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Effects of individual metering and charging of heating and domestic hot water on energy consumption of buildings in temperate climates.

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ABSTRACT

Individual metering and charging of heat and domestic hot water is one of the possibilities for reducing the energy consumption in existing multifamily buildings and, with this aim in mind, the EU-directive 2012/27/EU enforced the installation of individual heat consumption meters. Even though some experimental evaluation of energy savings that may be achieved in multifamily buildings with individual metering & charging systems can be found in the literature, the majority of these research pieces are focused on case studies or taking into consideration conditions related to cold climates, and there is still a lack of studies focused on evaluating its effects in more temperate climates that can be also found in Europe. Thus, in this paper, the potential of individual metering and charging of heat and hot water for saving energy in residential buildings in temperate climates is evaluated and quantified. To do so, a literature review on implementation of this system is carried out and presented firstly to get a better understanding of its implications on energy consumption in buildings. Afterwards, heating and hot water consumption data collected in a multifamily building where individual metering and charging system was implemented is evaluated in detail. With the aim of quantifying the actual its effect on heating and hot water consumption, data corresponding to four complete heating seasons (two heating seasons prior to the its implementation, and the two first heating seasons after implementing it) have been evaluated in detail, following a specific method described in the paper. Results show that individual metering and charging has brought a reduction of normalized energy consumption of 15-20% during the first two years after implementing it, and simple payback periods are around 10 years. These results confirm that individual metering and charging affects directly on user behaviour encouraging inhabitants to change their habits to reduce their energy consumption, and this effect is significant even in European temperate climates, such as the evaluated case study shows.

Keywords: *Individual Metering and Charging; heat cost allocation; Heat Metering; Energy Efficiency; Adaptative behaviour; Occupant behaviour; Multifamily buildings*

1 Introduction

Nowadays, amongst the energy consumption sectors, buildings are responsible for 40% of the overall primary energy consumption in EU as well as one third of related global greenhouse gas emissions [1]. For this reason, the European Union has enforced different directives during the last decades aimed to reduce the energy consumption in both new and existing buildings. In this context, on 14 November 2012, the Directive 2012/27/EU on energy efficiency promoted by the European Commission was published in the Official Journal of the European Union [2]. This Directive aims to increase the energy efficiency within the EU in order to achieve the objective of saving 20% of the primary energy consumption by 2020. One of the proposals included in this directive consists of using individual metering and charging (IMC) for heating, cooling and Domestic Hot Water (DHW) in multi-apartment buildings with centralized heating systems. This suggestion was based on the idea that the fact that each household in a multi-apartment building pays according to its own energy use (instead of a collective pay based on floor areas, for example) involves a reduction of energy consumption by creating a "saving behaviour" [3]. Thus, the EU-Directive 2012/27/EU (article 9) establishes that "*individual consumption meters shall also be installed by 31 December 2016*" in multi-apartment buildings with a central heating/cooling source "*where technically feasible and cost-efficient*" [2]. However, the article is quite general and specific implementation and solutions depends to a large extent on its transposition by the member states.

The use of individual consumption meters is not something new. In fact, the need for individual metering emerged when central heating was introduced in the largest cities in Europe in 1920s, and the first studies about this issue date from that decade [3]. Moreover, maybe because of the aforementioned Directive, the amount of studies related to IMC has slightly increased in the last decade. It must be highlighted that the majority of these recent studies aimed to evaluate the actual effects of IMC implementation in buildings are focused on case studies with cold climatic conditions. For instance, an experimental research conducted during 17 heating seasons in a multifamily building located in Lublin (Poland) is presented in [4], and P. Michnikowsky proposes a method for allocating heating cost in multifamily buildings by means of analysing a building located in Poznan (Poland) in [5]. Similarly, several research pieces have been conducted based on Swedish climate conditions, such as: [3], where a deep statistical analysis is carried out with the aim of investigating how widespread is the use of IMC in cooperatively owned multi-apartment buildings); [6], where the effects of IMC on indoor thermal conditions in 14 apartment blocks located in Lund are evaluated; [7], where the results of a survey aimed to analyse the incentives for a landlord to use IMC is presented; [8], where a research piece aimed to develop a cost-efficient method for estimating the size of heat transfer between adjacent apartments (and then, using these estimations for reallocation of heating costs) is conducted; or [9], where a simulation of three apartments is carried out with the aim of evaluating how different issues (solar radiation, heat production, apartment location within the building...) affect the accuracy of IMC. In this last case, the climate input data used were for Malmö. Some studies from other European countries can be also found in literature (e.g.UK [10] or Denmark [11], to name but a few examples). All mentioned cases present a high level of winter severity (taking as reference the $HDD_{15/15}$ in 2017, Lublin had 2088 HDD; Poznan 2453; Lund, Malmö and Copenhagen around 2250; London 1538; and Stockholm 2965)*. However, there is a lack of studies focused on evaluating its effects in more temperate climates.

Thus, this paper presents the first findings related to the effects of implementing an IMC system in a temperate climate, based on data obtained for four heating seasons (2 before installing the IMC, and 2 with IMC system implemented) from a case-study building located in Bilbao, northern Spain (in 2017, Bilbao had 932 $HDD_{15/15}$)*. This research piece assesses how installing IMC influences the DHW and heating consumptions of the building and its related costs. While some authors have reported that learning curve of users for these is about 3 years [4], this study covers two complete heating seasons after implementing IMC, so it can be expected that results related to reduction of heat consumption will be sensible higher in the next months. Hence, the main research question guiding this study is:

- Which are the main effects on energy and economic consumption that IMC implementation has in a temperate climate, such as Spain? (RQ1)

To answer this question, a stepwise research work has been conducted. Firstly, a literature review has been carried out, with the aim of addressing the next question:

* Data collated from the following climate stations: Orzechowskiego, Lublin, PL (22.58E,51.22N); Poznan, PL (16.83E,52.42N); Koebenhavn/Kastrup, DK (12.65E,55.61N); London, GB (0.45W,51.48N); Stockholm/Bromma, SE (17.90E,59.37N); and Bilbao/Sondica, ES (2.91W,43.30N). These data are available in degreedays.net

- Which are the main barriers, potentials and issues related to IMC identified by other authors, and what is their weight in the current context of Spain? (RQ2)

After carrying out the literature review, a case study located in Spain has been evaluated. To do that, the following question has to be faced:

- How can be analysed and disaggregated energy consumption with DHW and heating purposes when available data are aggregated? (RQ3)

According to these research questions, three are the main objectives faced with this paper. First, this work aims to present an overall picture of IMC systems by means of a deep literature review (RQ2). This literature review addresses the implementation and effects of IMC on energy consumption, focusing on identifying the recurrent issues which must be taken into consideration for its implementation, and finally analysing how they influence the specific context of southern Europe, namely in Spain. Secondly, the study aims to define a simple method to disaggregate energy data related to DHW and heating purposes. In existing centralized heating installations with no IMC systems, these data are usually available in aggregated form, so making it difficult to assess the actual effect of a given measure on heating or DHW consumption (RQ3). The third objective of this paper is to quantify and asses the actual effect of IMC on energy use in a temperate climate, by assessing a case-study located in northern Spain (RQ1). Finally, the main findings related to the implementation of IMC systems in temperate climates, based on both the literature review and the results obtained from the case study, are summarized.

The remainder of this paper is organized as follows: Section 2 presents the aforementioned overall picture of IMC systems by means of a literature review. The methods followed to assess the Spanish case study are detailed in Section 3. Section 4 presents the obtained results, while their discussion is next presented in Section 5. Finally, the main conclusions are addressed in Section 6.

2 Context

In this section, a literature review on IMC systems is presented, including firstly a short mention on how users' behaviour can affect the energy consumption in buildings.

2.1 Influence of occupants' behaviour on energy consumption

The idea of IMC is closely linked with the effect of occupants' behaviour on energy consumption. Since 1970s, when Socolow's Twin Rivers study showed that the energy consumption of a dwelling depends not only on the physical features of the building, but also on the occupants' behaviour [12], the effect of occupants' influence on the energy consumption in buildings has been profusely analysed, being currently a relevant topic in the area of energy use in buildings [13]. In this sense, several studies have pointed out large differences in energy consumption for similar buildings due to the occupants' behaviour [14], showing that, as stated within the Annex 53 framework, human behaviour could have an impact even greater than the building characteristics or other factors [15].

Relationships amongst behavioural patterns, user profiles and energy use are thoroughly analysed in [16]. This latter point is also illustrated in a representative research piece where the example of energy use data obtained from a field survey in 110 similar dwellings (building characteristics, orientation...) is presented [17]. Energy use of the dwelling with the highest consumption was 12 times bigger than energy use of the dwelling with the lowest, despite the fact that every dwelling exhibited similar characteristics, except for the occupants' behaviour. In [18], the effect of different control settings on energy consumption of energy systems is analysed, showing that, amongst the different control settings evaluated, the greatest impact is that related to the occupants' behaviour: reductions over 10% can be achieved when lowering 2 °C the average indoor temperature set-point in temperate climates.

It can be stated, then, that energy use is also closely related to human behaviour and, consequently, may be reduced through behavioural changes [19]. In consequence, driving factors with influence on these behaviours have been a point of interest in many studies [20]. In the light of this effect, household energy conservation has also been a topic of interest within applied social and environmental psychological research for a number of decades. In the 70s the background was the energy crisis, whereas currently there are also environmental problems such as global warming. Abrahamse et al. [19] review various intervention methods aimed to reduce energy consumption, one of which is the feedback, i.e. the way the energy bill is presented. Several studies taking into account different parameters and kinds of feedback (frequency, comparative feedback...) are reviewed, and significant energy savings as a consequence of the mentioned intervention are reported. Another example on the relationship between billing information and household energy consumption was conducted in 1995 in Oslo [21], and many studies have been developed since then, both showing the effects of providing feedback on efficient energy use (although an important share of them are focused on electricity consumption such as the literature review presented in [22] shows, studies focused on heating consumption and thermal adaptation [23] can be also found) and how occupants' awareness can decrease significantly their energy consumption [11].

However, occupants are not likely to modify their behaviour if they have no motivation (e.g. economical motivation, environmental awareness, social drivers...). Thus, individual metering, together with feedback elements, are seen by several authors as promising strategies for reducing the energy consumption in residential buildings [10]. Individual metering and feedback are related to diverse motivations for reducing energy consumption. For instance, Gunay et al. [24] compare users' behaviour in apartments with bulk-metering and apartments with sub-metering and show how sub-metered apartments kept the temperature lower than apartments with bulk-metering with the aim of reducing the energy bill, but also for environmental reasons.

2.2 Individual Metering and Charging

Individual metering and charging allows each apartment paying for its own use of heating and DHW. They can be used either for heating and DHW, for heat only or for DHW only. As several authors claim, IMC can increase occupants' awareness of costs and, in most cases, result in saving behaviours and more efficient energy use [7].

IMC involves two different aspects: the measurement of the consumption and the allocation of the cost amongst the different apartments supplied by a centralized system.

Regarding the first issue (i.e. measuring the consumption), DHW consumption is usually measured with flow meters mounted in the DHW incoming pipe. As far as heating consumption is concerned, two different methods are considered in the Energy Efficiency Directive (2012/27/EU), as Siggelsten mentions in [7]:

- Flow metering. Using an energy meter mounted on the radiator circuit.
- Radiator metering. Using heat cost allocators mounted at each radiator to measure heat emitted by them.

A third method is considered by ASHRAE [25], which consists on allocating energy costs on the basis of relative thermal comfort amenity, by means of measuring actual indoor temperatures through sensors in different locations of the dwelling. In this case, the principle is to charge residents for energy costs in proportion to the level of thermal comfort maintained in their apartments [7].

The selection of the proper method will depend on the specific features of each energy system and building. Even though flow metering method allows reaching a more accurate information of individual heating energy use, if each dwelling of a given building is supplied by more than one radiator circuit, this method may not be a cost-efficient method, being then radiator metering a better option.

