Indoor Thermal Comfort

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A neutral or comfortable environment is an environment that allows metabolic heat production to be balanced with heat exchange (loss and/or gain) from the air around the worker. Outside this situation of balance, there may be adverse situations in which the exchange of heat energy constitutes a risk to the person's health, since even taking into account the body's thermoregulation mechanisms, they cannot maintain a constant and adequate internal temperature. Even though the milder climate scenario and constant evolution of thermal building regulation are in light of European initiatives, in Portugal, there are few houses where occupants can remain all the time in perfectly comfortable temperature conditions without resorting to heating or cooling. According to the Long Term Strategy for the Renewal of Buildings (ELPRE), this results from the combination of several factors, namely, low energy use for air conditioning compared to energy needs and aged building stock with poor energy performance. In fact, around 70% of the dwellings currently certified have low energy efficiency (C or less).

indoor thermal comfort | thermal building policies | residential buildings | Mediterranean climates

1. Introduction

Buildings account for approximately 40% of global energy consumption, and it is predicted that the buildings' energy demand will continue growing worldwide in the coming decades [1][2][3][4]. Compared to 50 years ago, the energy demand from buildings (residential and commercial) has grown 1.8% per year [5], and it is predicted to grow from 116.8 EJ in 2010 to over 184.2 EJ by 2050, with most of this increase being from developing countries [6]. Three-quarters of total energy consumption in the buildings sector is residential, where there is great potential to improve energy efficiency [7]. Although it is generally recognized that energy efficiency is the cheapest way of reducing carbon emissions, the last years showed that the construction sector was frequently a missing opportunity [8]. This happens due to the higher initial costs, but also because of the lack of know-how and awareness (from owners, tenants, and stakeholders) regarding cost-effectiveness of the energy retrofit measures [9], especially if a life cycle cost approach is considered and ancillary benefits of energy retrofit measures are taken into account [10][11][12][13][14].

In accordance with this, a significant number of studies are presented in literature in order to improve building energy efficiency, namely on thermal insulation (building envelope) [15][16][17], life cycle analysis and numerical optimization [18][19][20], technical and economic analysis of energy-efficient measures for buildings renovation [21][22], control of lighting systems and heating/cooling, ventilation, and HVAC installations [23][24].

In modern societies, most of the population spends the day inside buildings for work, leisure, or rest activities. This context explains the increase in the installation of air conditioning systems in both residential and service buildings in recent decades, with this investment being a dominant part of the energy bill.

As the years go by, society becomes more developed, requiring more energy and greater thermal comfort. With this, there is a concept called energy efficiency that allows responsible use in the services that are used on a daily basis [25]. As such, the rational use of air conditioning systems will make it possible to reduce energy consumption and, consequently, reduce costs without depriving the indoor thermal comfort of the occupants and ensuring an indoor air quality environment.

The internal human body temperature remains approximately constant around 37 °C. This feature obliges humankind to constantly seek a thermal balance between themselves and the surrounding environment, which influences internal temperature. A small deviation from this value may trigger various body reactions and, in extreme cases, lead to death. In the event of illness, for survival, the internal temperature of the organism has 32 °C as its lower limit and 42 °C as its upper limit [26].

Technological advances in various sectors began during the Industrial Revolution, and civil construction was not left out of this context. The constant development of new construction techniques and materials, as well as the increased speed in the circulation of goods and products, meant that the way of thinking about buildings underwent drastic changes. Additionally, due to technological development and increase in the standard of living of modern societies, the conception of buildings, whether for housing, work, or leisure, has come to be guided by a set of functional requirements in which comfort, being of direct and immediate perception of the user, gains particular prominence. When there is a psychological perception of this balance, researchers can speak of thermal comfort, which is defined by ISO 7730 [27] as a state of mind that expresses satisfaction with the environment surrounding a person (neither hot nor cold). It is therefore a subjective sensation that depends on the occupants' biological, physical, and emotional aspects, thus not being able to satisfy all the individuals occupying an enclosure with a given thermal condition.

