case (123 out of 128), whereas the luxury system could also be a cost-effective option if a 20-year period is evaluated (62 out 128), mainly in large apartments.

On the other hand, in the warmest climate in Spain (represented by Almería), according to the obtained results, the potential of these systems is quite limited. The basic system presents payback periods higher than 20 years in all scenarios evaluated for typology 1, and only 4 scenarios present a GPW-20 value higher than 1600€, all m in Typology 2, when an 8% yearly increase in the energy cost is considered.

To summarise all these data, the average values of GPW in each location by typology and zonal criteria are presented in Table 5. It can be stated that, in the case of the mildest winter climatic area, the use of these systems is hardly justified from the economical point of view, and only a basic system could be justified in the case of large apartments. The coldest climate area in Spain (in this study represented by Burgos) is just the opposite. The investment corresponding to a basic system would present an average payback period shorter than 10 years in the small apartment (T1), even using the daytime-night time zonal criterion (Z2); whilst in the case of the large apartment, GPW values show that the luxury system defined by Baizaee et al. would involve payback periods close to 10 years. The intermediate climatic zone, represented by Bilbao, would present good values for justifying the economic feasibility of the simple system in typology T1, and the luxury system would be justified in large apartments, represented by typology T2.

Table 5. Average values of GPW in each location, by typology (T) and zonal criteria (Z)

		Almería		**Bilbao**		**Burgos**	
		GPW10	**GPW20**	**GPW10**	**GPW20**	**GPW10**	**GPW20**
T1	**Z2**	10.71 €	24.27 €	170.49 €	386.40 €	346.21 €	784.64 €
	Z3	13.42 €	30.41 €	223.53 €	506.60 €	459.01 €	1040.37 €
T2	**Z2**	240.03 €	544.00 €	658.63 €	1492.68 €	1161.22 €	2631.72 €
	Z3	375.42 €	850.84 €	1061.28 €	2405.22 €	1973.44 €	4472.50 €

5 Conclusions and future works

This paper assesses the potential for implementing zone-control systems in residential buildings in climates of southern Europe, from both the energy and economic points of view. To do so, and considering different climate conditions in Spain, the impact of two different zone-control systems are evaluated for two different apartment typologies, occupancy patterns and building characteristics.

The results obtained in terms of energy savings are coherent with other studies found in the literature focused on applying this kind of systems in northern Europe (energy savings of around 15-25%). They show that zone-control systems could be a cost-effective strategy to reduce the heating consumption (and its associated emissions) in residential buildings for two out of the three climatic conditions evaluated (C and E). These values demonstrate that basic systems present acceptable payback period values in intermediate climate areas (Bilbao, in this study); whilst, in the coldest areas of Spain (Climate zone E, represented by Burgos in this study), they present acceptable payback periods even for “luxury systems”, and less than ten years in several scenarios, especially in large apartments.

Additionally, this study also provides results that prove the economic feasibility of these systems, with the exception of the climatic zone with the lightest winter severity. This outcome is significant, if we take into consideration the fact that these latter winter severity conditions represent about 14% of the total population of Spain and 8.13% of the total surface of the country; whereas the area represented by climatic zones C, D and E covers more than 60% of the total population and 77% of the total surface area of the country.

This paper presents a first approach for evaluating the potential of implementing these systems in such climates. They show promising results and may well be a good base for further and more detailed analysis of this strategy. This potential can be significantly boosted with the irruption of smart heating systems and occupancy prediction systems, which could result in the automated operation of residential heating systems, thus optimising global performance. The actual effects of combining these strategies should be evaluated in the future by testing under different conditions, due to the difficulties of using computer modelling to consider the real interaction between people and controls in an adequate way.

Finally, the variability of the results due to the consideration of different values of some parameters (door opening, occupancy and heating schedule) should be highlighted. In many cases, these values are very changeable and, to some extent, unpredictable (especially in the case of residential buildings). The effect of these parameters on the final energy results underlines the need for an accurate definition of these values when simulation models are defined, as well as the necessity of carrying out sensitivity analyses or presenting the results with ranges of potential values, instead of providing a fixed value. Also worth highlighting is the interest in continuing to carry out research into user behaviour and interactions between users and buildings (how simulation models have to be implemented to evaluate their effects on energy consumption), as an effective strategy for reducing the energy consumption in residential buildings.

6 Acknowledgements

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