In regard to the second aspect, the allocation of the cost of centralized DHW and/or heating systems amongst the different apartments aims to cover all operation costs of the system (i.e. fuel cost, energy losses, inefficiencies, maintenance of installation and auxiliary energy cost). These costs can be assigned in two different ways: consumption independent (consumption and cost are decoupled) or as a function of the actual heat demand. In the first case, flat rate charging (e.g. adding a fuel surcharge per dwelling based on the actual cost of heating the whole building, and divided equally among the flats, usually taking into consideration flat sizes or similar criteria) is a typical example of decoupling where users cannot influence their cost and, consequently, they have no economic incentive to develop an efficient energy use. In the latter case, a relation between heating costs and actual energy consumption is established and, in consequence, it has the potential of encouraging final users to optimize their heating system operation, to develop thoughtful ventilation practices and to use DHW in a more careful way by means of financial stimuli [10]. In this case, the heat consumed in every dwelling of the building must be measured using one of the methods presented before.

On the other hand, it must be taken into account that the cost associated to implementation of an IMC system (whatever it is) is not just the cost for purchasing and installing the meters, but also an administration cost must also be considered [3], which is usually included as fixed cost in terms of operation costs.

When introducing allocators, cost related to heating and/or DHW system is usually divided into two parts: a variable cost (proportional to the actual energy consumption) and fixed cost (which is paid regardless of meters or allocators readings, and it can be distributed according to the liveable area) [26]. Fixed cost usually covers those costs related to system maintenance and heat losses through the system. However, these latter costs, associated to inefficiencies and energy losses through the system, are not frequently known with accuracy and the share of fixed part with respect to the total cost varies significantly amongst buildings. In fact, there are arguments about whether energy losses should be included in the variable part or not. An analysis on the effects of having a higher or lower percentage for the fixed expenses is presented in [27].

The potential of IMC systems for saving energy, however, is not only related to economic incentives, but also to their potential of being an instrument for providing information about energy use, and consequently increase awareness on energy consumption, as shown by Henryson et al. [28], where the potential of reducing energy consumption by just reporting information was demonstrated.

2.2.1 Background and literature on individual metering

The beginnings of individual metering systems can be linked to the development and implementation of central heating systems, which started getting introduced in Europe in the 1920s. These systems, together with several advantages, brought up the dilemma of how to transfer to final users costs associated to a given central system.

In some countries such as Sweden this dilemma was solved by using consumption-independent allocation methods. In other countries such as Germany, implementing central heat systems became an opportunity for installing individual metering and it carried the first approaches about how costs related to centralized systems could be allocated amongst their users using a consumption-dependent way [8].

Since then, during the last century, IMC systems have been implemented in different European countries at different levels and, due to the recent approval of the aforementioned 2012/27/EU-Directive, with growth prospects. As well as Germany, where its implementation is mandatory since 1981, other countries with wide experience are Austria (mandatory since 1992), Switzerland and Denmark (mandatory since 1999 in both cases) [6].

Because of this development, the effects of IMC on energy consumption and indoor environment have been object of attention in different studies. Many of them are based on the working hypothesis that the relation between actual consumption and costs established by IMC systems involves a more efficient use of heating systems and a careful use of DHW, as a consequence of the economic motivation. Thus, different authors show energy savings related to heating and DHW between 10-20% and even close to 40% in Sweden [8]. T. Cholewa and A. Siuta-Olcha also reported energy savings of 20% associated to an installation of heat cost allocators in Poland [4].

On the other hand, as a consequence (or cause) of their effect on energy consumption, IMC systems have a direct effect on the indoor temperature of dwelling where means for controlling heating systems (such as thermostatic valves or thermostats) are enabled. This issue is somehow taken for granted in all of the mentioned studies, but research pieces focusing particularly on this aspect can also be found in literature, such as the work presented by S. Andersen et al. in [11]. This work aims to investigate the heat cost allocation as a psychological driver for occupants' behaviour regarding control of the indoor environment, taking into account not only indoor temperature but also indoor air quality.

Besides Europe, in US and Canada, where energy costs are included in the rental fee in many apartments, outcomes of individualizing energy metering have been a topic of interest in many works. In [24], a study conducted in Canada shows that occupants living on bulk-metered apartments keep their flats about 2 °C warmer than those living in sub-metered apartments, reporting that the latter ones showed more awareness of their thermal comfort and more predisposition to personal adaptive behaviours. Similar conclusions can be drawn from [29], where US data were used to carry out the study.

Finally, it must be highlighted that, even though the potential of IMC systems for enhancing the use of available means for temperature control, this might not be enough, taking into consideration some studies which evidence that the mere existence of thermostats does not automatically results in lower energy consumption [30]. For that reason, some authors recommend combining its potential financial motivation with advice provision and information campaigns [10].

2.2.2 Recurring Issues related to individual metering and charging

As shown in the previous section, several studies published in the last years highlight that there is consistent evidence that metering in combination with consumption dependent charging can act as an incentive for more efficient heating behaviours in buildings with centralised heating systems. However, its implementation in some countries is slower than expected and, in some cases, strong resistance against IMC can be found, being the users' perception of a low cost efficiency measure one of the barriers mentioned by some authors [3]. Moreover, some recurrent issues related to the fairness of a good cost-allocation system, which must be taken into consideration in an implementation of IMC, can be also identified in the literature. These issues are mainly related to individual metering of heating; individual metering of water does not have similar problems. The aim of this subsection is to identify and present the main recurrent issues related to IMC found in the literature with the objective of creating an overall picture of individual metering.

Some of these issues can be linked with the dilemma presented in [10]. In general terms the heat consumption of a dwelling is influenced by two groups of variables: those related to physical building properties and those related to occupant behaviour [10]. The dilemma emerges from the fact that the second group of variables depend on the occupant, but the first group is out of the occupant control.

The first issue directly related to this dilemma is the *split-incentive* situation that arises in rented dwellings, which is a usual topic in many assessments of energy saving measures in buildings and it is usually evaluated also focusing on policy contexts in different countries. Three single examples of this can be found in [31] (United States), [32] (France) and [33] (Canada). As mentioned by S. Siggelsten and S. Olander [3], if heating and/or DHW costs are included in the rent, the tenants have no economic incentive to adapt their behaviour to save energy. On the other hand, if those costs are excluded (as with IMC), the landlord loses economic incentives to improve the building physics with the aim of reducing the energy consumption.

Another issue mentioned by some authors is somehow related to the first group of variables (those related to the building physics properties) and it is based on the idea that the amount of heat supplied to a certain dwelling is not the amount of heat “actually” consumed in the dwelling due to the heat flows between apartments and heat losses to the surroundings [26], effect that some authors refer to as “Stolen heat” [34]. As mentioned in [3], an apartment with a favourable location in the building (with adjacent apartment above, below and at both sides) can achieve almost all its need for heating energy from the adjacent apartments. This effect is even more noticeable in old buildings that lack of thermal insulation between adjacent apartments. Thus, the question raised in [3] is if measurements of the amount of heat delivered to each specific apartment are sufficient to allocate heating cost between the apartments of a building. This problem about heat transfer between dwellings in multifamily buildings has been mentioned and studied by many authors, such as [35], where a study in an existing residential multifamily building located in Milan (Italy) with poor thermal insulation (both in façade walls and between adjacent dwellings) is carried out, proposing solutions to overcome the identified problems through a revision of the criteria for the allocation of energy costs; [36], where a review on the major issues related to reform with the heat-metering system are elaborated by comparing the pros and cons of several metering methods; as well as some of the previously mentioned research pieces [4, 6, 8, 26]. The development of methods driven to correct this effect has also been an object of different studies. For example, P. Michnikowski proposed in [5] a different method for correcting errors in the allocation of the heating cost taking into consideration heat transfer from adjacent apartments.

Hence, location of a dwelling in a building can have a significant effect on its heat demand [7] (and not only due to the aforementioned heat exchange between apartments, but also due to other aspects such as orientation or solar gains), and in consequence, it is a point to be taken into account when implementing

IMC. This issue is also mentioned in [3, 6, 8, 36]. Some researchers and IMC systems suppliers propose the use of correction factors for compensating apartments which have a greater need for heat as a consequence of its relative location in the building [5, 7, 26]. However, there is an open discussion with different opinions about whether this is a proper method [3]. As an example of this point, Morgenstern et al. raise the question of if a heat pricing mechanism for protecting people in unfavourable flat configurations without reducing the general incentive to reduce the heating use is conceivable [10].

Other issues related to building physics are heat gains from uncovered heating network pipes [26] or the fact that, if the DHW system is not working properly, it can result in an increased amount of water to be flushed out before it gets hot enough, which involves that tenants have to pay for an amount of water which is not actually used [3].

Finally, the potential influence of IMC on the indoor environment is mentioned in different papers, not only focusing on indoor temperatures [6, 11], but, as mentioned before, also on indoor air quality [11]. That is, measuring the delivered heat can involve that residents, with the aim of lowering their own heating cost, manipulate the ventilation patterns and reducing the amount of air changes, reducing the indoor air quality (so increasing risk of health problems) and damaging the building [7]. All mentioned issues are summarized in Table 1.

Table 1. Recurrent issues related to IMC identified in literature

Issue	References
Split-incentive	[3, 10, 31-33]
Heat flows amongst apartments and heat losses	[3-6, 8, 26, 34-36]
Unfavourable location of an apartment in a building	[3, 5-8, 10, 26, 36]
Heat gains from uncover network pipes	[3]
IMC effects on indoor environment	
Indoor temperature	[6, 11]
Indoor temperature and air quality	[11]

Some of the mentioned handicaps, especially those related to building physics and location of the dwelling, could be overcome, apparently, by allocating costs according to indoor thermal comfort instead of delivered heat. This would mean that users pay according to the desired indoor temperature, using then the third method considered in ASHRAE and previously mentioned in the introduction of section 2.2 in this paper. However, some authors point out the shortcomings related to this method [7].

These issues, which must be taken into consideration in existing buildings where the occupants have lived for several years without IMC (and in consequence, implementation of an IMC system involves a change in the way that energy system costs are allocated), are especially important in low-income social housing: due to the fact that energy costs often represent a substantial part of the occupants' income and, on the other hand, flats are assigned to tenants and they do not chose thermally unfavourable or favourable flats [10]. Morgenstern et al. concluded that IMC, in some cases, may come into conflict with the fuel poverty agenda.

In short, all these issues are, in certain manner, linked to the fairness. The fairness of individual metering comparing to bulk-metering has been addressed in different papers, such as in [37] (in this case, centred on electric metering, but the underlying question is similar), and this concept can be thoroughly discussed (one interesting understanding of fairness is presented in [10]) but it is out of the scope of this paper.

2.2.3 Spanish Context

Unlike other European countries, district heating systems (which in other countries usually present an important potential of implementation of IMC) are not very extended in Spain [38]. However, at the same time, central heating systems were implemented in many buildings during the 60s and 70s, and the implementation of centralized systems in new buildings has increase significantly during the last decade.

As far as Spanish regulation is concerned, several milestones related to the individual charging and metering can be identified. In 1999, Regulation for Thermal Installations in Buildings (acronym in Spanish RITE) came into force after being approved by Royal Decree 1751/1998, on 16th of July 1998. From then on, individual metering for DHW and heating is compulsory in new buildings with centralized heating systems. Existing buildings with central heating systems, however, remained out of scope of application of this regulation (except in the case of updating the energy system; in that case IMC must be implemented taking advantage of renovation works). According to RITE 2007, approved by Royal Decree 1027/2007, on 20th of July 2007, IMC are considered as saving and energy efficiency measures and its implementation in existing buildings is recommended but voluntary, getting necessary to be approved by at least 60% of the building owners.

The previously mentioned European Directive (2012/27/UE) involves a change in this point, becoming its implementation compulsory both in new and existing buildings. However, even though this Directive should have been transposed by June 2014, the corresponding Royal Decree has not been approved yet.

