Journal of Building Engineering 76 (2023) 107230

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

A novel strategy to guarantee a minimum indoor temperature in social housing buildings

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A R T I C L E I N F O

Keywords:
Energy management
Energy poverty
Social housing
Indoor temperature

A B S T R A C T

Energy poverty, along with climate change, is becoming one of the most worrying issues in Europe. Many people live without a minimum thermal comfort in their homes because they are not able to afford high energy bills. In other words, the indoor temperature of many dwellings remains below the recommended temperature during long periods, particularly in winter. This is more frequent among low-income families, which are over-represented in 'Spain's social housing. In this paper, we present a simple and novel procedure to manage heating energy consumption in order to guarantee a minimum indoor temperature in social housing dwellings. To test the procedure, a social housing building located in the Basque Country, in northern Spain, has been selected as the case study. The heating consumption and outdoor temperature have been monitored for three winters and a *characteristic curve* for the heating consumption has been derived using the methodology proposed. Thanks to this procedure, the indoor conditions of the dwellings have improved by 80.9%, helping to alleviate energy poverty. The results show that the method is reliable, since the heating consumption needed to guarantee a specific indoor temperature could be estimated with an acceptable error rate. In the end, several aspects of this case study are discussed, and conclusions that propose certain suggestions to energy policies are derived.

Abbreviations and units

AUGE	pre-payment system of the social housing dwellings
DHW	Domestic Hot Water, Domestic Hot Water consumption [m^3]
HR	Relative Humidity [%]
HVAC	Heating, Ventilation, and Air Conditioning
GHG	Greenhouse Gases
MAE	Mean Absolute Error
MW	Mineral Wool
NRPEC	Non-Renewable Primary Energy Consumption [$kWh/m^2 \cdot y$]

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https://doi.org/10.1016/j.jobe.2023.107230
Received 13 February 2023; Received in revised form 29 June 2023; Accepted 30 June 2023
Available online 1 July 2023

PC_{18}	Predictive Curve for the heating consumption until 18 °C of indoor temperature is reached [%]
PUR	Polyurethane rigid foam
Q_T	Total heating consumption [kWh]
Q_{18}	Heating consumption until 18°C of indoor temperature is reached [kWh]
RMS	Root Mean Square
RMSE	Root Mean Squared Error
T_{in}	Indoor Temperature [°C]
T_{out}	Outdoor Temperature [°C]
U	Thermal Transmittance [W/m^2·K]

1. Introduction

1.1. Literature review

The United Nations Covenant on Economic, Social and Cultural Rights recognized the importance of housing, including 'the right of everyone to an adequate standard of living for himself and his family, including adequate housing' [1]. Although the right to a home has been developed and made concrete in general terms, there is no human right to housing of a particular quality. Nor does social housing appear in human rights, even though harmful housing conditions have been recognized to interfere with a tenant's human rights by some courts, and providers are usually obliged to use the 'decent' home standard. For those in need, among the 20 key principles of the Pillar of Social Rights [2] is 'access to social housing or housing assistance of good quality shall be provided, including support for access to essential services, e.g., water, sanitation, or energy'.

Huge differences exist between countries when speaking about social housing. In terms of tenure, social housing is provided for rent in most countries, but the sale of dwellings is also possible in many. Moreover, social housing is increasingly limited to lower income and vulnerable households [3]. Among what might be called the welfare-state economies, the most important distinction is between countries that consider housing as a mechanism for providing for all types of households (an approach usually called universalist), and those that emphasize provision for lower-income households (denoted as targeted). The first group includes the Netherlands, France, and Sweden; while the second includes the United Kingdom, Ireland, Norway and West Germany [4]. Universalistic models consider housing to be a primary public responsibility and thus hold the objective of providing the whole population with decent quality housing at an affordable price. Targeted models consider the market to be in charge of allocating housing resources to individuals, and therefore the objective is to satisfy only the excess of housing demand not satisfied by the market. Targeted models can be generalist, if housing is allocated according to the income level; or residual, if allocated according to a set of vulnerability indicators [5]. Spanish social housing is considered to be a targeted model, where housing is allocated according to a set of vulnerability indicators [5], particularly income. Thus, the model is the residual, targeted model. Consequently, low-income tenants are overrepresented in social housing [6,7].

Nowadays, the issue of environmental sustainability and energy saving has gained increasing importance on the European agenda, through specific measures and dedicated funds relating to measures to combat fuel and energy poverty for social housing tenants [5]. Even more so after the war in Ukraine, the European Commission has launched the REPowerEU plan [8] to end the EU's dependence on Russian fossil fuels. The text refers to energy poverty during the energy transition:

> "… *the fast decoupling from Russian energy imports can lead to higher and more volatile energy prices. Targeted measures are needed to minimize volatility, keep prices in check and protect the individuals in or at risk of (energy) poverty in order to ensure a fair transition for all.*"

To respond to this aim, energy savings and an accelerated roll-out of renewable energy to replace fossil fuels are to be promoted in the EU, including the residential sector. Although social housing does not have a leading role in the proposals, it contains a welcome commitment to work to ensure that vulnerable consumers at risk of energy poverty have access to solar energy through social housing installations. More measures are expected to be approved by the European Commission.

Even older, high rise or poorly insulated structures, known as hard-to-treat buildings, can be retrofitted to achieve high energy efficiency standards. The government also expects social housing providers and landlords to be in the forefront of the development of renewable energies. This means implementing energy efficiency measures; for instance, retrofitting buildings (improving such building techniques as thermal bridges, envelope insulation, or replacing old windows by new, efficient windows), installing renewable energies and replacing old heating or cooling systems with more efficient ones, depending on the necessities in the location [9,10]. Another key factor to guarantee a successful performance after the renovation is to closely monitor the energy consumption [11]. Other actions could include using passive and control strategies to minimize energy consumption and improve indoor comfort [12].

Moreover, several researchers have demonstrated that the best retrofitting decisions are made by analysing real measured data [13,14]. Although simulation programmes can be used to build up behaviour estimations, they tend to assume some standard values [15]. Unfortunately, they are not as accurate as when analysing the real data of a building, since some factors can behave completely differently to the assumed behaviour [16,17]. Several researchers have found that the users considerably affect a building's behaviour, and they are therefore the key to obtaining energy efficiency and indoor comfort conditions [18–23]. For instance, Terés-Zubiaga et al.

