Building energy demand assessment through heating degree days: The importance of a climatic dataset

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ABSTRACT

The weather is one of the main factors to consider when designing a building because it represents the most important boundary condition to affect the dynamic behaviour of the building. In the literature, many studies use the degree day to predict building energy demand. However, linking the results obtained from a generic building simulation tool with defined degree days, will not give reliable energy evaluation. The goal of this study is to demonstrate that the assessment of building energy demand through the use of the degree day is correct only if the determination of the climate index is a function of the same weather data. The relationship between Heating Degree-Day and heating energy performance was identified by determining some simple correlations, in order to obtain a preliminary evaluation of energy demands. The authors used Heating Degree Days based on three climate data-sets, developing different relationships and feedback. For the extraction of these correlations, numerous dynamic simulations on non-residential buildings characterized by high-energy performance were carried out. From the analysis of the results, it is clear that the relationships with higher correlation coefficients (higher than 0.9) are those that are a function of the degree calculated from the same climatic file used during the simulations. The proposed methodology, validated in this work for an Italian case study can be extended to any country and can be used to improve the reliability of any decision support tool based on climatic indexes.

Keywords:
Heating energy demand
Degree days
Building thermal balance
Weather data
Building simulation model
Empirical correlations

Nomenclature

a, b	coefficients of linear regression related to climate information
CDD	cooling degree days [K day]
DD	degree days [K day]
DD_m	monthly degree days [K day]
h	altitude [m]
H_d	heating energy demand [kWh/(m^2·year)]
HDD	heating degree days [K day]
N	number of locations used
N_g	number of days in a heating period
N_m	number of days in the month
R^2	correlation coefficient
S	losses surface [m^2]
S/V	shape factor [m^{-1}]
SI	solar irradiance [W/m^2]
T_i	average daily temperature [°C]
T_r	reference indoor thermal comfort temperature [20 °C]
T_s	second reference temperature [12 °C]
U_0	overall U-value [W/(m^2·K)]
U_{floor}	floor thermal transmittance [W/(m^2·K)]
U_{roof}	roof thermal transmittance [W/(m^2·K)]
U	thermal transmittance value [W/(m^2·K)]
U_{wall}	wall thermal transmittance [W/(m^2·K)]
U_{window}	window thermal transmittance [W/(m^2·K)]
V	heated volume [m^3]
α	correction coefficient [kWh/(m^2·year)]
θ_b	base temperature [°C]
θ_{max}	maximum daily temperature [°C]
θ_{min}	minimum daily temperature [°C]
θ_o	outdoor temperature [°C]
$\theta_{o,m}$	monthly mean temperature [°C]
θ_1	*HDD* correction coefficient [kWh/(K·m^2·year)]
θ_2	*S/V* correction coefficient [kWh/(m·year)]
σ_θ	standard deviation of the variation in temperature throughout the month

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1. Introduction

Global warming owing to the increased in the concentration of greenhouse gases in the atmosphere, caused by the ever-increasing use of fossil fuels to meet energy demands, has become an international concern. To enable detailed energy planning, it is necessary to understand the manner in which climate change affects the increase in atmospheric temperatures, therefore, making the historic 20-year averages unreliable. In the future, the temperature increase will determine the setting of new energy budgets [1]; indeed, climate change is reshaping the energy performance of buildings and cities [2,3]. The variation in the energy performance of buildings in terms of space heating and cooling in the future (until 2030) was investigated by [4]. Outdoor temperature variations directly affect water resources, power generation, agriculture, construction, and, in particular, energy consumption for the cooling and heating of buildings [5]. As several works [6,7] have outlined, building energy consumption is considerably affected by these temperature changes. For example, in [8], the impact of climate warming on the Swiss building energy demand was investigated by means of the Degree Days (*DD*) method. In [9], energy consumption for heating/cooling was analysed in different locations, demonstrating that *DD* affect the behaviour of building consumption against the standard degree. In [10], a new methodology was proposed for assessing energy demands for space heating in buildings on the city scale: a *DD* method was applied, coupled with the use of a dynamic urban meteorological model that computes a building energy budget day. In [11], it was demonstrated that the change in the urban climate affected the energy performance in the city of Rome, with a heating consumption reduction of up to 21% in residential buildings and 18% in office buildings, as well as an increase in cooling consumption of up to 74% in residential buildings and 53% in office buildings. In other studies, the authors assessed the impact of climate change on electricity consumption, which increases over time; in [12], it was determined that the electricity demand in Australia will increase by between 2.7% and 4.5% by 2050; in a review [13], the impact on cooling loads was found to be significant at approximately 13%. The European Union (EU) has always paid attention to environmental issues [14] and energy supply [15]. Since its formation, the EU has identified various measures [16,17] that, when implemented, will achieve important standards for energy saving, greenhouse gas emission reduction [18], and renewable energy production [19]. In 2013, the EU took another step forward by defining the "2030 Framework for Climate and Energy Policies" [20]. The 2030 Framework outlines the importance of continuing along the path towards energy saving and energy efficiency, which member states have already initiated. The proposed targets that each member state must achieve are reducing emissions by 40% compared to 1990 levels and promoting the production of at least 27% renewable energy in the EU.