At the same time, since 1981, when RICCACS (Regulation for Heating, Cooling and DHW installations, by its initials in Spanish) came into force, every centralized heating system must be configured by ring circuit networks. Up to then, thermosiphon heat pipes or vertical pipes with forced circulation were usual configurations, where in both cases each vertical main pipe supplies radiators of different apartments (see Fig. 1, A and B). Unlike these configurations, in a ring circuit network (C), each ring circuit supplies heat to a single apartment, making easier to determine the heat supplied to each apartment by using a single flow meter and two temperature sensors (to register temperature variation) per apartment.

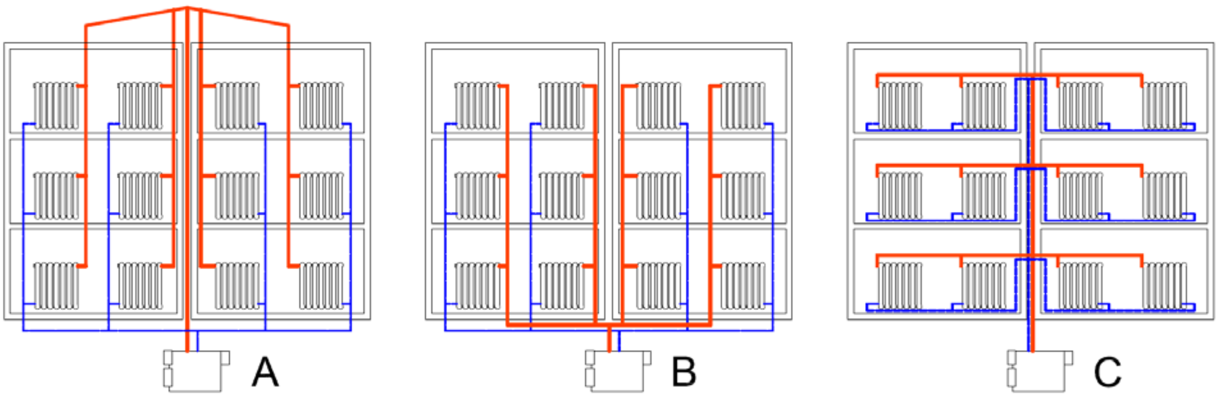

Fig. 1. Different heating system configurations (A: thermosiphon heat pipes; B: vertical pipes with forced circulation; C: ring circuit network)

Moreover, it must be taken into consideration that during the 60s, 70s and 80s (when, as previously mentioned, an important share of the central heating systems in Spain were installed), Spanish building stock grew significantly, and the thermal performance was not a priority in the majority of those buildings during their construction [39]. In consequence, these buildings present in general a poor energy performance with high energy consumption values. According to data presented by "Ista" in 2016, currently, there are about 1.7 millions of dwellings in Spain with central heating systems, and it is estimated that only 8% have implemented an IMC system for allocating cost in a consumption-dependent way [40].

As previously mentioned, not many works can be found about the actual impact on energy consumption of IMC implementation in temperate climates, and namely, in Spain. According to a statistical data-based study carried out by AERCAA (Spanish association for heating cost allocation, by its initial in Spanish) and University of Alcalá [41], IMC implementation can involve an average of 25% of energy savings of heating consumption in central heated buildings. As far as cost allocation criteria are concerned, IDAE (Spanish Institute for Diversification and Energy Saving) have recently published a guide focused on centralized heating and DHW systems where some recommendations for defining fixed and variable costs are presented [42]. Along the same line as the references previously presented, this guide mentions that cost allocation criteria must encourage a rational energy use, and it recommends a fixed cost for covering heat losses in distribution, management, maintenance and other recurrent issues mentioned in literature, and a variable cost based on energy consumption.

3 Materials and methods

The experimental study presented in this paper was carried out using data collected in a seven-storey building located in Bilbao, northern Spain, during the period comprised between November 2013 and June 2017. The climate of the studied area, located in latitude 43º N, is oceanic. The proximity to the ocean makes summer and winter temperatures relatively temperate, with low intensity thermal oscillations. The Spanish Technical Building Code [43] identifies 6 levels of winter and 3 levels of summer. Winter severity is described by a letter: the mildest winter is represented by the letter "A" and the coldest by the letter "E" (additionally, the sixth letter is α, for representing the winter severity in Canary Islands). Winter severity in Bilbao, according to this classification, is defined by letter "C" (see Fig. 2). Average maximum temperature is between 25 °C and 26 °C during summer period, while the average minimum in winter can vary between 6 °C and 7 °C. Heating season usually covers from November-December to March-April. Regarding summer period, the great majority of residential buildings have no cooling systems for that period.

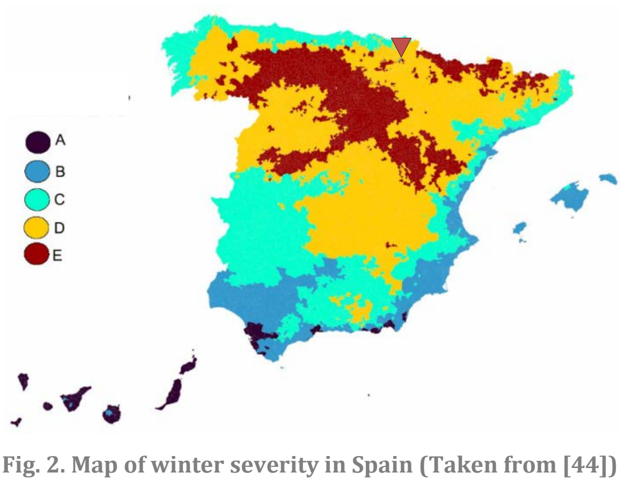

Fig. 2. Map of winter severity in Spain (Taken from [44])

3.1 Case Study

The studied building was built up in 1985. A general picture of the building as well as a schematic layout are presented in Fig. 3. It comprises 142 dwellings and the net floor area is 13375 m^2 (being about 95 m^2 the average size of each apartment).

Fig. 3. Case study building. General views of west (left picture) and east façade (right picture) and scheme of the distribution of apartments on the typical floorplan

3.1.1 Building features and energy system

External walls of the building are composed by two layers of hollow bricks (14.5 and 4.5 cm respectively) separated by a thermal insulation layer of 5 cm, with a U-value of 0.55 W/m^{2}K. Indoor surfaces of walls are plaster over gypsum. As far as windows are concerned, they are double glazing (3+3) with wooden frame. Horizontal and vertical interior partitions amongst apartments present no thermal insulation.

With respect to the energy system, there is a centralized system which supplies both heating and DHW to all apartments of the building. This installation, depicted in Fig. 4, is composed by 3 diesel-fired boilers (2x700 kW + 350 kW) connected in cascade, with a total heating capacity of 1750 kW. It provides the DHW and heating circuits with hot water (60°C) which, in turn, is distributed to the flats through different ring circuit networks. Some small parts of the risers and pipes which compose the circuit have been recently thermally insulated (the part of pipes or risers in surrounding the new devices installed), taking advantage of an update carried out in the energy system, but the length affected by this change is negligible comparing to the total length of the circuit. In this case, each dwelling of the building is supplied by just one DHW circuit and one radiator circuit. Consequently, as mentioned before, flow metering system turns out to be a proper method to measure the heating consumption of each apartment.

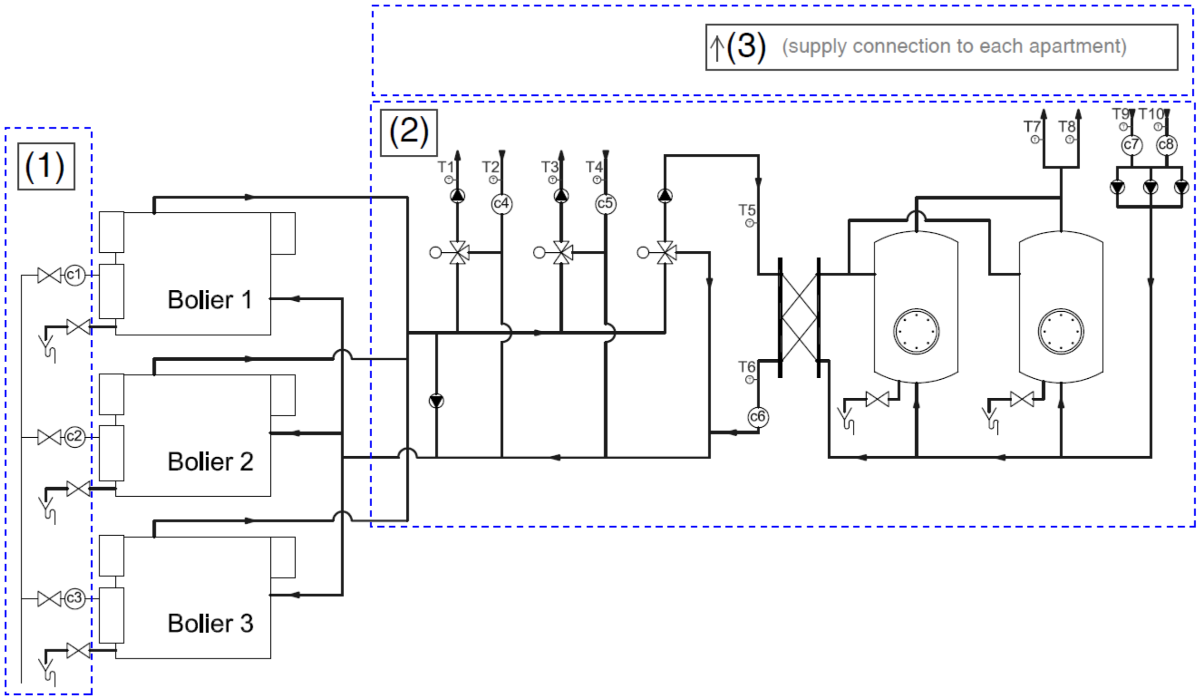

Fig. 4. Energy system for DHW and heating

3.1.2 Energy cost allocation methods applied in the building and system operation

Concerning energy cost allocation methods, two different periods are identified in the case study building. Until June 2015, energy costs (both those related to DHW and those related to heating) were allocated in a consumption independent-way. During the heating season, if the outdoor temperature was below 11 °C at 13.30 h, the heating system was activated and kept on working until 22.00 h; otherwise, (i.e. if the outdoor temperature was higher than 11 °C at 13.30 h), the system started running at 16.30 h until 22.00 h. Meanwhile, the DHW system was on from 4.00 h to 23.59 h.

The IMC system was installed in June 2015. Flow meters were installed in the DHW incoming pipe and the radiator circuit of each flat with the aim of measuring the DHW consumption [m^3] and the thermal energy delivered to each apartment [kWh], respectively. Moreover, zone valves and thermostats in each apartment were also installed. Thus, from that moment on, each apartment started paying quarterly a fixed amount aimed to cover the fixed costs of the system (consumption independent cost) and a variable consumption dependent cost, function of the actual heating and DHW consumption (€/kWh for heating and €/m^3 for DHW).

The operation schedule of the energy system was also changed after the IMC installation. From then on, the heating system is available from 7.00 h to 22.00 h with a linear production temperature-curve from 55 °C to 85 °C, depending on the outdoor temperature (15 °C-0°C). As far as DHW system is concerned, no changes were carried out until May 2017, when the DHW availability was set uninterruptedly (24h/day).

Furthermore, with the aim of monitoring the installation in detail and so evaluate the energy losses through the whole system, some flow meters and temperature sensors were installed in different parts of the installation in February 2017. These flow meters and temperature sensors' locations are also displayed in Fig. 4 (number 2).

3.2 Data collection

In this paper, consumption data measured during 4 heating seasons are compared, and the effect of the IMC on energy consumption is analysed. To that effect, the amount of heat delivered to the building with heating and DHW purposes is assessed. Data sources used, as well as the method for data processing, are presented next.