[16] found that the average indoor temperature varies considerably due to the occupants' use, since the values obtained are lower than expected during winter periods in social housing in Spain. In the majority of cases, these lower temperatures are a consequence of the energy poverty often experienced by the occupants of low-income social housing. Due to their low income, many occupants tend not to turn on heating systems and do not ventilate their homes during winter periods. Unfortunately, this increases the possibilities that the tenants will suffer significant health and social problems [24,25]. It is even a reason of increased mortality rates during extreme winter and summer periods [26]. This lack of indoor comfort is one of the main causes of energy poverty [27,28] in social housing. Then, despite complete building retrofitting, if tenants do not behave as expected, the energy efficiency and indoor comfort will not be as good as estimated. Therefore, a balance between energy efficiency, indoor comfort and the construction and use cost should be found when rehabilitating social buildings [29–31] in order to ensure cost-effective social housing.

However, solving the energy poverty problem within social housing is not an easy task. For social housing providers, the obligations include making repairs to the home supplied [32]. Since the 1980s, the fulfilment of these responsibilities has been under threat as public expenditure pressures have grown due to the increasing importance of liberalisation and privatisation [4]. The liberalisation of the energy markets forces tenants to be considered as consumers with the freedom to contract their basic supplies. This is why social housing services usually include only the rent, so tenants have to contract other basic supplies (i.e., water or energy). While the contract with the tenants sets out the rent to be paid for the dwelling, other energy-related payments cannot be included, irrespective of whether the right to energy is fulfilled or not [33]. This is what the Energy Efficiency Directive (EED) [34] aims to address, the fact that the tenant is a consumer who freely exercises his right to contract energy. However, there is evidence that individual heat metering and billing is not always a fair solution for social housing, depending on how the dwellings are built and on the existing regulations in the field of rent and energy bills [35]. In this sense, several alternatives have arisen to provide fair solutions regarding energy supply in social housing.

For instance, some social housing providers explore partnerships with energy suppliers. In Scotland, the landlord, taking the narrative on energy-related social justice to its logical conclusion, teamed up with six other social landlords to set up a "not-for profit energy supplier" known as Our Power (although the company ceased to trade on 25 Jan 2019) [36]. Moreover, in the United Kingdom, the Midlands's landlord WHG teamed up with Co-op Energy to provide its 40,000 residents with discounted gas and electricity, launching a new tariff called FuelGood Simplicity [37]. In addition, collective energy purchasing has received increased attention in recent years throughout Europe [38].

Another interesting initiative is the Energiesprong project, which proposes that tenants of social housing should pay the housing association an energy service plan, which is equivalent to the energy bill before the renovation. Thus, the housing association can use this new income stream to partly fund the renovation work [39]. The EED should support all the above mentioned initiatives, and give both national and local levels the possibility of finding the most appropriate solutions for a fair energy transition.

1.2. Introduction to the procedure

Alokabide [40] is the Basque public company for public rental and it is the landlord of an extensive social housing park located all over the Basque Country (North of Spain). As other similar landlords, only the rent of the dwelling is offered to tenants, not the basic supplies such as heating, DHW or electricity. The installation of pre-paid meters is being forced upon buildings with centralised energy systems due to unpaid bills, while the adverse effects of the measure are minimised through a small energy poverty project. In order to design the renovation of the building stock, energy audits are being carried out and data on the energy consumption of the tenants have been gathered [41]. Furthermore, the temperature and humidity of some of the dwellings are being monitored. As has already been proved, the consumption profile of the tenants of the Alokabide social buildings shows a usage of heating and electricity lower than an average resident, due to the issue of energy poverty in social housing [42]. As the energy performance is known for the whole building stock of Alokabide, it is possible to determine the difference in energy demand among them. Finally, energy inequality is documented for two tenants living in two dwellings with a very different energy performance; although they are supposed to have the same rights within Alokabide, one is paying high energy bills in an inefficient dwelling and the other has low energy costs in a performant dwelling.

Therefore, in order to fight against this energy injustice and to tackle the energy poverty of the tenants, Alokabide carried out an innovative project named BEB-18 (*Bero eta Erosotasuna Bermatuta*, in the official language of the Basque Country, which means Guaranteed Heat and Comfort), in which Alokabide is committed to providing its tenants with optimal interior conditions by financing them with a minimum indoor temperature. The core of the project is a change in the heating management of an inefficient building, without reforms to the heating production system. In other words, the objective of this BEB-18 project is to implement a novel procedure throughout the social housing stock to manage heating in such a way that it can guarantee a minimum indoor temperature of 18°C. This could be against the principles of the EED; however, as stated before, there are several initiatives which aim to achieve a fair energy transition and to empower tenants. In addition, despite the fact that the implementation of this initiative would suppose an increase in the energy cost covered by Alokabide, energy poverty would be reduced and the provision of energy services to the tenants would be fairer, while the energy efficiency of the building would also improve.

This paper describes the procedure developed to demonstrate the viability of the abovementioned BEB-18 project. To do so, a multifamily building of the social housing stock managed by Alokabide was monitored using the already installed pre-payment system. It might seem that the methodology presented in this research is merely another prediction method of the heating demand of the building. Prediction methodologies for the heating and cooling demand of buildings have already been widely analysed by the scientific community, using different approaches such as regression models and heating degree days [43–46]. Even more today, with the development of computer science and the advent of such techniques as the *Internet of Things* or *Deep Learning*, major breakthroughs are being made towards the prediction of the heating and cooling demand in buildings [47–50]. However, the aim of the BEB-18 project is to develop a simple methodology, using basic metering, to estimate the heating demand needed to maintain a minimum temperature inside a dwelling. The use of simple methodologies had already been proposed some years ago, specifically in 1998, by T. Olofsson et al. [51]. They proved that, by monitoring indoor and outdoor temperature and the space heating during a period from 10 to 35 days, the heating demand could be predicted with an accuracy of 5%. The use of simple methodologies to predict the demand has been used in other studies, but they are more focused on district heating or large residential areas [52–54].

In summary, the aim of this work is to develop and validate a simple procedure that could be used by the energy managers of social housing to predict the heating needed to reach a minimum indoor temperature within the dwellings. Note that, for this project, a minimum indoor temperature of 18°C has been chosen, but the procedure could be used with any other set indoor temperature. The method uses data from pre-installed heating and indoor temperature meters and the nearest public weather station for the outdoor temperature. After filtering and analysing the data collected for 1 winter period (approximately 3 months), an experimental model (*predictive curve* from now on), which correlates both the heating consumption under 18 °C and the total heating consumption, together with the outdoor temperature, was derived. With this mathematical correlation, the heating needed to guarantee 18°C (or any other indoor temperature) inside the dwellings can be obtained, thus helping to tackle energy poverty, as well as improving the energy use of the building.

To achieve the goals of this work, the following research questions were set:

- Is it possible to guarantee a minimum indoor temperature in social housing dwellings?
- Which experimental set-up is needed to develop this methodology?
- Is this methodology applicable to other social housing buildings?