A neutral or comfortable environment is an environment that allows metabolic heat production to be balanced with heat exchange (loss and/or gain) from the air around the worker. Outside this situation of balance, there may be adverse situations in which the exchange of heat energy constitutes a risk to the person's health, since even taking into account the body's thermoregulation mechanisms, they cannot maintain a constant and adequate internal temperature. In these situations, researchers can speak of thermal stress due to heat or cold. As an example, field studies conducted by [28], which included on-site questionnaire surveys, environmental monitoring, and in-situ physical measurement on several buildings, located in regions with a subtropical and partly semi-arid climate, showed that the 'neutral' temperature was 28.5 °C, and the upper limit of the comfort range in warm indoor air temperature conditions was 31.5 °C.

The thermal environment can be defined as the set of thermal variables of the surrounding environment which influence the human organism. It is, therefore, an important factor that intervenes not only in the health and well-being of people but may also impact productivity and concentration. To evaluate the environmental conditions to which certain building occupants are exposed, objective methods or criteria are usually employed, namely: (a) air temperature; (b) air humidity; (c) mean radiant temperature; (d) air velocity; (e) metabolism; and (f) clothing.

In the study of the thermal environment, two situations must be considered: (i) Thermal overload or thermal “stress”, which relates to the exposure of the human body to environments of extreme temperatures; (ii) thermal comfort, which does not involve extreme temperatures, relates to the temperature, humidity, and air velocity existing in places that, as a whole, may cause discomfort. Any of these situations can be measured through special techniques, calculating indices that provide information on the environmental quality of the workplace.

2. Thermal Comfort

Thermal comfort has always been a very vast subject due to its variables, the parameters, and factors that influence it in a given social and climate context. Because there has always been ambiguity and subjectivity around this subject, some thermal comfort measures have emerged to clarify and provide harmonised methodologies to access the feeling of thermal comfort.

Complementing the definition of generic comfort assessment models, where temperature ranges are defined with certain degrees of acceptability, for the indoor climate, depending on the type of buildings and occupants, many authors have worked on the form of indices, which summarises the degree of discomfort or “stress” into a single number felt by the human being in each environment. This “discomfort index” can be calculated in time and space, representing a unique indicator of the thermal performance of a building, referring to a given area and to a certain time (usually on an annual basis). These indices are essential for comparing measures and design strategies, from the point of view of the comfort of its occupants.

From the literature survey, several indices can be found. For instance, Epstein and Moran [29] found 46 thermal comfort indexes (between 1905 and 2005). Later, Carlucci and Pagliano [30][31] completed the aforementioned list and identified 78 indexes. Despite the enormous indices available, they can be grouped into different categories. One of the first classifications, proposed by Macpherson [32], distinguishes such indices based on the following criteria:

- Indices based on the calculation of the heat balance of the human body (rational indices);
- Indices based on physiological effort (empirical indexes);
- Indices based on the measurement of physical parameters (direct indexes).

More recently, new indexes have been proposed, with the objective of evaluating the long-term comfort conditions inside a building, either through experimental monitoring or through dynamic simulation [31]. However, there was a need to somehow standardise this kind of indicator, and ISO 7730 [27], proposed indexes based on the classic

Fanger model, namely: (a) Percentage out of range (comfort); (b) PPD weighted; (c) Average PPD; (d) Accumulated PPD.

This standard is based on requirements for general thermal comfort (predicted mean vote (PMV), operative temperature) and local thermal discomfort (radiant temperature asymmetry, draught, vertical air temperature differences, floor surface temperatures).

International standards, such as ISO 7730 [27] and EN 16798 [33][34], present some methods to quantify discomfort indices [30]. Three of these indices were adapted in the European standard EN 16798 [33][34], extending its scope to the adaptive approach. In 2008, Nicol et al. [35] proposed the “Overheating risk” index based on the statistical data collected for the European project SCATS (senses thermal discomfort in temperature-free floating buildings for various climates in Europe). More recently, in 2010, the “Exceedance M” index, which quantifies hours of discomfort, weighted by the number of occupants on average per hour, was proposed by Borgeson and Brager [36]. This index can be applied based on the Fanger model or based on the adaptive model proposed in ASHRAE 55 [37]. For the indices of evaluation of the long-term discomfort, based on comfort evaluation models, the grouping of the indices in four families is proposed by [6]:

- Indices-% (POR—percentage out of range): based on the number of hours of discomfort, in relation to the total hours occupied; it should be noted that this index does not value the severity of the conditions outside the comfort range;
- Indices-sum (or “accumulated”): sum of the busy hours of discomfort. They can be weighed by the severity of the discomfort or not.
- Risk indices: incorporate in the calculation the non-linear relationship between the perception of discomfort and the distance to the comfort interval;
- Average indices: as the name implies, the calculation is based on the average of the parameter evaluated.