3.2.1 Data sources

The primary means of collecting data was through the maintenance logbook of the installation, where monthly readouts from the three diesel flow meters (one for each boiler; number 1 in Fig. 4) are reported since November, 2013. These diesel flow meters (Contoil VZO 8) have a resolution of 0.01 l, with a maximum flow rate of 200 l/h, a nominal flow rate of 135 l/h and a minimum flow rate of 4 l/h, and a maximum permissible error of ±1% of actual value. On the other hand, individual DHW [m^3] and heating consumption [kWh] of each apartment (available since June 2015) were used to evaluate energy consumption trends of the building (number 3 in Fig. 4). The water meters ("Domaqua-m" by Ista) present a nominal flowrate (Q_n) of 1.5 m^3/h, a maximum load (Q_{max}) of 3 m^3/h, a minimum flowrate (Q_{max}) of 30 l/h and a transitional flowrate (Q_t) of 120 l/h (Class B). There are also data available from energy meters installed in February, 2017 in DHW and heating circuits (number 2 in Fig. 4). As far as weather data are concerned, outdoor temperatures were provided by the Basque Government from a meteorological station located in Deusto, Bilbao. This station measures variables such as air temperature, relative humidity, global horizontal irradiation and wind speed, amongst others, with a 10-min sampling frequency. Heating degree-days (18/15) for the four years were calculated using daily average values of these measurements. The different data sources and their main features are summarized in Table 2.

Table 2. Summary of data sources

REF	Source	Measurement	Resolution	Available since	Location
[A]	Diesel flow meter (x3)	Gasoil input in boilers [l]	Monthly	Nov, 2013	Fig. 4 (1)

[B]	DHW flow meter (x142)	DHW delivered in each apartment [m^3]	Monthly	Jun, 2015	Fig. 4 (3)
[C]	Heating energy meter (x142)	heat delivered for heating in each apartment [kWh]	Monthly	Jun, 2015	Fig. 4 (3)
[D]	Flow meters (x5) and temperature sensors (x10)	Energy delivered in different points of the system	Hourly, daily, weekly, monthly	Feb, 2017	Fig. 4 (2)
[E]	Temperature sensor	Outdoor temperature	Daily	Nov, 2013	Outdoors

3.2.2 Disaggregated monthly values of DHW and heating

One of the main barriers to be faced in this work is that energy consumption prior to the IMC implementation is aggregated, and no information about the share of the energy used for DHW and for heating is available (in Table 2, [A]; the three boilers supply both heating and DHW system). For that reason, a preliminary assumption for calculating the share of energy associated to DHW and that corresponding to the heating system is defined at the beginning, and then adjusted using individual consumption data available since 2015 as reference (in Table 2, [B] and [C]).

With this aim in mind, consumption trends of the building during the last two years are analysed. Monthly DHW [m^3] and heating consumption [kWh] of the building are depicted in Fig. 5. The graph shows clearly that DHW consumption in the summer period decreases significantly, and in consequence, the hypothesis of assuming that DHW consumption is constant over the year, and then, assuming a monthly constant DHW consumption value equal to that of July or August (directly obtainable from the total energy consumption of these months, since there was no heating) is dismissed. Finally, Heating Degree Days (HDD) are used as reference to identify the periods with no heating (each period is defined according to the readouts collected in the logbook of the installation). To do that, $HDD_{18/15}$ are calculated for every period. The subscript "18/15" is the base assumed for HDD (which usually is expressed as HDD a/b) and then calculated using Eq. 1:

$$HDD_{a/b} = \sum\nolimits_{i=1}^{n} \left(a - T_{avd,i}\right) \cdot X_c \qquad \text{Eq. 1}$$

where a is the heating base temperature; b is daily average outdoor base temperature (if average temperature is higher than b, heating system is not necessary); n is the number of days of the evaluated period; $T_{avd,i}$ is the average outdoor temperature for the day "i"; and X_c is a logic coefficient, which is 0 when $T_{avd,i}$ is higher than b and 1 when $T_{avd,i}$ is lower than b.

Thus, the readout corresponding to the last period with no $HDD_{18/15}$ before each heating season is assumed as the reference for calculating the DHW consumption for the upcoming heating period. Then, daily average DHW consumption values are calculated for that period, assuming that daily DHW consumption value constant for the next heating season.

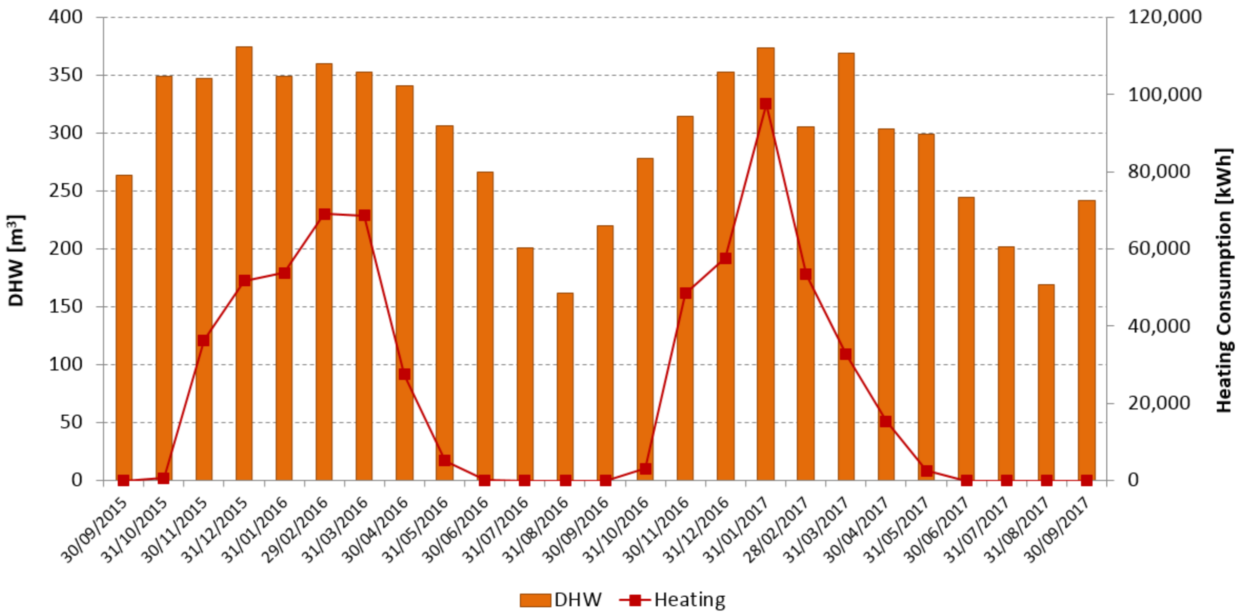

Fig. 5. DHW and heating consumption of the building (Sept, 2015-Sept, 2017), according to data registered in [B] and [C] (see Table 2).

According to the aforementioned assumption, the average DHW consumption values per day for every heating season evaluated are presented in Table 3. Daily energy consumption used for DHW (DHW_{Daily_ave}) are calculated according to Eq. 2.

$$DHW_{Daily\_ave} = \frac{C_{die,n} \cdot LHV_{die}}{n} \qquad \text{Eq. 2}$$

where $C_{die,n}$ is the diesel consumption of the boilers for the given period (in litres), LHV_{die} is the lower heating value of diesel (9.98 kWh/l) and n is the number of days constituting the given period.

Table 3. Daily DHW consumption assumed for every heating season

Heating Season	Period considered	Readout (consumption of the three boilers) [l]	Energy consumption for DHW per day [kWh/day]
13/14	Sep, 27th – Oct, 11th (2013)	1174 l	836.39 kWh/day
14/15	Sep, 24th – Oct, 27th (2014)	2961 l	895.48 kWh/day
		Average value before implementing IMC	*866,19 kWh/day*
15/16	Aug, 14th – Sep, 21st (2015)	3265 l	857.49 kWh/day
16/17	Sep, 23rd – Oct, 19th (2016)	2192 l	841.39 kWh/day
		Average value after implementing IMC	*849.44 kWh/day*

Besides, the actual energy share used for DHW during the last two heating seasons (according to the available readouts) is compared to the energy share for DHW calculated following the proposed procedure. Those values are depicted in Fig. 6, where calculated values (in light grey) and actual values (in dark grey) are compared. It can be observed that during the heating season the share of energy used for DHW is about 20%, being the remaining 80% associated to heating purposes. The difference between the calculated and the real values is also depicted in the graph with red dots. As shown, during the heating season, the difference is in general lower than 6.5%, with the exception of April, 2016 and the last two months (March and April, 2017), where the difference is quite higher (8,57%, 9,41% and 15,31%, respectively).

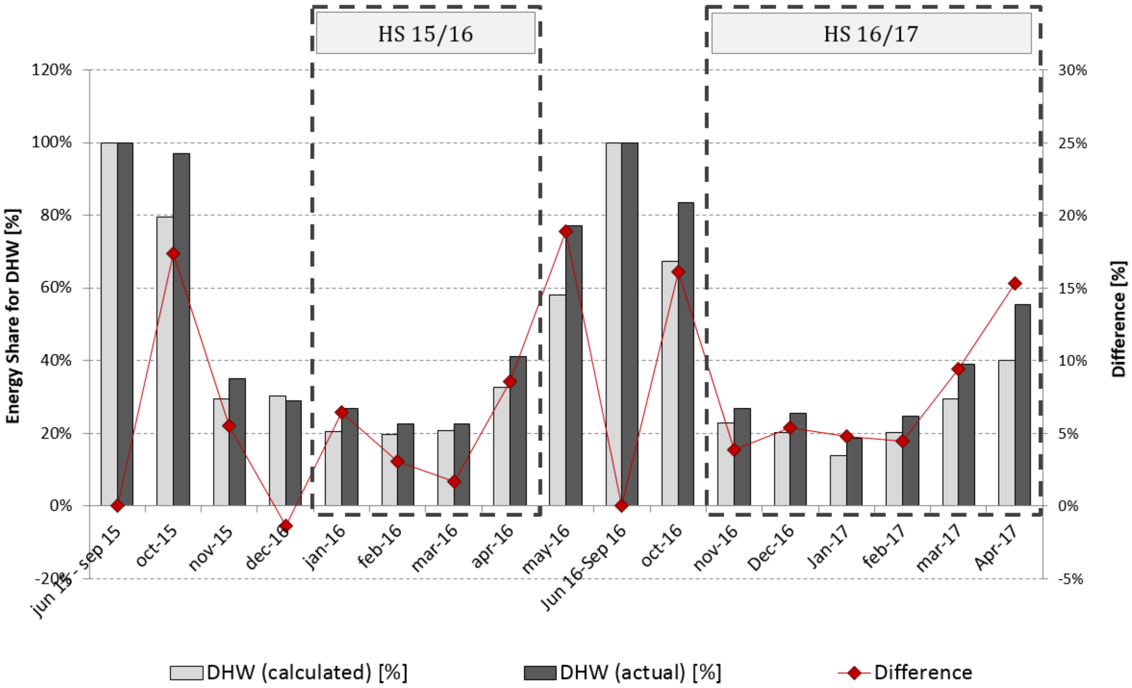

Fig. 6. Energy share for DHW. Calculated values Vs. actual values

Moreover, with the aim of increasing the consistency of the conclusions presented in this paper, a sensitivity analysis is also carried out. In it, the effect of the energy share assumed for DHW on the heating energy savings is evaluated. In any case, in the light of values presented in Fig. 6, the method implemented can undervalue slightly the energy consumption for DHW during the heating season, and then, overestimate heating consumption. The effect of this uncertainty is later evaluated by mentioned analysis presented in section 4.1.1.