2. Materials and methods

The building analysed belongs to the social housing stock of Alokabide. In these buildings, the basic supplies, such as water or energy consumptions, could be much lower than in a standard building. For instance, in the analysed building, 15% of the dwellings consume less than 25% of the average heating consumption of the building. Thus, it is important to keep in mind that the user profile of a social dwelling is different when comparing it with a standard energy consumer, with no restrictions due to low-income.

2.1. Description of the building

The building analysed is a residential building located in the city of Vitoria-Gasteiz in the north of Spain. It consists of 126 dwellings distributed around three entrance halls per block. The development is made up of two rectangular blocks with a north-south orientation. The northern block consists of 8 floors with 72 dwellings; whereas the southern block consists of 6 floors with 54 dwellings (See Fig. 1).

Two types of dwelling can be found within the analysed building. The first have 84 m^2 of useful surface, with 3 bedrooms facing north and the kitchen and living room facing south. Two thirds of the 126 dwellings belong to this group (coloured blue in Fig. 1). The dwellings of the second type are smaller, with 64 m^2 of useful surface. The whole dwelling is orientated to the south (indicated in orange in Fig. 1).

The HVAC system is a centralised system used to supply the DHW and heating needs of the dwellings. There is also a solar thermal installation, but it was being repaired during the monitored period. The centralised system consists of 2 natural gas boilers, with 3 power modules each, with a total power of 1,000 kW. The nominal performance of the boiler is 90.4%, but the combustion gases reveal a real performance of less than 85.0%. Furthermore, it should be mentioned that some years prior to this research, a survey to the tenants of this building was carried out, among other aspects, to address the number of dwellings using portable heating devices, such as stoves. The result was that around 7% of the dwellings used portable heating devices. Thus, for this research, the influence of these devices in the heating consumption of the centralised system is considered to be negligible.

Regarding the external envelope, the main façade is composed of concrete and a non-ventilated air chamber, with 4 cm of MW and 4 cm of PUR insulation, providing a thermal transmittance of 0.31W/m^2·K. The thermal transmittance of the roof is 0.33W/m^2·K and the windows are made of aluminium with a global thermal transmittance of 3.30W/m^2·K.

With all of this, the energy performance certificate gives a Non-Renewable Primary Energy Consumption (NRPEC) of 99.80 kWh/m^2·y (Rating D in the Spanish Technical Code, CTE-DB HE) and GHG emissions of 21.10 kg CO_2/m^2·y (also rating D). Indeed, the selected building for the case study is not an excessively bad building in terms of external envelope and energy consumption, but the reality is that almost half of the housing stock managed by Alokabide is of this type of building [55].

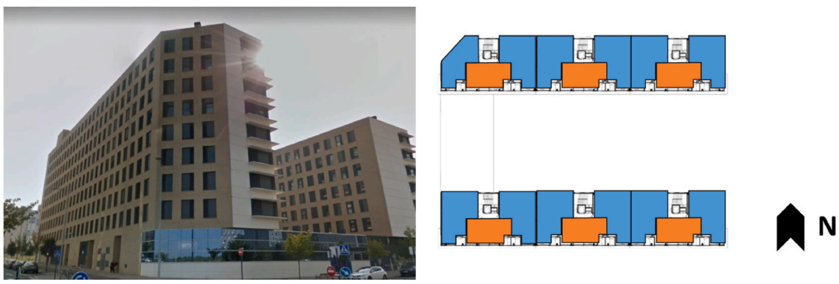

Fig. 1. Picture of the analysed building (Google Maps, 2021) and distribution of the dwellings.

Table 1 summarises the general HVAC and external envelope characteristics of the building.

2.2. Description of the monitoring system

All of the indoor and outdoor variables collected over the two winter periods (from December 2020 to April 2021, and from December 2020 to March 2021) are shown in Table 2. Each of the dwellings has a self-management device for the pre-payment service of the basic supplies (heating and DWH), named AUGE [56]. This system was designed to help in the energy management of dwellings, providing information of the indoor conditions and the energy consumption in real time for the tenants. The system is basically composed of a domestic thermostat and a display control device and is located in a visible and accessible area of the living room. The measurement accuracy of the temperature is ±0.5 °C.

The AUGE system also allows a set-point temperature to be established and the heating consumption below and above that temperature to be recorded. Thus, during the two-winter period, an indoor temperature of 18°C was set, and the heating consumption was measured until this temperature was reached within the dwelling. This heating consumption has been denominated Q_{18}, as shown in Table 2. The total heating consumption (Q_T) of the dwelling is also measured using the AUGE system and is compared with the Building Management System (BMS) measurements, in order to check the reliability of the AUGE system.

Regarding the outdoor temperature, the nearest public weather station [57] was chosen to collect the data. This decision was made in order to simplify the data collection methodology; although, obviously, a weather station located on the building itself would improve the accuracy of the method. Nevertheless, for this building, the nearest public weather station is located at a distance of only 3.20 km.

Of the variables shown in Table 2, the ones used for the analysis of this work were the indoor temperature (T_{in}), outdoor temperature (T_{out}), total heating consumption (Q_T) and heating consumption until 18°C (Q_{18}). The DHW and the HR were only recorded as extra data to check the user profiles of the dwellings. The outdoor temperature was collected every 10 min and the indoor temperature was measured each 15 min. The total heating consumption and the heating consumption until 18°C were measured every hour. Despite the fact that the methodology could be applied on an hourly basis, the calculations for this work were made using the daily average values, again, to simplify the applicability of the methodology.

3. Theory

The aim of this study is to derive a mathematical correlation (*predictive curve* from now on) which allows the heating consumption needed to keep a minimum specific indoor temperature to be calculated, depending on the outdoor temperature. An indoor temperature of 18 °C has been selected as an appropriate temperature to maintain a minimum of comfort during the winter. Nevertheless, any other indoor temperature can be selected by the energy manager applying this procedure by following the steps described below.

In order to develop the procedure, the monitoring of the heating consumption during a winter season (at least 4 months) is needed. The experimental set up has been explained in section 2. In this section, the mathematical methodology used to derive the *predictive curve* is explained so it is available for other researchers to be replicated.

3.1. Data filtering and analysis

For this study, the specified data were collected over two winter seasons. For both winters (2020-2021 and 2021-2022) data were collected from December until the end of March. The first step of the methodology is to filter the data. The following assumptions have been made in order to simplify the analysis:

- If the average daily outdoor temperature registered during a specific day is below 0°C, that day is excluded of the data set. This is just in order to simplify the analysis, because when the average daily temperature is below 0°C, the heating consumption increases considerably and may distort the data set. Besides, for the first winter, only 3 out of 146 days registered temperatures below 0°C.