For most of these indices, there is a greater prevalence of summer discomfort due to overheating [32], some of which are extensible in the winter (but never the opposite), and therefore the case studies are, in most cases, services. Another typical mention to “thermal stress indexes” in this context of thermal comfort is made in the health literature [35].

Several limitations are pointed out to each of the mentioned approaches. The most important limitations refer to the “boundary conditions” in the calculation process of indices, starting with the definition of the hot and cold seasons (start, end, and duration) [38]. Moreover, there is no harmonised criterion for calculating the different indices. For example, EN 16798 [33][34] suggests that the index shall be calculated for 95% of the building area, with the various compartments being weighted by the volume of each. In turn, the Exceedance M index weights discomfort by the number of occupants in each compartment. On the other hand, the POR (percentage out of range) indices do not incorporate the severity of the discomfort or the distance from the parameters to the desirable ones.

Finally, it should be noted that, in the case of single values, it is necessary to use this type of index with great care and discretion, always conducting a sensitivity analysis of the results. A study carried out by Carlucci and Pagliano [31] applied 16 indexes of long-term discomfort in offices located in Rome, which allowed them to conclude that the discomfort values had absolutely no relation, with variations of up to 70% among them, especially for the overheating risk. They also concluded that the strategy of optimising a building from the point of view of the project for thermal comfort is thus strongly conditioned by the index of discomfort used.

The evaluation and quantification of thermal comfort have been widely studied over time, however, constitutes itself a complex exercise, as it depends on a wide variety of factors, part of which is measurable (environmental and occupation) and part of which is not measurable (psychological and sociological individual factors). The condition of thermal comfort happens when the thermal exchanges that are established between the human body and the environment that surrounds it are in balance.

In the last twenty years, a new approach to the assessment of thermal comfort has gained strength, the adaptive model, proposed by Humphreys and Nicol [39] who considered that the conditions in climatic chambers were very far from the real environmental conditions (see **Figure 1**), i.e., did not consider the human ability to adapt to different environments through actions such as putting on more clothes, opening and closing windows, etc.