Once DHW consumption for each measured period has been determined, it is subtracted from the total energy consumption of a measured period, obtaining then the consequent energy consumption for heating. This heating consumption is afterwards distributed amongst the days of the period proportionally to the HDD of each day of that period (in similar way to other works found in literature such as [45]), according to Eq. 3:

$$HC_{m,n} = \frac{C_n}{HDD_n} \cdot HDD_m \qquad \text{Eq. 3}$$

Where $HC_{m,n}$ is the heating consumption for a given day "m" of a period "n", C_n is energy consumption assigned to heating during the given period "n", HDD_n are the Heating Degree Days for that period "n", and HDD_m are the Heating Degree Days for the day "m".

This way, assuming direct proportionality between heating and degree days, the overall heating consumption can be distributed by days, and a virtual daily profile for DHW and heating is calculated based on monthly, aggregated energy readouts registered in the maintenance logbook. Registered data of fuel consumption in each boiler (in litres), as well as obtained virtual daily profiles, are depicted in Fig. 7.

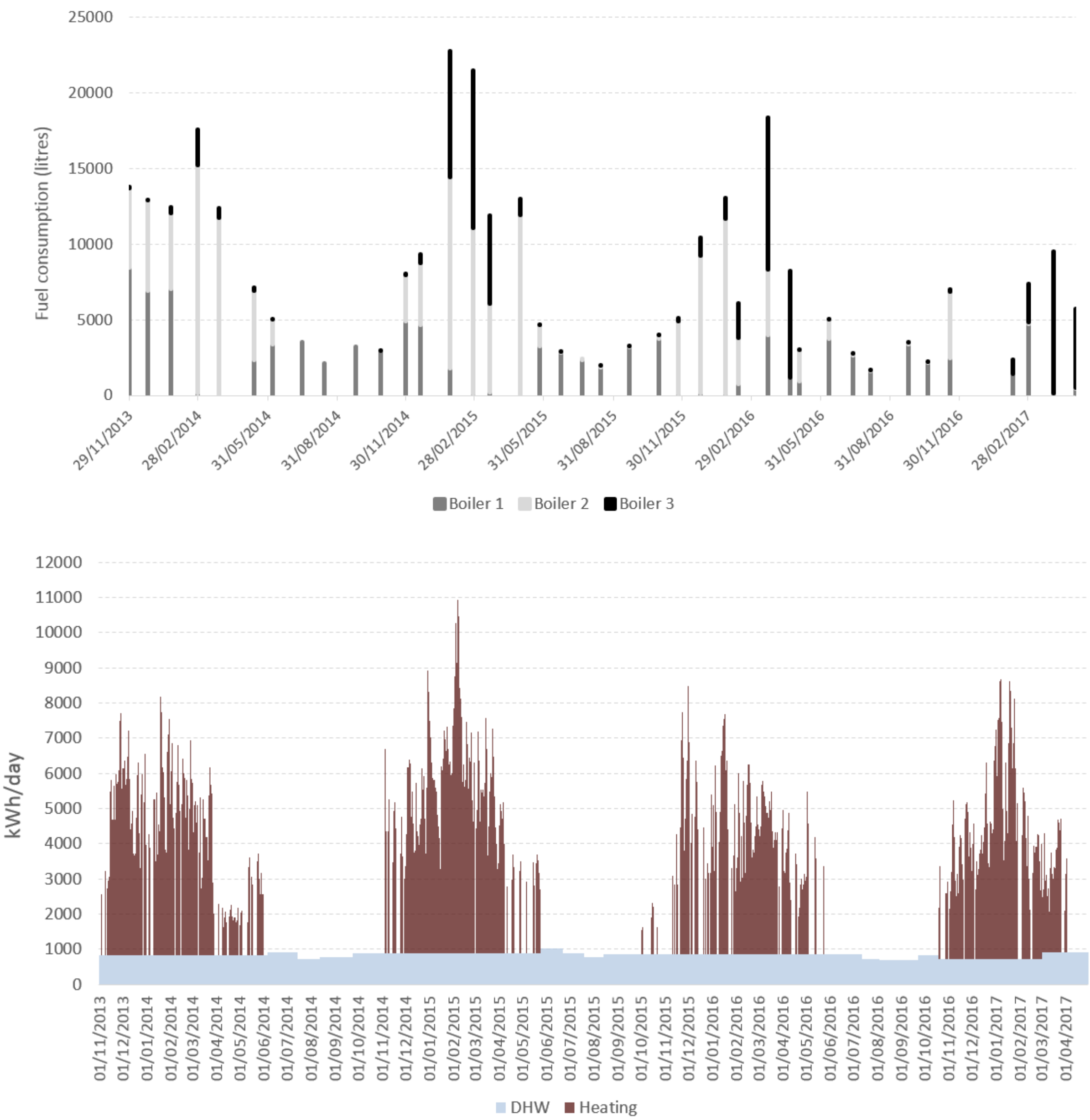

Fig. 7. Registered fuel consumption in each boiler (above) and virtual daily profile for DHW and Heating (below)

This method is applied to the four-years' period assessed in this study. The workflow of the method described in this section is graphically depicted in Fig. 8.

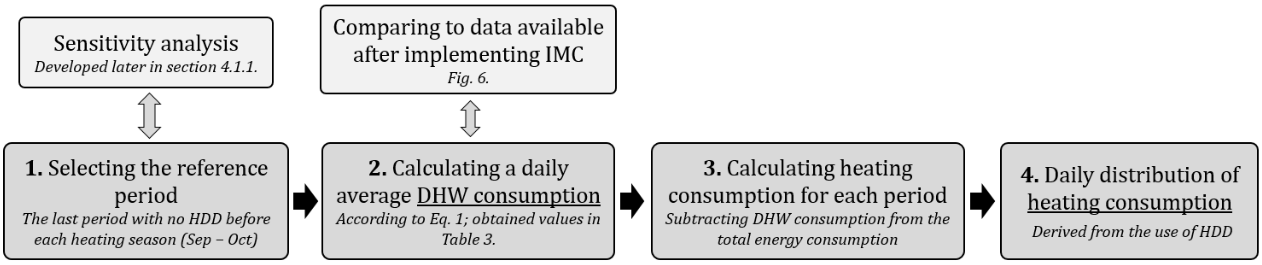

Fig. 8. Workflow of the method followed for disaggregating values of DHW and Heating consumption

3.2.3 Assessment of heating consumption

Heating consumption before and after implementing IMC is evaluated to assess the effect of IMC system on it. Monthly heating consumption of the building since November, 2013 is calculated using aforementioned virtual daily profile for DHW and heating, and the monthly values during the heating seasons evaluated are observed and compared. With the aim of reducing the effects of the possible inaccuracies on the absolute DHW consumption values assumed, only those months with more than 100 HDD will be considered in this study. Based on this criterion, the four heating seasons evaluated are presented in Table 4.

Table 4. Heating seasons assessed

Heating season	13/14	14/15	15/16	16/17
Months considered	Nov 13 – Mar 14	Dec 14 – Mar 15	Jan 16 – Apr 16	Nov 16 – Apr 17

Besides, in order to include a meaningful pre/post intervention analysis for the building and with the aim of taking into account the effect of the different yearly weather data on the energy consumption, energy consumption for heating is normalized with respect to heating degree-days (HDD). This method is usually used in this kind of analysis, and can be frequently found in literature (e.g. [4]). Normalized consumption is calculated according to Eq. 4:

$$C_{normalized} = \frac{C_n}{HDD_n} \qquad \text{Eq. 4}$$

where C_n is energy consumption for heating during a given period and HDD_n are the Heating Degree Days for that given period.

3.3 Data analysis procedure

The results obtained after this data processing are evaluated from an energy and economic point of view. Energy results are presented in section 4.1, whereas economic results are presented in 4.2. Based on normalized heating consumption values, economic savings resulting from the reduction of heating and DHW consumption are calculated. Thus, economic savings resulting from the reduction of heating consumption can be expressed as presented in Eq. 5.

$$Heating_{Sav} = \left[\left(C_{normalized,2013-2015} \cdot HDD_{(2015-2017)}\right) - \left(C_{normalized,2015-2017} \cdot HDD_{(2015-2017)}\right)\right] \cdot Cost \qquad \text{Eq. 5}$$

where: $C_{normalized,2013\text{-}2015}$ is the normalized heating consumption [kWh/HDD] before implementing IMC (2013-2014 and 2014-2015 heating seasons) calculated for each scenario applying the method described in section 3.2.3; $C_{normalized,2015\text{-}2017}$ is the normalized heating consumption [kWh/HDD] after implementing IMC in June 2015 (2015-2016 and 2016-2017 heating seasons) calculated for each scenario applying the method described in section 3.2.3; and $HDD_{2015\text{-}2017}$ are the total Heating Degree Days of 2015-2016 and 2016-2017 heating seasons (obtained following the method presented in section 3.2.3), and cost is the aforementioned fuel cost [€/kWh].

Similarly, economic savings resulting from the reduction of DHW consumption are calculated as presented in Eq. 6:

$$DHW_{Sav} = \left(DHW_{Daily\_ave\_2013-2015} \cdot n_{2015-2017} - DHW_{Daily\_ave\_2015-2017} \cdot n_{2015-2017}\right) \cdot Cost \qquad \text{Eq. 6}$$

where the $DHW_{Daily\_ave\_2013\text{-}2015}$ represents the normalized energy consumption for DHW during the two years before implementing IMC [kWh/day]; $n_{2015\text{-}2017}$ is the number of days of the two heating seasons after implementing IMC; and $DHW_{Daily\_ave\_2015\text{-}2017}$ represents the normalized energy consumption for DHW during the two years after implementing IMC [kWh/day]. DHW_{daily_ave} are calculated for each period through the method presented in section 3.2.2. by means of Eq. 2.

As far as data sources are concerned, it must be observed that both energy and economic results are calculated by comparing energy consumption values before and after implementing IMC. In order to avoiding inaccuracies as a consequence of using different data sources of energy consumption corresponding to pre- and post-intervention period, the same data source has been used to obtain those data. Then, values of fuel consumption in boilers are used as main data source in both cases (in Table 2,

[A]), together with weather data obtained by outdoor temperature sensors (in Table 2, [E]) in order to calculated normalized consumption. This method was only modified for obtaining data corresponding to December 2016 and January 2017, since no reading was registered in the logbook. In this case, it was calculated by extrapolating the sum of energy consumption (DHW and Heating) registered in every individual metering (in Table 2, [B] and [C]).

4 Results

Following the method presented in the previous part, monthly profile for DHW and heating is defined. Calculated consumption values, as well as monthly Heating Degree Days (18/15) are depicted in Fig. 9.

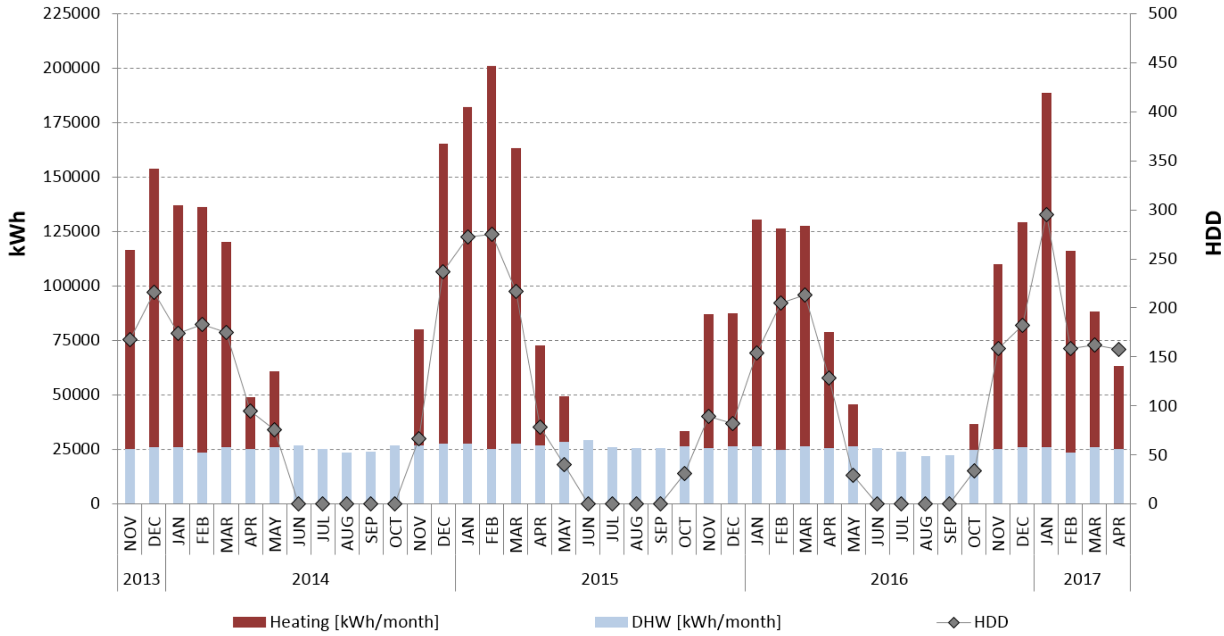

Fig. 9. Calculated monthly energy consumption used in the building for heating and DHW, and HDD during the four heating seasons studied (November 2013-April, 2017)

4.1 Energy results

According to aforementioned method, Fig. 10 shows the monthly average amount of weather-normalized heat used in the building and monthly $HDD_{18/15}$ of the four heating seasons studied. As mentioned in part 3.2.3, only those months with a monthly $HDD_{18/15}$ higher than 100 have been taken into consideration in the study.