Table 1
General, HVAC and external envelope characteristics of the building.

Location	Vitoria-Gasteiz, Basque Country, Spain	
Year of construction	2010	
General description of the building	2 building blocks arranged as: • North block: lower floor as common areas and 8 floors of dwellings • South block: lower floor as common areas and 6 floors of dwellings	
Types of dwellings	• 76 dwellings of 3 bedrooms and $84m^2$ • 54 dwellings of 2 bedrooms and 64 m^2	
Useful surface of the building	$12{,}025m^2$	
Compactness ratio of the building	2.5	
Description of heating and DHW installations	Centralised natural gas boiler, nominal performance of 90.4%	
External envelope	Concrete façade, U = 0.31W/m^2·K Roof, U = 0.33W/m^2·K Windows, U = 3.30W/m^2·K	
Energy Performance Certificate	Non-Renewable Primary Energy Consumption (NRPEC)	99.8 kWh/m^2·y – Rating D
	CO_2 emissions	21.1 kg CO_2/m^2·y – Rating D
	Heating demand	55.1 kWh/m^2·y – Rating D

Table 2
Indoor and outdoor variables collected over the two-winter period, per dwelling, on a daily basis.

		Monitored parameter	Unit	Source
Indoor data	**Thermal comfort**	Indoor temperature (T_{in})	°C	AUGE system
		Relative humidity (HR)	%	
	Domestic hot water	DHW consumption (DHW)	m^3	AUGE system and BMS
	Heating consumption	Total heating consumption (Q_T)	kWh	
		Heating consumption until reaching 18°C (Q_{18})	kWh	AUGE system
Outdoor data	**Weather conditions**	Outdoor temperature (T_{out})	°C	Public weather station

- If the heating consumption under 18°C (Q_{18}) registered during a specific day is greater than the total heating consumption (Q_T), this does not make sense. Only when the difference between both values is slight (caused by common monitoring error), it is supposed that the heating consumption under 18°C equals the total heating consumption ($Q_{18} = Q_T$). If the values differ considerably, that day is excluded from the data set.

With these simple assumptions, the data set is ready to be analysed.

3.2. Derivation of the characteristic curves and influence of the previous weather conditions

Once the data set has been filtered, the *characteristic curve* for the total heating consumption and the heating consumption under 18°C may be obtained. In order to do this, the type of relation between the daily outdoor temperature data and the daily heating consumption was analysed. Several types of mathematical adjustments were used to find the best correlation between the daily outdoor temperature data and the daily heating consumption. These mathematical correlations were, namely, linear, exponential, logarithmic and polynomic (2nd degree). With this, the idea is to find the best correlation to model both the total heating consumption and the under 18°C heating consumption and derive the respective *characteristic curves* as follows:

$$Q_{18} = f(T_{out}) \tag{Eq. 1}$$

$$Q_T = f(T_{out}) \tag{Eq. 2}$$

Equations (1) and (2) were derived using the daily data collected during the winter of 2020–2021.

The weather changes locally from one day to the next. In addition, with climate change, these changes are accentuating and becoming more and more abrupt. These oscillations in the climate can significantly affect the energy consumption of the building due to the behaviour of the tenants. For instance, during a winter period, there may be several days in a row with warm temperatures and then the temperature suddenly plummets. In many cases, users will not turn on the heating that same day, but instead wait for the situation to stabilise. Thus, in order to absorb the influence of the previous weather conditions, a Root Mean Square (RMS) analysis was carried out. Equations (1) and (2) were derived for different situations, using the outdoor temperature and the heating consumption of the day immediately before and up to 7 days before. Having derived each *characteristic curve* with the sensitivity analysis, the results were compared, and the final *characteristic curve* was chosen as a balance between the accuracy of the exponential correlation and the one that best fits the climate changes.

3.3. Derivation of the predictive curve

Once the *characteristic curve* for the total heating consumption and the heating consumption under 18°C (equations (1) and (2)) have been derived and adjusted using the RMS analysis, the *predictive curve* for the heating consumption under 18 °C may be derived as follows:

$$PC_{18} = \frac{Q_{18}}{Q_T} \tag{Eq. 3}$$

Equation (3) represents the relation between the heating consumption under 18°C and the total heating consumption. The result should always be between 0 and 1, since the assumptions made for the data set include that the Q_{18} registered is always lower than the Q_T. Therefore, using Equation (3), the energy needed to warm the dwelling up to 18°C of indoor temperature may be derived as follows.

$$Q_{18} = Q_T \cdot PC_{18} \tag{Eq. 4}$$

Equation (4) predicts the heating consumption needed to warm the dwelling up to 18°C on a specific day. Knowing the total heating consumption (Q_T) of that day and the characteristic curve, which is constant for the building, the heating consumption needed to reach 18 °C inside the dwelling may be calculated using the said Equation (4). Note that, obviously, the result of Equation (4) may contain a certain error, which directly depends on the measuring precision of the indoor temperature device, the heating metering and the accuracy of the outdoor temperature measurements. The analysis of the error of the *predictive curve* is described in the following section.

3.4. Correlation and error analysis

Finally, this study includes the verification of the accuracy of the *predictive curve* using the data collected during the second winter of analysis, 2021-2022. Thus, having measured and analysed the outdoor temperature and the total heating consumption of each day for the months of December 2021 to March 2022, the heating consumption under 18°C needed each day may be calculated using equation (4).

The results for the heating consumption under 18°C, obtained using equation (4), are compared with the actual heating consumption under 18°C, which were collected during the second winter. The error analysis was carried out using the Mean Absolute Error method and the Root Mean Squared Error method.

The Mean Absolute Error (MAE) measures the average error rate in a series of predictions, regardless of the direction. The MAE is the average value of the samples that determines the absolute value of the deviation between the predicted/calculated value and the measured value. The MAE is a linear score, which means that all individual differences are weighted equally in the mean.

$$MAE = \frac{\sum_{i=1}^{n} |y_i - \hat{y}_i|}{n} \quad \text{Eq. 5}$$

where y_i is the observed/measured value for the i^{th} observation, $\hat{y}_i$ is the predicted/calculated value for the i^{th} observation, and n is the sample size.

On the other hand, the Root Mean Squared Error (RMSE) measures the average size of the errors. Expressing the formula in words, the RMSE is the difference between the predicted/calculated value and the corresponding measured value squared, in each case, and averaged across the sample. Finally, we take the square root of the mean. The RMSE gives a relatively high weight to large errors because the errors are squared before they are averaged. This means that the RMSE is most useful when large errors are not particularly desirable.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{n}} \quad \text{Eq. 6}$$

where y_i is the observed/measured value for the i^{th} observation, $\hat{y}_i$ is the predicted/calculated value for the i^{th} observation, and n is the sample size.