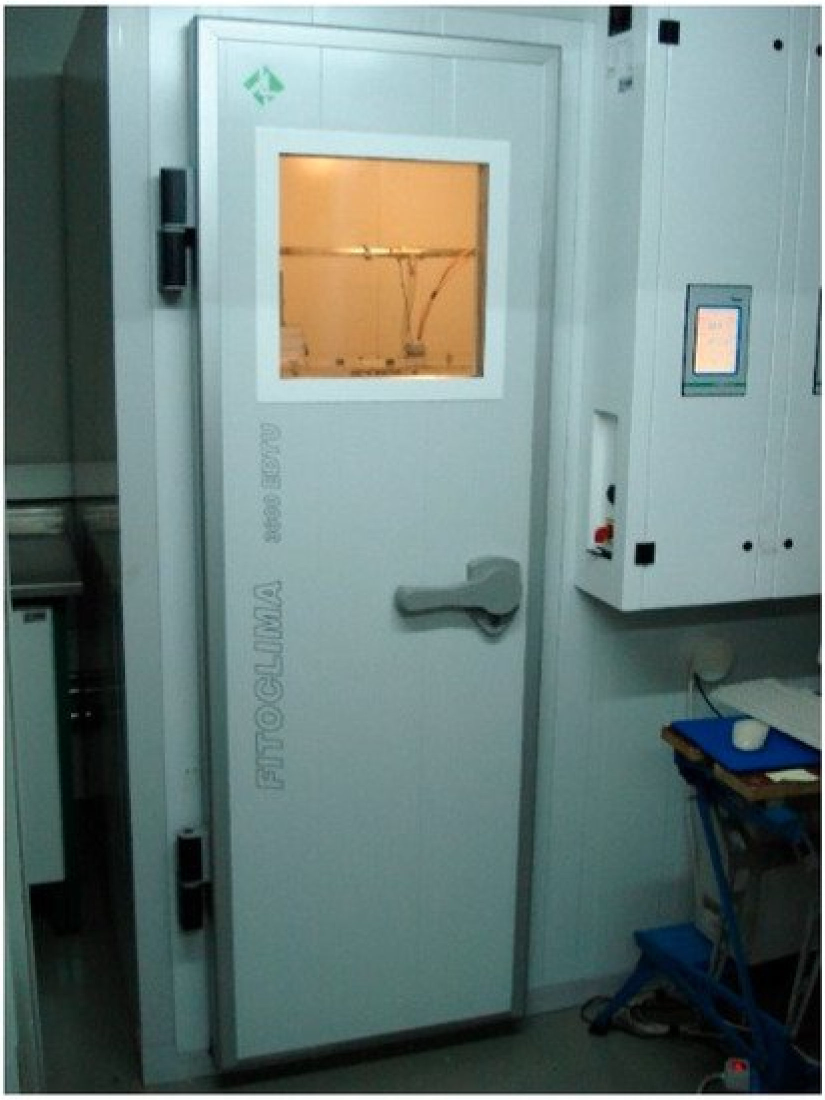

Figure 1. Example of climate chamber used in the University of Porto.

The analytical approach proposed by Fanger [40] is the basis of the international standard for comfort evaluation, ISO EN 7730 [27]. The sensation of thermal comfort is influenced by environmental factors, namely (ASHRAE 55 [37]): air temperature, mean radiant temperature, air velocity, and relative humidity, and individual factors: metabolic rate and basic clothing insulation.

Moreover, air movement may provide desirable cooling in warm conditions, but it may also increase the risk of unacceptably cool drafts [41]. As example, the experimental study developed by Gong et al. is presented [42], who analysed the perception of locally applied airflow, with 6 air velocities between 0.15 m/s and 0.9 m/s and different ambient temperatures and local temperatures, in 24 persons working in an office. The different combinations were maintained for 15 min, during which the subjects responded to questionnaires on their thermal and draft sensations. The results showed that the subjects preferred air movement was between “just right” and “slightly breezy” and they preferred their thermal sensation was between “neutral” and “slightly cool”, with an acceptable air velocity range between 0.3 m/s and 0.9 m/s.

In addition to the definition of comfort assessment models, where temperature ranges are defined with certain degrees of acceptability, depending on the type of buildings and occupants, many authors have worked in the form of indices, which translate into a single number, the degree of discomfort or stress experienced by humans in a given environment. This discomfort, in the form of an index, can be calculated in time and space, representing a unique indicator of the thermal performance of a building for a given area and for a certain period (usually on an annual basis), i.e., defining the variable “°C.hd” as a discomfort indicator (hourly degrees of discomfort).

2.1. Building Regulations and Recent Initiatives

Thermal comfort is related to the energy performance of buildings, ensuring that buildings have certain characteristics to provide a minimum comfort. Thermal adaptation in the built environment can be attributed to three different processes: behavioural adjustment, physiological acclimatization, and psychological habituation or expectation [35][43]. The thermal comfort temperature is not always constant, and the range of values in which it varies is from 18 °C to 25 °C. Maximum energy demand values and minimum air renewal rate values are other examples of important parameters to feel comfortable in a building.

The first regulation concerning indoor thermal comfort in Portugal was the Decree-Law no. 118/98, Regulation on conditioning systems in buildings (RSECE), in which the thermal comfort and indoor environmental quality needs of buildings involved using ventilation, heating, cooling, humidification, and dehumidification systems. The Decree-Law no. 79/2006 established the Buildings Energy Certification System based on Directive 2002/91/CE and renovated the previous Decree-Law no. 118/98.

Later, in 2020, Decree-Law no. 101-D/2020 established the requirements applicable to buildings for the improvement of energy performance and regulates the Energy Certification Scheme, transposing Directive (EU) 2018/844, and partially transposing Directive (EU) 2019/944. One of the most controversial changes of this new legal framework among construction stakeholders was the exclusion of the thermal comfort project, which was no longer mandatory as a specialty project in the scope of the minimum energy performance requirements for new buildings. Thus, Decree-Law 102/2021, of 19 November, introduced the first alteration to Decree-Law 101-D/2020, of 7 December, restoring the obligation to present the thermal comfort project as a specialty project. Decree-Law 101-D/2020, revised the normative and regulatory framework applicable to the energy performance of buildings. The law establishes requirements for new buildings and existing buildings undergoing renovation, with a view to achieve a building stock with almost zero energy needs. A detailed review of historic thermal building regulations can be found in previous research of the authors [44].