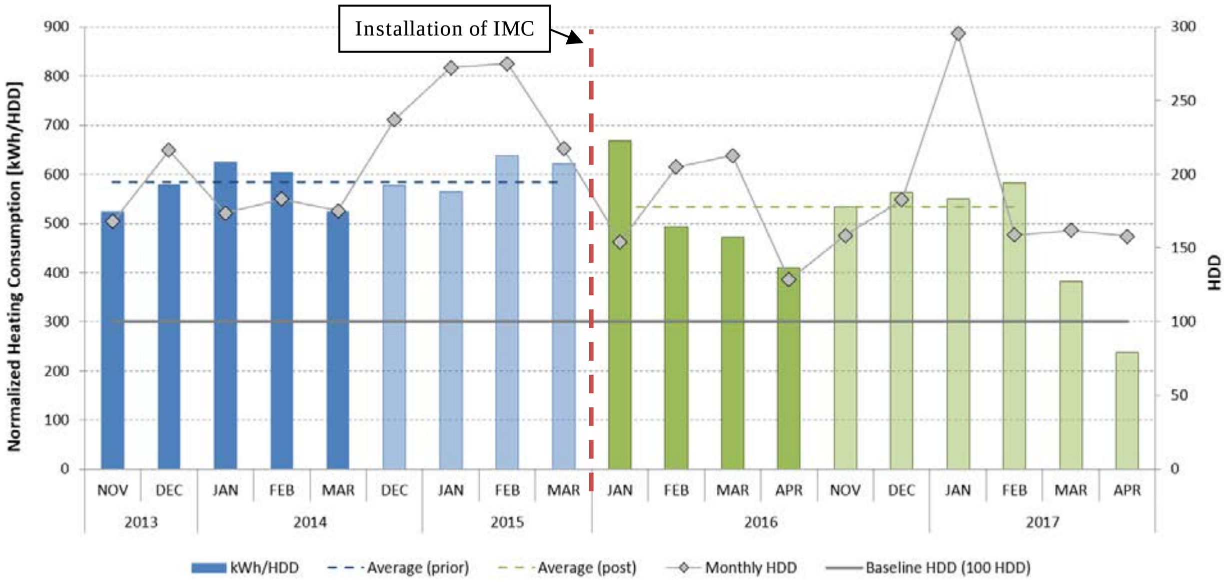

Fig. 10. Monthly average amount of weather-normalized heat used in the building and HDD during the four heating seasons studied (months when HDD>100; energy data source: [A] in Table 2)

Similar average weather-normalized heat consumption values can be observed for the first two heating seasons studied, before installing the IMC system (namely, 586.04 kWh/HDD for the heating season 2013/2014, and 602.41 kWh/HDD for 2014/2015) with an average value of 593.32 kWh/HDD for the nine months studied. During that period, the minimum value was reached in March 2014 (538.45 kWh/HDD) and the highest value is found two months before, in January 2014 (639.21 kWh/HDD). On the other hand, although values corresponding to the “post-intervention” seasons are more variable, a sensible reduction on weather-normalized heat consumption can be observed in these periods. Thus, an average value for heating consumption of 514.88 kWh/HDD is obtained for 2015/2016 and that average value drops to 476.67 kWh/HDD for 2016/2017. Even though when the last two months (March and April 2017) are not taken into consideration (their normalized heating consumption values are quite lower than the other months of post intervention period) the average value for 2016/2017 would be 558.95 kWh/HDD, still significantly lower than those average values obtained for 2013/2014 and 2014/2015, before installing IMC system. Thus, even being a conservative scenario, a reduction of 10-15% is observed when normalised heating consumption before and after implementing IMC is assessed.

4.1.1 Sensitivity analysis

As mentioned before, there is an uncertainty linked to the hypothesis assumed in order to determine the share of the total energy used for DHW and for heating purposes. With the aim of assessing the effect of this uncertainty on obtained results of normalized consumption, a sensitivity analysis is carried out, where different hypothesis for estimate the share of DHW demand are evaluated. Thus, four alternative scenarios (apart from the assumed scenario S0) have been considered in this sensitivity analysis, which are presented in Table 5 together with DHW consumption before and after implementing IMC (calculated considering each scenario). To define these scenarios, not only the data corresponding to the last period with no HDD (see Table 3) but also those related to the first period without HDD after the previous heating season (see Table 6) are taken into account:

Table 5. Scenarios taken into consideration

Scenario	Description	Average DHW consumption [kWh/day]	
		Pre-renovation	Post-renovation
Scenario 0 (S0)	This is the assumed reference scenario, where the average value of the share of total thermal energy consumption for DHW (prior and post-intervention) is calculated based on the last period without HDD before each heating season (usually, *September-October*, see Table 3)	866.19	849.44 (-1.93%)
Scenario a (Sa)	In this case, the share of total thermal energy consumption for DHW is calculated based on the first period without HDD after the previous heating season (usually, *May-June*, see Table 6)	914.78	867.28 (-5.19%)
Scenario b (Sb)	In this case: - DHW consumption before implementing IMC is calculated according to the hypothesis described in scenario a (see Table 3) - DHW consumption after implementation has been estimated assuming the lowest value assumed in Sa (see Table 6).	914.78	854.54 (-6.59%)
Scenario c (Sc)	This scenario takes into account a significant increment of DHW consumption (more than 20%) after implementing the IMC. To do that: - DHW consumption before IMC implementation is assumed according to the hypothesis described in S0. - DHW consumption after implementation has been defined assuming the higher value registered considering all periods with less than 100 HDD.	866.19	1056.46 (+21.97%)
Scenario d (Sd)	Sd presents another extreme scenario, where a 40% of reduction on DHW consumption after implementing IMC is considered. It would be the most conservative (and unlikely) scenario for analyzing the IMC effects on heating consumption.	1000	600 (-40%)

Table 6. Daily DHW consumption assumed for every heating season when the first period without HDD after the previous heating system is considered

Heating Season	Period considered	Readout (consumption of the three boilers) [l]	Energy consumption for DHW per day [kWh/day]
13/14	Jun, 20th – Jul, 22nd (2013)	2933 l	914.73 kWh/day
14/15	Jun, 6th – Jul, 15th (2014)	3575 l	914.83 kWh/day
		Average value before implementing IMC	*914.78 kWh/day*
15/16	Jun, 22nd – Jul, 20th (2015)	2469 l	880.02 kWh/day
16/17	Jun, 10th – Jul, 12th (2016)	2740 l	854.54 kWh/day
		Average value before implementing IMC	*867.28 kWh/day*

The first two alternative scenarios (Sa and Sb) are created by assuming energy consumption of May-June to define the DHW consumption before and/or after implementing IMC (which, in short, involves assuming energy savings on DHW between 5-7% after implementing IMC). The third and fourth alternatives (Sc and Sd) are defined to evaluate extreme variations on DHW demand (an increment of more than 20% on energy consumption for DHW after implementing IMC in Sc, and a reduction of 40% for DHW in Sd). The variation on DHW consumption resulted in each case is also presented in Table 5 (in the column "Post-renovation" for each scenario, in brackets). Energy savings (both for DHW and heating purposes) for each scenario are calculated comparing the normalized energy consumption after implementing the IMC system (period 2015-2017) with the normalized energy consumption before implementing the IMC system (period 2013-2015), calculated both according to the previously presented method applied in each scenario. Obtained results after applying these hypotheses are presented in Table 7.

Table 7. Normalized heating consumption, assuming the DHW consumption presented in Table 5 for each scenario

	S0	Sa	Sb	Sc	Sd
DHW variation [%]	**-1.93%**	**-5.19%**	**-6.59%**	**+21.97%**	**-40%**
Heating Pre [kWh/HDD]	593.6	584.77	584.77	593.60	572.39
Heating Post [kWh/HDD]	498.13	465.23	497.00	462.58	539.40
Heating variation [%]	**-16.08%**	**-15.31%**	**-15.01%**	**-22.07%**	**-5.76%**

Looking at these results, it can be stated that normalized heating consumption barely varies regardless of assuming as reference DHW consumption in June or in September to calculate the DHW consumption during the winter seasons. Data show that assuming no changes (or moderated reductions, between 0% to 7%, the presented in S0, Sa and Sb) on DHW consumption after implementing the IMC, energy savings over than 15% are achieved on normalized heating consumption. As far as scenarios c and d are concerned, (the extreme cases), the first (Sc) involves an energy savings related to heating purposes higher than 20%. Even in the latter case (and improbable case), the most unfavorable case if the focus of the assessment is pointed on heating consumption, energy savings related to heating would be higher than 5%. In short, in the light of the results of this sensitivity analysis where the effects of possible inaccuracies on DHW calculation during the winter periods before implementing the IMC are evaluated, it can be affirmed that the energy savings on normalized heating consumption during the last two years have been close to 15%-16%, if the most probable scenarios are taken into consideration (S0, Sa and Sb, assuming also a DHW reduction from 0% to 7%) and, in any case, it may range from 5% to 20% if extreme scenarios (Sc and Sd) are included in the analysis.

4.2 Economic results

The impact of IMC on economic issues have been evaluated based on the savings in building scale, achieved as a consequence of the reduction of fuel consumption. In this section, savings achieved in the last two heating seasons are calculated. The four additional scenarios considered in the sensitivity analysis are also evaluated, in order to assess the effect of the DHW consumption related assumptions on the calculation of economic savings. Economic savings linked to the reduction of fuel consumption are taken into consideration (e.g. changes on auxiliary energy consumption and other costs related to system operation are assumed as negligible, and then, they are not be taken into account in this assessment).

A simple payback period is also calculated, taking into account that the implementation cost was about 92000€, which involved 600-700€ per apartment (the differences amongst apartments depended on specific conditions of each one: location of the valves, distribution, etc).

Thus, obtained normalized consumptions (both DHW and heating, see Table 7) are used for calculating the total energy consumption from June 2015 to June 2017 and, once energy consumption is obtained, the total cost is calculated assuming that fuel cost is 0,1 €/kWh. Then, as described in detail in section 3.3, economic savings (both for DHW and heating purposes) for each scenario are calculated comparing the cost related to the actual energy consumption after implementing IMC system with the cost related to the hypothetical consumption during the same period (2015-2017) if normalized energy consumption ($C_{normalized}$) would be the obtained before IMC was implemented (i.e. during the period 2013-2015).

Calculated savings are depicted in Fig. 11, where heating related economic savings (in red), DHW related economic savings (in blue) and total economic savings (the grey line) are depicted for each scenario. As shown, every scenario gives similar economic savings during 2 heating seasons, around 18000 €, which involves a simple payback period of 10 heating seasons, that is 10 years.