The MAE and RMSE methods can be used together to diagnose fluctuations in a series of prediction errors. The RMSE is always higher that the MAE. The greater their difference, the greater the variance of each error in the sample. However, if RMSE = MAE, all the errors will be equal. Finally, it must be mentioned that the RMSE and MAE values should be between 0 and infinity and the lower the value, the better the prediction.

In addition, Spearman and Pearson analyses were used to confirm or reject the relationships between the total heating consumption and the outdoor temperature. For this purpose, the total heating consumption and the outdoor temperature of a third winter (2022-2023) were collected. These data were compared with the characteristic curve (Equation (2)) derived with the data of the first winter. The test was performed using both methods, as Pearson is used for linear correlations and Spearman for monotonic relationships. The variables follow a linear correlation when the calculated Pearson coefficient is closer to 1 or −1; and a monotonic correlation when the calculated Spearman coefficient is closer to 1 or −1, and the correlation is strong if greater than 0.5 or less than −0.5.

In this study, the data of the first winter (2020-2021) is collected to derive the *predictive curve*, which is validated using data set of the second winter (2021-2022). Finally, data for a third winter (2022-2023) has also been collected, but only to perform the Spearman and Pearson analyses in order to stress the relationship between the total heating consumption and the outdoor temperature. In the end, as proposed in sections 3.1 and 3.3, to apply the presented procedure it should be enough to collect data of one winter in order to derive the *predictive curve*.

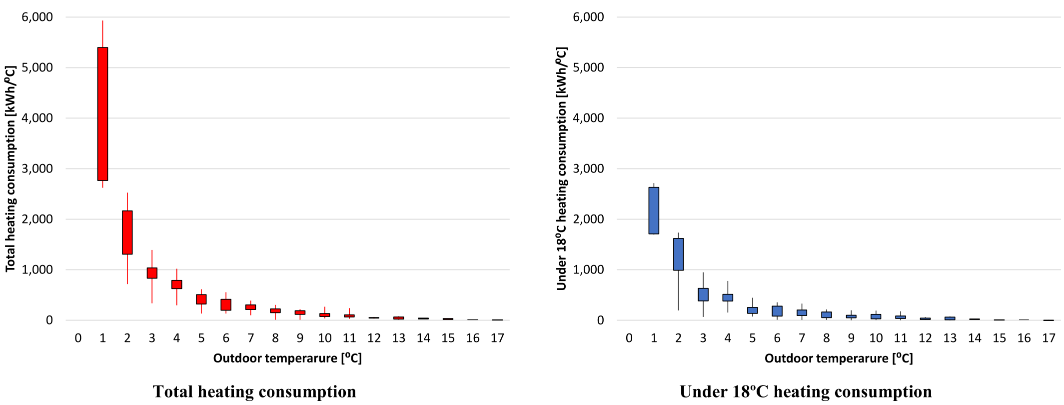

Fig. 2. Sample of the dataset for the total heating consumption and the under 18°C heating consumption used for the analysis.

4. Results and discussion

In this section, the results of the analysis of the data set collected during the two-winter period, the derivation of both the characteristics and predictive curves, and the application of the predictive curve to obtain the under 18°C heating consumption during a specified period are presented.

4.1. Analysis of the data set

Once the filtering assumptions, previously explained in section 3.1, had been applied to the collected data during the first winter (from December 2020 to March 2021), the following data set was obtained.

Fig. 2 shows the scattering of the total heating consumption and the under 18°C heating consumption, in relation with the outdoor temperature. For each one-step degree of the outdoor temperature (from 0°C to 17°C), the minimum, maximum, and 25% and 75% percentiles are shown for both the total heating consumption and the under 18°C heating consumption.

Several aspects can be deduced from Fig. 2. First of all, it is clear that there is a high scattering within the heating consumption collected for the same outdoor temperature. The scattering is higher for the total heating consumption than for the under 18°C heating consumption. Furthermore, it is also evident that the scattering increases with a lower outdoor temperature. Considering that only two types of dwellings exist in these buildings; regarding the useful surface and orientation (the small dwellings face south and larger with a north-south orientation), the high scattering of the heating consumption is probably mainly due to user behaviour; especially if the user profile of these social buildings is taken into account. There is now much research in the literature concerning the influence of user behaviour on household consumption [58–60].

Regarding the shape of Fig. 2, it seems that the data set follows an exponential trend. However, as explained in section 3.2, several types of correlation have been used to find the best adjustment.

Table 3 shows the results when using different mathematical correlations to model the relation between the outdoor temperature and the heating consumption.

As depicted from the results shown in Table 3, and as expected, the mathematical correlation that best fits the data set is the exponential. The logarithmic correlation could also be an accurate adjustment, but the physics of this phenomenon is better represented with the exponential equation, since the logarithmic could lead to negative values for the heating consumption. In short, the exponential correlation is the one that best fits the data set.

4.2. Derivation of the characteristic curves

As depicted in Table 3, the exponential correlation is the best, but the value of the R^2 could be improved. In order to obtain an accurate characteristic curve for the total and under 18°C heating consumptions, the exponential correlations have been improved by considering a RMS analysis, as explained in section 3.2. In this sense, Table 4 shows the characteristic curves for the total and under 18°C heating consumptions according to the sensitivity analysis for 1, 2, 3 and 7 days, using the data set of the first winter.

Table 4 show that the value for R^2 gets better as the number of days considered for the RMS analysis increases. This means that the characteristic curve fits the data set better. However, as explained in section 3.2, our aim was to reach a compromise between the accuracy of the exponential correlation and the correlation that best fits the reality. The RMS analysis using the previous 7 days provides the best values for the R^2. However, considering 7 days for the analysis involving the outdoor temperature and the heating consumption of a building may lead to ignoring changes in the weather and the thermal inertia of the building. Thus, using 3 days for the sensitivity analysis appears to be the option which can provide the most accurate results while also maintaining a realistic approach. For 3 days, the R^2 value considerably improves in comparison with 2 days; however, for 7 days, the R^2 value improves a little more, but not significantly; so, choosing 7 days would be not realistic in terms of the inertia of the local weather changes.

Thus, the equations for the *characteristic curves* of the total and under 18°C heating consumptions are indicated below. These equations show, as expected, that the lower the outdoor temperature, the higher the heating consumption needed in order to reach 18°C for the indoor temperature in each dwelling.

$$Q_T = A \cdot e^{(-b \cdot T_{out})} = 3735.8 \cdot e^{-0.380 \cdot T_{out}} \quad \text{Eq. 7}$$

$$Q_{18} = C \cdot e^{(-d \cdot T_{out})} = 2710.3 \cdot e^{-0.431 \cdot T_{out}} \quad \text{Eq. 8}$$

Finally, Fig. 3 shows the *characteristic curves* for both the total and under 18°C heating consumptions, considering 3 days for the sensitivity analysis. The red dots represent the data for the total heating consumption and blue dots represent the data for the under 18°C consumption, both collected during the first winter.