Considering the actual building stock situation, the unsatisfactory indoor thermal comfort of the population, as part of the Economic and Social Stabilisation Programme (PEES), the Portuguese Government launched the “More sustainable buildings” initiative in September 2020. At a value of 4.5 million euros, this programme was available until December 2021 and offered a maximum reimbursement of 70% of the investments made by the households, with a maximum limit of 15,000 euros per owner and 7500 euros per building or autonomous fraction. The beneficiaries are the owners of buildings located in mainland Portugal and built before the end of 2006. The “More sustainable buildings” programme covers six types of intervention:

- Efficient windows
- Thermal insulation
- Space heating/cooling and domestic hot water systems (e.g., heat pump)
- Renewable energy production equipment (e.g., photovoltaic panels)
- Optimisation of water management (e.g., pressure reducer)
- Incorporation of biomaterials, recycled materials, green roofs and façades, and bioclimatic architecture solutions.

More recently, the “Vale Efficiency” programme was set and aimed at combating energy poverty and reinforcing the renovation of buildings at the national level, enabling an increase in their energy and environmental performance, thermal comfort and living conditions, health and well-being of families, contributing to the reduction of energy bills and the ecological footprint. This programme is part of the Portuguese Recovery and Resilience Plan (PRR). Under this programme, 100,000 “efficiency vouchers” are to be handed out to economically vulnerable families by 2025, to the value of 1300 euros plus VAT (Value Added Tax) each, so that they can invest in improving the thermal comfort of their homes, either by intervening in their surroundings or by replacing or acquiring energy-efficient equipment and solutions. The present phase of the programme aims to deliver 20,000 vouchers. This programme covers mainland Portugal’s economically vulnerable families and those in a situation of potential energy poverty, who do not reside in social housing so that they can improve the energy performance of their permanent home and their living conditions.

3. Factors Affecting Indoor Thermal Comfort: Climate, Housing, and Living Conditions

3.1. The Special Case of the Dwellings Located in Southern Europe

Despite the low heating habits, Portugal, as other low-heating countries, presents discomfort conditions, especially in the winter season [45][46][47][48][49]. Fuel poverty is a very important problem all across of Europe, especially in southern countries, despite its better climates. New indices were created concerning climate, energy prices, and income for all European countries, and the results reinforce the low heating tendency, corroborated with the low energy bills for space heating (obtained from surveys [50]), for southern Europe and Portugal in particular. Hence, for those countries, if the actual heating patterns are mainly lower than the regulation assumptions (intermittent heating in space in time), this means they do not need to save so much energy as the regulation would recommend, as the energy consumptions are already low. It is not possible to save energy when it is not spent, but dwelling's performance in these countries has a wide range of possibilities to improve winter comfort conditions without compromising summer comfort.

These findings merge into the idea that a new approach is required to evaluate the thermal performance of existent dwellings located in low-heating countries. These are mainly southern European countries but may be any other more vulnerable to fuel poverty conditions. This is particularly important for countries such as Portugal, where higher values of "Lack of motivation to heat" (LMH) and lower effective heating consumptions were presented.

Still, in the southern Europe countries, many of these existing buildings do not have insulation at all and were built in a period of completely different construction techniques, favouring natural ventilation, using high inertia stone walls (not insulated) and wooden floors and roofs (which need to be ventilated). These techniques do not have the same behaviour when insulation is introduced and may develop significant pathologies, which is a common perverse consequence of non-appropriated insulation measures, besides the air-quality prejudice [51][52]. Furthermore, many of these ancient and historical buildings have an additional architectural value, which is not always compatible with the insulation introduction. Still, regarding all measures suggested on Energy Certification Schemes (ECS), a careful evaluation should be made of when to introduce them, since they represent high investments to households (especially in these poorest countries). Since heating consumptions are already low, the effective payback times associated are much higher than the theoretical values referred to on certificates. Will the household effort needed to pay for them be worthwhile?