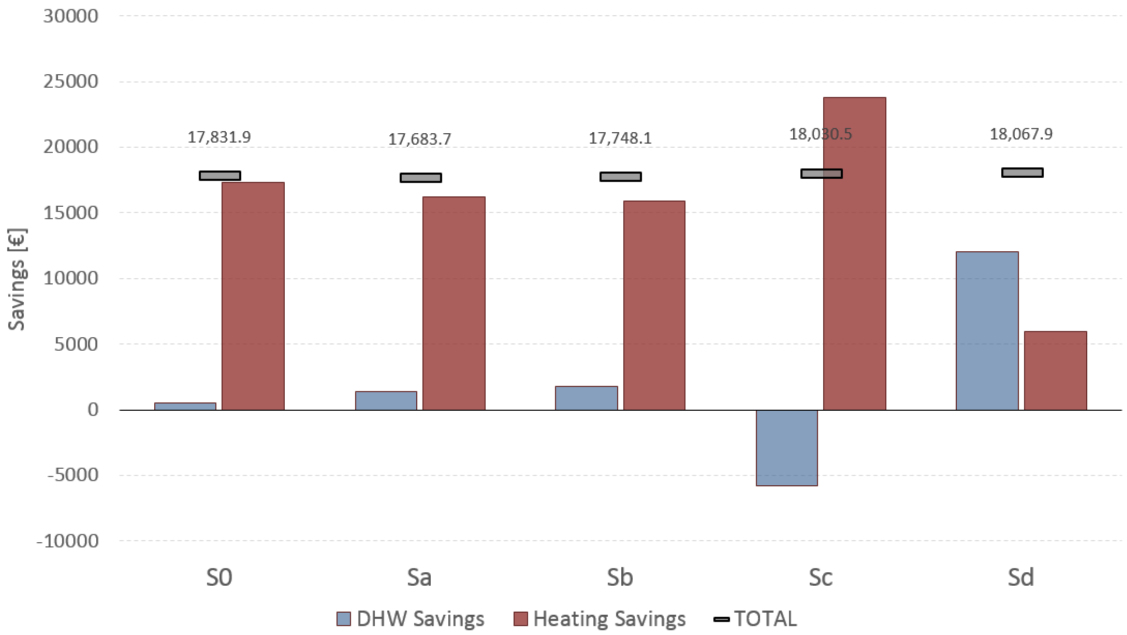

Fig. 11. Economic savings obtained in evaluated scenarios

Finally, the effects of winter severity on calculated heating related economic savings are evaluated. Thus, economic savings in different scenarios against $HDD_{18/15}$ are depicted in Fig. 12. $HDD_{18/15}$ corresponding to the evaluated heating seasons are also depicted in the graph. Average values before and after implementing IMC are similar (959 $HDD_{18/15}$ for 13/14 and 14/15 heating seasons; and 907 $HDD_{18/15}$ for 15/16 and 16/17 heating seasons; detailed data of $HDD_{18/15}$ for each month has been already depicted in Fig. 9). Winter severity in the region can range from 600 $HDD_{18/15}$ to 1200 $HDD_{18/15}$ (depicted by the dotted line rectangle in the graph), and this value ranges between 900 and 1000 $HDD_{18/15}$ in an usual winter. As shown in the graph, if the most probable scenarios are observed (S0, Sa and Sb) heating related energy savings range from 5000 € (in a heating season with an unusual low winter severity of 600 $HDD_{18/15}$) to 10000 €.

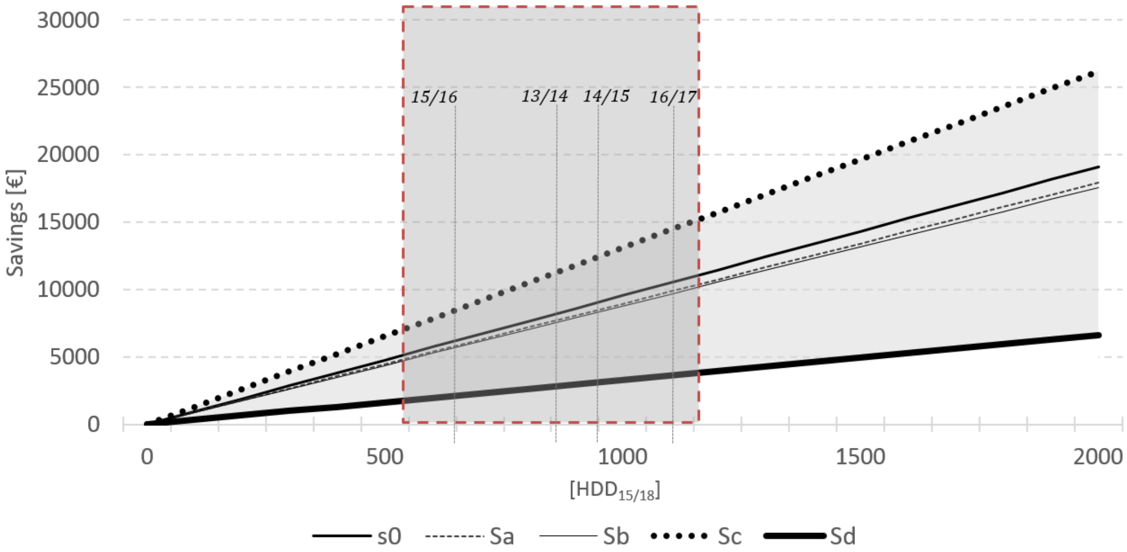

Fig. 12. Effects of winter severity [$HDD_{18/15}$] on annual savings [€] in the case-study building

5 Discussion

Three different sub-parts are presented in this section: firstly, the analysis of energy and economic results presented in the previous section is carried out; secondly, the recurring issues related to IMC which can be identified in the case study presented are mentioned, taken into account the literature review presented in section 2.2; and finally, based on literature review presented in this paper and case study analysed, opportunities and barriers identified for implementing ICM in Spain are presented.

5.1 Energy and economic results. Discussion

The results obtained in this research piece, together with the sensitivity analysis presented in section 4.1.1, show that during the last two heating seasons (after implementing IMC) normalized heating consumption has decreased around 15%.

Besides, it must be highlighted that, as well as the implementation of IMC and the installation of a thermostat in each apartment and zone valves in each radiator, other measures aimed to optimize the performance of the installation and to increase the users' comfort were carried out. Some of them, such as the installation of variable flow pumps, have no direct effect on the fuel consumption values evaluated in the previous section (but, however, they have an indirect effect on the cost allocation, since this change affects electricity consumption, and then, the operation cost of the system). Other measures aimed to increase the users' comfort, such as the time extension of heating and DWH availability (as described in detail in section 3.1.2), affect directly on consumption values evaluated, increasing them slightly (amongst other reasons, due to the increase of heat losses on recirculation). Even after these changes, energy savings on heating have achieved the 15%. Thus, it could be estimated that energy savings related to IMC implementation *per se* have been at least 15-20% on heating consumption during the first two years.

On the other hand, it must be taken into consideration that only the first two years after implementing IMC have been evaluated. As mentioned in the introduction section, the learning curve of users for these systems is reported by some authors to be around 3 years. Then, it is expected that the energy savings may still increase slightly during the following months, to reach a maximum normalized value after one or two heating seasons more.

As far as economic issues are concerned, economic savings calculated in this paper (around 18000€ during the first two years in every scenario considered, which involve a payback period of 10 years to recover the total investment of IMC implementation) are only related to the reduction of fuel consumption in boilers. Effects brought about by other measures (i.e. variable flow pumps involve on the one hand less electricity consumption and then savings on auxiliary energy and on the other hand, less heat losses in distribution pipes) are not considered in that case. To take into consideration these costs a comprehensive, detailed evaluation of the energy system should be carried out. Those effects would be also included somehow if the final cost paid by each apartment would be evaluated, since the cost allocation used currently should take into account all expenses generated by the system (as previously presented in section 2.2); amongst them, auxiliary energy, inefficiencies and maintenance. In any case, both evaluations are out of the scope of this paper, and it can be affirmed, thus, that increase the awareness and information about the expenses related to energy installation has been a co-benefit of the IMC implementation in this case-study.

Furthermore, concerning the payback period, only energy savings related to fuel reduction during the heating seasons; the heating seasons evaluated comprise 10 out of 24 months of the first two years, so shorter payback periods could be achieved if the expected reduction on DHW consumption during non-heating seasons is considered. Effect of winter severity has been also evaluated and presented in Fig. 12, where is observed that the HDD average values of heating seasons before and after implementing IMC are quite similar to the average value for that location (around 900-1000 $HDD_{18/15}$).

In short, and based on this discussion of results, it can be concluded that the economic effect of the implementation has been positive, with an acceptable expected payback periods, no longer than 10-12 years in a conservative scenario.

5.2 Issues identified in literature review applied to the case study

Some of the recurrent issues mentioned in section 2.2.1 and 2.2.2 have been also evaluated in the case study presented in this paper. Thus, *split-incentive* related issues are not a barrier in this case, since the majority of the apartments of the case study building are occupied by the owners. However, some other points have been found to be noteworthy by being especially relevant for implementing cost allocation method. Even though some parts or the distribution system were covered with thermal insulation with the aim to reduce heat losses, heat losses through distribution system are still relevant, and they are included in the fixed amount of the cost allocation. These heat losses are shared out between DHW and heating purposes, assuming that DHW represents 40% of the total energy consumption and heating the remainder 60%. Looking at final energy consumption registered by individual metering in each apartment, it is observed that the rate of final energy delivered is quite close to that assumption (39% DHW – 61% Heating). However, that assumption involves to assume that energy losses and inefficiencies are proportional in DHW and heating supply, which not always is like that (e.g. recirculation in DHW circuits may involve significant heat losses and, in consequence, DHW supply presents generally higher energy losses than heating supply). Analysing this issue would require a detailed evaluation of the energy system, which is out of the scope of this paper.

The feedback is mentioned in the literature review as a promising strategy for reducing the energy consumption. Currently, the feedback provided to users is through quarterly energy bills. Changes in the billing frequency (e.g. monthly energy bills) may bring along a higher user awareness and, in consequence, higher reduction of energy consumption. However, it would involve, at the same time, an increase of the billing related expenses (administration cost); thus, the cost-effectiveness of this measure would require a deeper analysis of these aspects.

5.3 Opportunities and barriers identified of implementing individual metering and charging in Spain

Finally, some considerations are presented related to the potential of IMC in the Spanish context, based on the literature review presented in this paper. The presented case study is located in an area with a winter severity classified with letter “C”, where energy consumption have decreased 15-20% as a consequence of implementing IMC, obtaining payback periods of about 10 years, depending on scenario assumed. This point shows that the aforementioned user perception of IMC as a low cost efficiency measures reported by different authors is not supported by facts, at least in this study case. Furthermore, as shown in Fig. 2, the most area of Spain presents a winter severity classified with letter "C" or higher ("D" or "E"), and then, it may expected higher energy savings in terms of absolute values, and lower payback periods (assuming that initial investment will be similar).

As mentioned before, centralized heating systems were usual in the buildings built in 50's, 60's, 70's and 80's, and, taking into account that individual metering is compulsory only since 1998, the majority of them have not consumption dependent way cost allocation. Besides, many of these buildings present a poor thermal performance (minimum thermal requirements for envelope were not defined by law until 1980, when NBE-CT 79 came into force). The case study building presented in this paper was built in 1985 so, a priori, buildings built before 1980 will present higher energy consumption values and then, a higher energy saving potential, which will involve lower payback periods than the obtained in this case study. Thus, IMC implementation in these buildings, together with other energy efficiency measures, may be a successful strategy directed to reduce energy consumption in the Spanish building stock. On the other hand, ring circuit networks for DHW and heating are compulsory in Spain since 1981. This makes easier to install the first (and more accurate) method proposed by ASHRAE (see section 2.2) for measuring individual consumption for heating purposes. In the remainder cases, radiator metering can be the most feasible option.