Table 3
Results of the adjustment of different mathematical correlations.

Type of Correlation	Total heating consumption	Under 18°C heating consumption
	R^2	R^2
Linear	0.2402	0.2158
Exponential	***0.7106***	***0.6962***
Logarithmic	0.6614	0.6218
Polynomic	0.5106	0.4738

Table 4
Results of the RMS analysis of the characteristic curves for the total and under 18°C heating consumptions.

RMS days	Total heating consumption		Under 18°C heating consumption	
	Equation	R^2	Equation	R^2
1	$Q_T = 3560.4 \cdot e^{-0.376 \cdot T_{out}}$	0.7106	$Q_{18} = 2232.4 \cdot e^{-0.416 \cdot T_{out}}$	0.6962
2	$Q_T = 3660.2 \cdot e^{-0.379 \cdot T_{out}}$	0.7321	$Q_{18} = 2563.6 \cdot e^{-0.429 \cdot T_{out}}$	0.7242
3	$\boldsymbol{Q_T = 3735.8 \cdot e^{-0.380 \cdot T_{out}}}$	***0.9050***	$\boldsymbol{Q_{18} = 2710.3 \cdot e^{-0.431 \cdot T_{out}}}$	***0.9003***
7	$Q_T = 3638.2 \cdot e^{-0.371 \cdot T_{out}}$	0.9391	$Q_{18} = 2827.9 \cdot e^{-0.424 \cdot T_{out}}$	0.9435

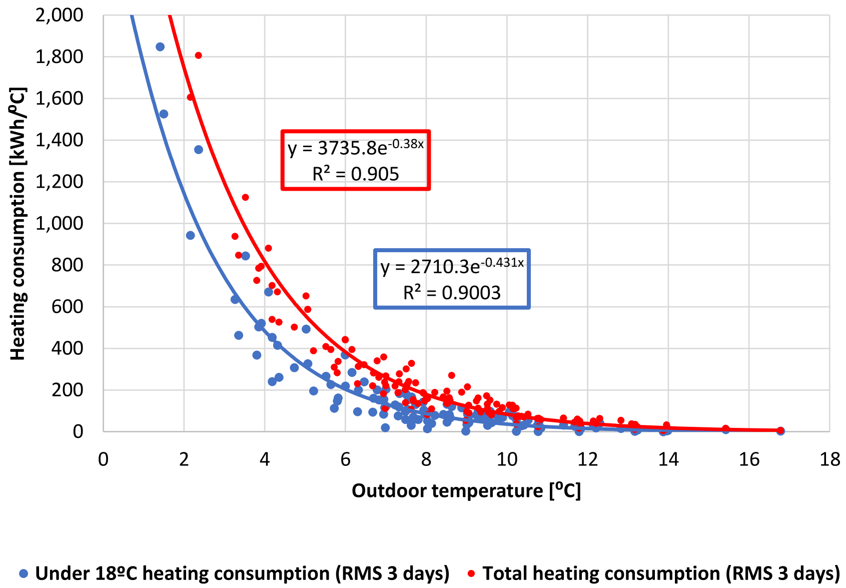

Fig. 3. Characteristic curves for the total and under 18°C heating consumptions, considering a sensitivity analysis of 3 days.

As expected, the characteristic curve for the total heating consumption provides greater values, for each value of the outdoor temperature, than the characteristic curve for the under 18°C heating consumption. In addition, the higher the outdoor temperature is, the smaller the difference between both characteristic curves. This means that, when the outdoor temperature is high, most of the total heating consumption is considered to be the same as the under 18°C heating consumption. On the contrary, with a low outdoor temperature, the total heating consumption increases and the difference between both characteristic curves also increases.

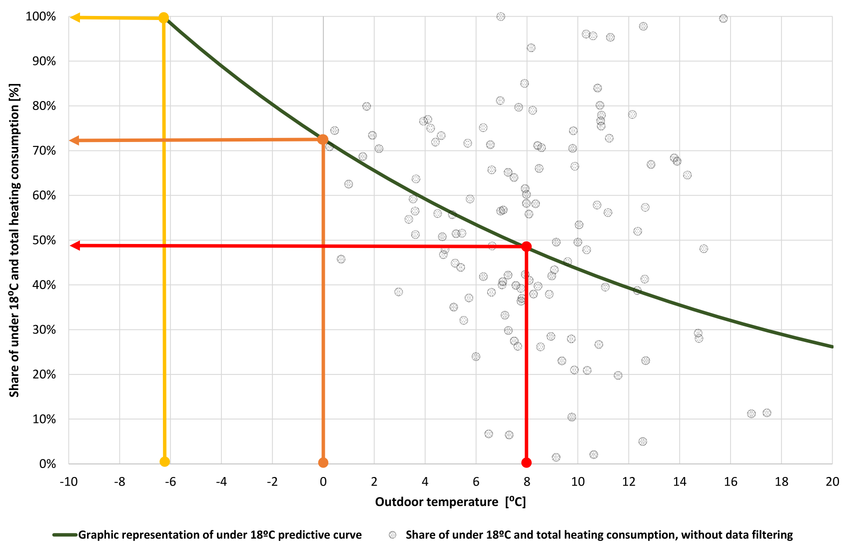

Fig. 4. Daily graphic representation of the *predictive curve* for the first winter.

4.3. Derivation of the predictive curve

According to equation (3), the *predictive curve*, using the *characteristic curves* for the total and under 18°C heating consumption (equations (7) and (8)), may be derived as follows:

$$PC_{18} = \frac{Q_{18}}{Q_T} = \frac{A \cdot e^{(-b \cdot T_{out})}}{C \cdot e^{(-d \cdot T_{out})}} = \frac{A}{C} \cdot e^{[(b-d) \cdot T_{out}]} \rightarrow$$
$$\rightarrow PC_{18} = \frac{2710.3 \cdot e^{-0.431 \cdot T_{out}}}{3735.8 \cdot e^{-0.380 \cdot T_{out}}} = 0.725 \cdot e^{-0.051 \cdot T_{out}} \qquad \text{Eq. 9}$$

Equation (9) is the *predictive curve* for the analysed building. If the heating under 18°C (Q_{18}) is cleared from equation (9), the following expression is obtained:

$$Q_{18} = Q_T \cdot \frac{A}{C} \cdot e^{[(b-d) \cdot T_{out}]} = Q_T \cdot 0.725 \cdot e^{-0.051 \cdot T_{out}} \qquad \text{Eq. 10}$$

Thus, given a total heating consumption and an outdoor temperature, the amount of energy needed to warm the dwelling (or the building) until 18°C may be derived using equation (10). That is to say, for a particular winter day, if the average outdoor temperature during that day was $\overline{T}_{out,1}$, and the total heating consumption of that specific dwelling was $Q_{T,1}$, the heating consumption of that dwelling until the indoor temperature reached 18°C may be calculated as:

$$Q_{18} = Q_{T,1} \cdot 0.725 \cdot e^{-0.051 \cdot \overline{T}_{out,1}}$$

Fig. 4 shows the graphic representation of the *predictive curve* for the heating consumption under 18°C (equation (9)), and three examples of how the *predictive curve* may be implemented.