Tigchelaar et al. [53] described the actual payback time, considering the "Heating factor" (percentage of actual energy use in the theoretical/"nominal" value given by regulation) for installing low-E glazing in Dutch dwellings. The authors showed that many investments may not be worthwhile, considering actual energy consumption, marked as dots in the picture. Considering the Portuguese "Heating gap" presented by Magalhães and Leal [54], which by definition is the same as the "heating factor", this gap was 95% in 2010 (considering the Portuguese regulation at the time [55]). This means that households in Portugal used only 5% of the energy that they would need to maintain the whole house at a minimum of 20 °C during the whole winter. Nevertheless, Magalhães and Leal [54] also showed that "nominal" conditions (e.g., 20 °C in the entire house during all winter) are likely an excessive standard in terms of comfort requirements and showed another theoretical gap of 55% that would be the "enough heating gap". This means it would be "enough" to spend 45% of "nominal" heating needs to reach comfortable conditions inside dwellings [54]. Considering this, it is possible to conclude that Portuguese consumption would not theoretically justify the measure of installing low-E glazing (regarding the specific context of the example), as its payback time would be, in most cases, too high, even if people start heating to reach "enough" winter comfort conditions. Note that the definition of "enough consumption to reach comfortable conditions" was defined considering the "theoretical heating energy demand under relaxed thermal comfort conditions" estimated from the national regulation-specific model developed by [54].

Taking into account all the previous findings, it is very important, thereby, to consider widely if the low-heating countries or the ones most exposed to fuel poverty are on the correct path, when it comes to thermal performance evaluation or energy efficiency policies definition, once there is the risk of spending important investments on those driven policies, with results much lower than expected. Moreover, in the worst scenario, it is important to keep in mind that the thermal pathologies are associated with internal insulation and high investment efforts of households without real payback, among others.

3.2. Heating Patterns

There is a wide range of literature concerning heating patterns in the residential sector in Europe. Most of these studies identify that, in Europe, permanent heating in the entire dwelling area and all the time is very rare. Kane et al. [48] showed that the average duration of the daily heating period was 12.6 h for 300 Leicester (UK) dwellings (from 4 to 22 h, those being the shortest and longest heating periods, respectively). In Southern Europe, Terés-Zubiaga et al. [47] showed that in 4 of 10 social housing dwellings monitored, located in Bilbao, the indoor average temperature was lower than 16 °C during the coldest period in winter, and two of them presented an average temperature lower than 16 °C when the whole winter was analysed. The total energy consumption of these social dwellings is lower than expected.

Santamouris et al. [46] showed that, in Athens city and low-income dwellings, the absolute energy use for heating purposes in all groups analysed varied between 4 and 30 kWh/m^2, with an average close to 18 kWh/m^2, and the time of use of the heating systems varied between 0.75 and 3 h per day, even if the colder months call for much longer heating times. Magalhães and Leal [54] monitored the indoor temperature of some of the coldest cities in Portugal and showed that there is a pattern of heating only the occupied rooms, and with higher temperature values on living rooms and lower values in sleeping rooms. According to Alber [49], 20–55% of the low-income households in Southern and Eastern Europe live in housing with leaking windows. In addition, about 15–25% of the low-income population in Southern Europe and Ireland cannot afford the expenses for heating, while in Portugal this value rises up to 73%.

On the other hand, several authors [56][57] have shown significant differences between theoretical consumptions, calculated by the regulation methodologies, and the actual consumptions, obtained from surveys or real bills. These differences happen in both ways, being actual consumptions higher or lower, but mainly lower than predicted. These differences are not totally random. It showed a consistent pattern, related to that commonly referred to as “rebound effect”, which may be briefly described as the tendency to spend more energy on more efficient in dwelling and technical systems, and the opposite, i.e., as a less efficient dwelling, less energy to heat will be spent in it [56][58].

A Portuguese survey carried out in 2010 figures that space heating weighs only 21% of the total household consumption annual bill on average [50]. This weight rises to 67% in the European average [59]. It could be expected that, on the other hand, cooling could have a more significant impact on the Portuguese bill, at least compared with the other European countries. However, data collected from the same survey prove that this is only a wrong assumption, as cooling weight is negligible and represents only 0.5% of the total Portuguese average energy bill. The same happens in the majority of European countries, except for some specific Mediterranean areas, such as Malta, for instance, where cooling can reach near 10% of the total energy bill [59].

Concluding, in the vast majority of cases, heating patterns are not on a 24 h cycle and in 100% of the floor area, but rather intermittent and zonal, especially in the Mediterranean region.

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