Other recurrent issue is the split incentive situation. The influence of this point is less accused in Spain (comparing to other European countries) since the ratio of tenants is lower than in other countries: almost 80% of the apartments are owner occupied, similar to Poland or Norway (83%), and unlikely other northern European countries such as UK, Sweden or Denmark (about 60-65%).

6 Conclusions

The present paper has presented a literature review on implementation of IMC systems and evaluated the effect of IMC on energy consumption in a study case located in northern Spain. It shows the first findings related to the effects during the first two years after implementing IMC in a multifamily building, and noteworthy trends have been identified. The result of this study confirms that IMC (together with a system to allow for the regulation of heat supply, such as thermostatic valves or similar) affects directly on user behaviour, boosting their awareness on energy issues and it encourages inhabitants to change their habits to reduce their energy consumption (as previous studies pointed out), but it shows, as a novelty, that this effect is also significant in a temperate climates and indicates that its implementation may be economically feasible in areas with this climate (RQ1). It reports reduction of normalized energy consumption close to 15-20% after two years of implementing IMC in the building, and obtained simple payback periods based on the reduction of fuel consumption in boilers are around 10 years. These values have been obtained even considering the effect of other measures aimed to increase the user comfort (such as the increase of the schedule of availability of DHW and heating) which indirectly can slightly increase the energy consumption of the system. Besides, taking into account that learning curve of these systems is reported to be about 3 years by some authors, and the fact that there is many areas in Spain with higher winter severity, it can be expected that payback period in many Spanish cases to be lower than obtained results.

Since data corresponding to the pre-intervention period were aggregated (energy consumption for DWH and heating purposes), a simple method has been applied to calculate which share of the total energy consumption corresponded to DHW production and which share was used for heating purpose (RQ3). Sensitivity analysis carried out shows that obtained results are quite consistent regardless of the different assumptions assumed for calculated the share of energy consumption for DHW.

The current context of Spain related to IMC implementation has been also assessed through the literature review presented in section 2 (RQ2). It is concluded that IMC (combined with an adequate feedback and a fair cost allocation criteria) can be a promising strategy to reduce energy consumption in centralized heated buildings by increasing users' awareness on energy issues. It must be highlighted, however, one of the key points in existing buildings is how mentioned cost allocation criteria are defined, which must be carried out taken into consideration not only energy performance related issues, but also other issues related to building itself, users and social context (e.g. taken into account aspects such as risk of energy poverty).

Future works have been also identified in this study. The work presented in this paper presents the first trends identified during the first two years of using IMC. Further analysis considering evaluating the evolution of energy consumption during the next heating seasons would be interesting in order to check the learning curve and confirm the reduction of normalized heating and DHW consumption.

As previously mentioned, taking into consideration all effects on energy use the system after implementing IMC (taking into consideration effects on auxiliary energy or maintenance, for instance) requires a comprehensive evaluation of the system and/or evaluating the final cost paid by each apartment. A detailed and comprehensive analysis of a case study would be recommended in order to evaluate the global energy and economic effects of implementing IMC in centralized heating and DHW systems.

Another topic to develop in future works is the Indoor Environment Quality assessment (IEQ), which is out of the scope of this paper. IMC changes the way that heating systems are used, and it would be interesting clarify to what extent energy savings achieved are due to a more awareness use of the system (e.g. avoiding overheating), or consequence of reducing IEQ (low temperatures, low ventilation rates...). IEQ can be assessed conducting a research piece evaluating both indoor temperatures in apartments (especially in those in unfavorable locations) and inhabitants' perception, by means of questionnaires and surveys.

Finally, it can be concluded that there is a lack of measurements and studies to assess what is the actual thermal performance of this kind of centralized installations. In the case study, several additional sensors were installed in February 2017 with the aim of evaluate the system performance in detail. There are not enough data so far, but studying registered data during the next years can allow identifying where are the inefficiencies of the systems (heat losses) and then, defining a more accurate cost allocation method and, eventually, implementing solutions to reduce those inefficiencies.

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8 References

[1] European Commission, Energy, transport and environment indicators. Eurostat (2012).

[2] European Commission, Directive 2012/27/EU on Energy Effciency (2012).

[3] Siggelsten S, Olander S. Individual metering and charging of heat and hot water in Swedish housing cooperatives. Energy Policy 2013;61:874-880.

[4] Cholewa T, Siuta-Olcha A. Long term experimental evaluation of the influence of heat cost allocators on energy consumption in a multifamily building. Energy Build 2015;104:122-130.

[5] Michnikowski P. Allocation of heating costs with consideration to energy transfer from adjacent apartments. Energy Build 2017;139:224-231.

[6] Dahlblom M, Nordquist B, Jensen L. Distribution and variation of indoor temperatures in apartment blocks with individual metering and billing of space heating costs—on building, apartment, and room level. Energy Efficiency 2015;8:859-880.

[7] Siggelsten S. Reallocation of heating costs due to heat transfer between adjacent apartments. Energy Build 2014;75:256-263.

[8] Siggelsten S, Hansson B. Incentives for individual metering and charging, Journal of Facilities Management 2010;8 (4):299-307.

[9] Siggelsten S, Nordquist B, Olander S. Analysis of the accuracy of individual heat metering and charging. Open House Int 2014;39:69-77.

[10] Morgenstern P, Lowe R, Chiu LF. Heat metering: socio-technical challenges in district-heated social housing. Build Res Inf 2015;43:197-209.

[11] Andersen S, Andersen RK, Olesen BW. Influence of heat cost allocation on occupants' control of indoor environment in 56 apartments: Studied with measurements, interviews and questionnaires. Build Environ 2016;101:1-8.

[12] Socolow RH. The Twin Rivers Program on Energy Conservation in Housing: Highlights and Conclusions. Energy Build 1977;1:207-242.

[13] Hong T, Yan D, D'Oca S, Chen C. Ten questions concerning occupant behavior in buildings: The big picture. Build Environ 2017;114:518-530.

[14] Andersen RK. The influence of occupants' behaviour on energy consumption investigated in 290 identical dwellings and in 35 apartments. Abstract from 10th International Conference on Healthy Buildings. Brisbane, Australia; 2012.

[15] International Energy Agency. Energy Conservation in Buildings & Community systems, Annex 53: Total Energy Use in Buildings: Analyses and Evaluation Methods. 2013.

[16] Guerra-Santin O. Behavioural Patterns and User Profiles related to energy consumption for heating. Energy Build 2011;43:2662-2672.

[17] Van-Der-Aa A. Uncertainty in modelling the energy performance of buildings and the occupants. Feedback from practical experience of models. SIMUREX 2012 - Conception optimisée du bâtiment par la SIMUlation et le Retour d'EXpérience. Book of proceedings;2012.

[18] Terés-Zubiaga J, Campos-Celador A, González-Pino I, Diarce G. The role of the design and operation of individual heating systems for the energy retrofits of residential buildings. Energy Conversion and Management 2016;126:736-747.

[19] Abrahamse W, Steg L, Vlek C, Rothengatter T. A review of intervention studies aimed at household energy conservation. J Environ Psychol 2005;25:273-291.

[20] Stazi F, Naspi F, D'Orazio M. A literature review on driving factors and contextual events influencing occupants' behaviours in buildings. Build Environ 2017;118:40-66.

[21] Wilhite H, Ling R. Measured energy savings from a more informative energy bill. Energy and Buildings 1995;22:145-155.

[22] Tsuda K, Uwasu M, Hara K, Fuchigami Y. Approaches to induce behavioral changes with respect to electricity consumption. J Environ Stud Sci 2017;7:30-38.

[23] Vellei M, Natarajan S, Biri B, Padget J, Walker I. The effect of real-time context-aware feedback on occupants' heating behaviour and thermal adaptation. Energy Build 2016;123:179-191.

[24] Burak-Gunay H, O'Brien W, Beausoleil-Morrison I, Perna A. On the behavioral effects of residential electricity submetering in a heating season. Build Environ 2014;81:396-403.

[25] ASHRAE. Guideline 8-1994: Energy cost allocation for multiple-occupancy residential buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta; 1994.

[26] Ziemele J, Pakere I, Blumberga D, Zogla G. Economy of Heat Cost Allocation in Apartment Buildings. Energy Procedia 2015;72:87-94.

[27] John JG, Harris D, Diakoulaki D, Lampropoulou H, Giannakidis G. Determination of fixed expenses in central heating costs allocation: An arising issue of dispute. Management of Env Quality 2015;26:810-825.

[28] Henryson J, Håkansson T, Pyrko J. Energy efficiency in buildings through information – Swedish perspective. Energy Policy 2000;28:169-180.

[29] Levinson A, Niemann S. Energy use by apartment tenants when landlords pay for utilities. Resource and Energy Economics 2004;26:51-75.

[30] Peffer T, Pritoni M, Meier A, Aragon C, Perry D. How people use thermostats in homes: A review. Build Environ 2011;46:2529-2541.

[31] Bird S. Hernández D. Policy options for the split incentive: Increasing energy efficiency for low-income renters. Energy Policy 2012;48:506-514.

[32] Charlier D. Energy efficiency investments in the context of split incentives among French households. Energy Policy 2015;87:465-479.

[33] Maruejols L, Young D. Split incentives and energy efficiency in Canadian multi-family dwellings. Energy Policy 2011;39:3655-3668.

[34] Gafsi A, Lefebvre G. Stolen heating or cooling energy evaluation in collective buildings using model inversion techniques. Energy Build 2003;35:293-303.

[35] Dall'O' G, Sarto L, Individual metering of energy in existing buildings: potential and critical aspects. Energy Efficiency 2014;7:467–476.

[36] Liu L, Fu L, Jiang Y, Guo S. Major issues and solutions in the heat-metering reform in China. Renewable and Sustainable Energy Reviews 2011;15:673-680.

[37] Thurgood AL, Kwit LM. Electric Submetering: "Master-metering" in cooperative housing is unfair, expensive and wastes energy. Strategic Planning for Energy and the Environment 1997;16:68-78.

[38] Eguaras M, Martín-Gómez C. Reasons why District Heating Systems were not extended in Spain. 39th World Congress on Housing Science Changing Needs, Adaptive Buildings and Smart Cities. Milan:Politecnico di Milano; 2013. Vol 2. p. 121 - 128

[39] Terés-Zubiaga J, Martín K, Erkoreka A, Sala JM. Field assessment of thermal behaviour of social housing apartments in Bilbao, Northern Spain. Energy Build 2013;67:118-135.

[40] El Confidencial, Más de 1.5 millones de pisos afrontan multas de 10,000€ si no ponen al día su calefacción: https://www.elconfidencial.com/economia/2016-12-13/hogares-calefaccion-consumo-multa-eficiencia-energetica_1302336/ ; 2016 [accesed 18 April 2018].

[41] Universidad de Alcalá, AERCCA. Estudio de Ahorros derivados de la contabilización individual de calefacción. Madrid: Universidad de Alcalá; 2016.

[42] IDAE. Guía práctica sobre instalaciones centralizadas de calefacción y agua caliente sanitaria (ACS) en edificios de viviendas. Información y consejos para las comunidades de vecinos. 1st ed. Madrid: Ministerio de Industria, consumo y comercio; 2008.

[43] Ministerio de Vivienda. Gobierno de España, Orden FOM/16352013, de 10 de septiembre, por la que se actualiza el Documento Básico DB-HE "Ahorro de Energía" del Código Técnico de la Edificación, aprobado por Real Decreto 314/2006, de 17 de marzo. (2013) 67137 - 67209.

[44] Álvarez S, Molina JL. Ventilative cooling issues in Mediterranean regions (the Spanish case), QUALICHECK. From www.qualicheck-platform.eu; 2016.

[45] Iturriaga E, Aldasoro U, Campos-Celador A, Sala JM. A general model for the optimization of energy supply systems of buildings. Energy 2017; 138:954-966