As expected, the graphic representation of the *predictive curve* (equation (9)), shown as a green line in Fig. 4, is exponentially negative. This means that the lower the outdoor temperature is, the higher the share of heating consumption that is considered as under 18°C heating consumption. Three examples of the implementation of the methodology are also shown in Fig. 4:

- When the average daily outdoor temperature is around 8°C (which was the average outdoor temperature during the first winter), the heating consumption under 18°C should be about 50% of the total heating consumption (the red line in Fig. 4).
- If the average daily outdoor temperature drops to 0°C (during the first winter, the outdoor temperature only dropped to 0°C on three days), the heating consumption under 18°C should be about 70% of the total heating consumption (the orange line in Fig. 4).
- Only if the average daily outdoor temperature drops to -6°C, which is unlikely to happen in this location, it would mean that the under 18°C heating consumption should equal the total heating consumption (the yellow line in Fig. 4).

Fig. 4 also shows, in soft green dots, the share between the under 18°C heating consumption and the total heating consumption for the first winter, but as if none of the previously explained data filtering had been done. That is to say, if the local weather inertia is not considered, it can be noticed that the scattering would be significant. This may be due to several reasons. Firstly, because of the inherent inaccuracies of the monitoring system; but the scattering may also be caused by the use profile of the heating systems. The use of heating is not consistent from one day to the next due to the condition of the social housing users. Thus, if the predictive curve

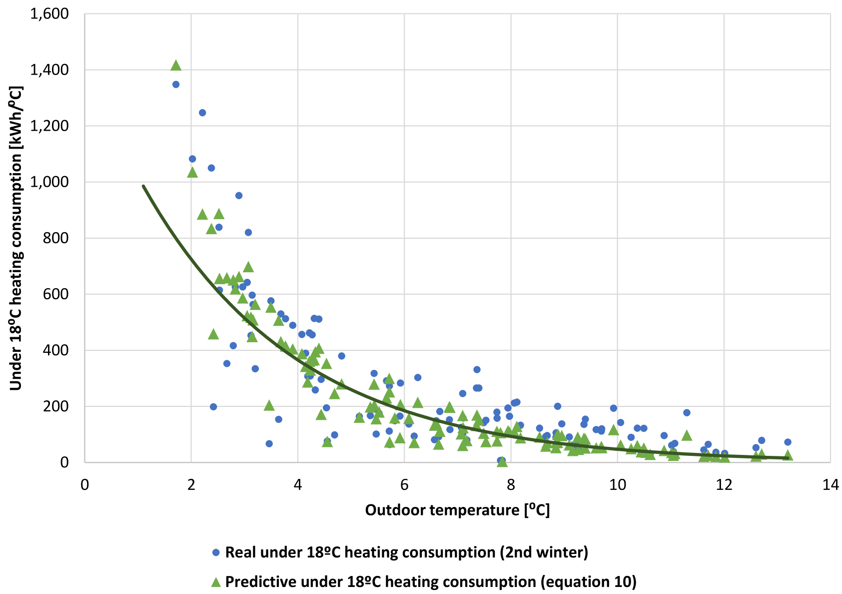

Fig. 5. Real under 18°C heating consumption, during the 2nd winter, and predictive under 18°C heating consumption, using equation (10).

(equation (9)) is used to derive the real heating consumption under 18°C, a homogenisation of this consumption is achieved, meaning a fair share between the social housing users.

4.4. Application of the predictive curve

Finally, the main objective of this study is to check the reliability of the use of the *predictive curve* (equation (9), derived with the data from the first winter) in future winters. For this, the data set for the second winter (from December 2021 to March 2022) is used. Fig. 5 shows the real under 18°C heating consumption, collected during this second winter, and the under 18°C heating consumption, derived from equation (10), using the total daily heating consumption and the average daily outdoor temperature.

Fig. 5 shows interesting results when comparing the real under 18°C heating consumption and the predictive under 18°C heating consumption. Firstly, it can be noticed that the predictive under 18°C heating consumption (in green dots) follows a very similar trend to the real under 18°C heating consumption for the second winter (in blue dots).

It can also be seen that the scattering of the predictive results (green dots) is lower than the scattering of the actual data collected (blue dots), in accordance with the results shown in Fig. 4. The MAE and RMSE methods are used to quantify the error between the real and predictive under 18°C heating consumption. Table 5 shows the MAE and RMSE errors between the real under 18°C heating consumption, collected during the first and second winters with the monitoring system, and the predictive under 18°C heating consumption, using equation (10).

The results in Table 5 show that the MAE error is relatively low, with a deviation of 52.5 kWh/°C per day, during the first winter, and 73.3 kWh/°C per day during the second winter. Moreover, the RMSE value is higher, 145.1 kWh/°C per day during the first winter, and 108.3 kWh/°C per day, during the second winter. In fact, during this second winter, the average under 18°C registered by the monitoring system was of 9.8 kWh per dwelling and day. When using the predictive curve, the average under 18°C heating consumption appears to be 8.4 kWh per dwelling and day. This means a difference of 14.3% between the real and predictive values.

Regarding the RMSE error, which analyses the scattering of the results, it is noticeable that, during the second winter, the scattering between the real and predictive values are even lower than the first winter. This means that the use of the predictive curve helps with the homogenisation of the under 18°C consumption among the users of the building.

Finally, Table 6 shows the results for both the Spearman and Pearson correlation analyses, in order to compare the measured values of Q_T/T_{out} during the 2022-23 winter with the predicted Q_T/T_{out} for that same period of time, using the *characteristic curve*.

Both coefficients are significant at the 0.01 level and close to 1, so, the relationship between the measured and the predicted values are statistically significant at the highest level. As Pearson is lower than Spearman, the correlation is monotonic rather than linear. As Pearson is close to 1, the linear correlation is positive, as expected. And as Spearman is also close to 1, the measured Q_T/T_{out} increases as the predicted Q_T/T_{out} increases. Graphically, this is almost a $y = x$ function, meaning that the measured values correlate almost perfectly with the predicted ones.

4.5. Additional considerations

As explained before, this paper develops and validates the under 18°C *predictive curve* as a novel procedure to mitigate energy poverty in social housing buildings. As the procedure has been developed, other aspects have been considered that are beyond the scope of this work, but which are summarised below.

Firstly, with this procedure, the indoor conditions of 80.9% of the dwellings improved. Specifically, in previous winters, during the colder months of the year, at least 50% of the dwellings registered indoor temperatures lower than 17°C. During these last two winters, when the under 18°C methodology was being implemented, only 10% of the dwellings registered indoor temperatures lower than 17°C. This is particularly needed in social housing and low-income families. Furthermore, it helps to achieve a fairer use of heating among the dwellings of collective buildings since, if a tenant is allocated to a colder dwelling, this methodology compensates for that injustice. Otherwise, if heat cost allocation mandated by the EED is used, a family living on a first floor will pay more for heating than a family living on a middle floor. And the only difference will be the position on a list or a lottery. From the point of view of how to fairly allocate a public resource, individual metering creates an inequality that the proposal described in this article attempts to solve. The same can be said for the social housing stock as a whole, a family living in an inefficient building in the Basque Country will pay more than another family occupying a dwelling in an nZEB building.

Secondly, it has also been proved that the efficiency of the centralised system increases. This is because, in this type of social housing with centralised heating and DHW systems, the energy of the boilers is often lost through heating distribution pipes, as the users do not actually use the heating system due to low incomes or because they would rather use individual heaters with cheaper fuels. If a minimum indoor temperature of 18°C is assured in the dwellings, the energy of the heating system is actually being used inside the dwellings and is not lost through the distribution pipes. An improvement of 8.9% in the overall efficiency of the centralised system was obtained in reference to previous winters.

Table 5
MAE and RMSE errors between the real under 18°C heating consumption and the predictive under 18°C heating consumption.

	MAE [kWh/°C]	RMSE [kWh/°C]
1st winter (December 2020 – March 2021)	52.5	145.1
2nd winter (December 2021 – March 2022)	75.3	108.3

Table 6
Correlation analysis for measured values of Q_T/T_{out} during the 2022-23 winter and the predicted Q_T/T_{out} for that same period of time.

Variable	Number of Observations	Spearman's rho	Pearson
Measured Q_T/T_{out} vs predicted Q_T/T_{out}	81	0.9589 **	0.9471 **

* Significant at the 0.05 level, ** significant at the 0.01 level, and ns not statistically significant.

5. Conclusions

In this work, we present and test a simple and novel procedure which allows energy managers of social housing buildings to guarantee a minimum indoor temperature in the dwellings. Our procedure, although initially designed for an indoor temperature of 18 °C, can be adjusted to accommodate different target temperatures. The methodology is based on the derivation of a *predictive curve* for the building which allows the heating consumption needed to warm the dwelling until that specific indoor temperature to be calculated, depending on the total heating consumption and the outdoor temperature.

To test the effectiveness of our procedure, we selected a social housing building in the north of Spain comprising 126 dwellings as a case study. With the data collected during the first winter (2020-2021), the *predictive curve* was derived. This predictive curve was tested with the data collected during the second winter (2021-2022). An MAE error of 14.3% was found between the under 18°C heating consumption, calculated with the predictive curve, and the real 18°C heating consumption, collected by the monitoring system, during the second winter.

Furthermore, the total heating consumption and the outdoor temperature of a third winter (2022-2023) has been collected, and a Spearman and Pearson correlation analysis has been carried out to test the characteristic curve of the building. Both coefficients are significant at the 0.01 level and close to 1, so the relationship between the measured and predicted values are statistically significant at the highest level.

By implementing this procedure, we observed improved indoor conditions in 80.9% of the dwellings and an overall efficiency increase of 8.9% in the centralised heating system. As explained in the discussion section, the presented procedure may be against the principles of the EED, as it proposes a sort of "flat energy rate". However, the results demonstrate its efficacy and reliability in managing heating and ensuring a minimum indoor temperature in centrally centralised social housing buildings. Also, the source of inequalities among tenants that occurs when random allocation in dwellings is performed is solved with this proposal. This in line with other initiatives, such as the Energiesprong, and also with the opinion of Housing Europe, both not fitting directly with the EED, but currently in progress. Thus, in the authors' opinion, this procedure may provide valuable insights for energy policies to be considered in future revisions of the EED.

6. Future work

For future work, the main objective is the extrapolation and validation of the methodology in other buildings. The idea is that, following the steps summarised below, the energy manager of any social housing building will be able to implement the methodology presented in this work:

1. Install an energy management device in the dwellings that can monitor the total heating consumption and the heating consumption under a specific indoor temperature, such as the AUGE system indicated in this work.
2. Collect the daily data during a winter period (approximately 3 months) and also collect the outdoor temperature using, for instance, the nearest public weather station.
3. Derive the *characteristics* and *predictive curves* of the building following the methodology described in this work.
4. In the following winters, use the *predictive curve* to calculate the heating consumption needed to warm up the building until the specified temperature.

Another aspect that could be improved is the fitting of the *characteristic* and *predictive curves*. This would imply the addition of several variables that have been avoided in this proposal; for instance the location of the dwelling within the building, the occupancy of the dwellings, or the consumption of electrical appliances. All of these aspects may affect the heating consumption of the dwellings and the accuracy of the methodology could consequently be improved. However, it should also be taken into account that including these variables significantly complicates the methodology, which is far from the initial intention of the authors, which is to develop a methodology that is simple to apply.

Author contributions

Pablo Hernandez-Cruz: Term, Conceptualization, Methodology, Data Curation, Writing - Original Draft; **Irati Uriarte:** Conceptualization, Methodology, Data Curation, Writing - Review & Editing; **Juan María Hidalgo-Betanzos:** Conceptualization, Methodology, Data Curation, Writing - Review & Editing; **Íñigo Antepara:** Validation, Formal Analysis, Data Curation, Writing - Review & Editing; **Iván Flores-Abascal:** Writing - Review & Editing. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgements

The authors would especially like to thank Alokabide S.A., the Social Housing institution of the Basque Government that manages public rental dwellings, specifically the technical team formed by Íñigo Aberasturi, Aitor Pradovaso and Carlos Orbea.

The work has also been partially developed in the framework of the EnePoMAP Project, which has received funding from "la Caixa" Foundation under the project code LCF/PR/SR20/52550013.

Finally, this work also received support from the Laboratory of Quality Control of Buildings of the Basque Government and the research group ENEDI from the University of the Basque Country UPV/EHU.

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