In this context, the interventions necessary for achieving these energy targets affect the key economic sectors of individual member states, particularly industry, transportation and the civil sector. The estimation of heat demands/loads is a complex task. However, in the civil sector, it is important to assess the contribution of all activities taking place within buildings in terms of energy consumption.

Taking into account these considerations and previous studies, the importance of the quality of climatic data in accurately evaluating the energy needs of a building cannot be underestimated. The climatic parameters represent important boundary conditions for building design, affecting the transient behaviour of the building envelope during its useful life [21]. Among these parameters, the *DD* could be used to quantify energy demands.

In general, the *DD* value is considered as an index of the energy consumption of buildings, and represents an old but simple method used in Heating, Ventilating and Air-Conditioning (HVAC) industries to estimate the heating and/or cooling energy requirements [22]. Essentially, *DD* provides the summation of temperature differences over time, calculated between a fixed indoor reference temperature and the outdoor air temperature, whenever the latter is less/more (for heating/cooling requirements, respectively) than the former. The reference temperature for buildings is a known variable (base temperature), and corresponds to the outdoor temperature at which the heating/cooling systems do not need to run to maintain indoor comfort conditions.

In addition to the base temperature, the external temperature value is very important; not taking the variation of this value into account in the *DD* calculation makes it unreliable for use in the assessment of the building energy demand. For example, in London and Edinburgh from 1976 to 1995, the *DD* value decreased by approximately 10% [23]. It is conceivable that Heating Degree Days (*HDD*) may drop by 30% to 40% in the UK by the 2080s, owing to a constant increment in the outdoor temperature. In this context, it will be important to evaluate the impact of climate change on the estimation of *DD* and building energy demands. More recent works have been carried out for different countries: Romania [24], Turkey [25,26], Australia [27], Greece [28], China [29,30], Spain [31], Switzerland [8], Saudi Arabia [5,32], Morocco [33], and France [10]. Although the general direction of the temperature effect on energy use is similar for most studies, the relative change in the energy demand differs significantly according to the location, time period, and methodology used [34]. It is widely recognised that the correct estimation and prediction of the building energy demand represents a crucial point to perform scenario analyses, which may determine the best energy policy for compliance with standards for new and existing buildings set by the EU [35] and other countries.

It must be emphasised that, if the *DD* index is not correctly calculated, determining the building energy performance as a function of *DD* may lead to imprecise evaluations. To link the building energy performance with the correct *DD* value, it is necessary to calculate *DD* based on the same Typical Meteorological Year (*TMY*) used for the building energy evaluation. Because the building energy requirements are strictly dependent on the external climate, the authors believed that it could be more convenient to provide a correlation that allows for the evaluation of the energy demand with a high level of accuracy and without excessive computational costs or user expertise, while knowing only the dependence of the *DD* values. However, the close correlation between *DD* and the building energy requirement is valid only if the building energy assessment has been conducted using the same updated database that led to the *DD* determination.

Each city is characterised by a certain *DD* value, which is calculated based on individual laws and standards and on a specific climate dataset. For this reason, during analysis of the energy performance of a building, it is incorrect to link the results obtained from a generic building simulation tool with a defined *DD* value indicated in a law or standard. The correlation between the heating energy demand of a building (H_d) and a *DD* value calculated using different standards or a specific climate file will produce different relationships and feedback. To demonstrate this, the authors developed several simple correlations to evaluate the heating energy demand knowing only the *DD* value. This was achieved by taking three climate datasets for the same location and using them to calculate different *DD* values to represent three varying scenarios. For the extraction of these correlations, numerous dynamic simulations (13 models simulated in five climatic zones, represented by 3 different cities) were carried out on non-residential buildings characterised by high-energy performance. Owing to an in-depth analysis of the results, it was possible to identify a specific correlation for each case, in which the heating energy demand was a function of the *DD*, and its validity was evaluated using the respective correlation coefficient (R^2). Furthermore, a comparison of the relationships obtained from three different weather datasets underlines the fact the building energy demand assessment is dependent on the *DD* only if the climatic index is a function of the same weather data used during the simulations. This is demonstrated by the higher R^2 coefficients.

The proposed methodology, which is validated in this work for an Italian case study, can be extended to any country and/or climatic region, and can be used to improve the reliability of any energy building decision support tool based on the use of climatic indexes.

2. Degree days: definitions

Generally, *DD*s for a location are defined as the sum of only the positive differences between the base temperature and the daily average outdoor temperature, extended to all days of a conventional twelve-month period. In the case of *HDD*, the differences between outdoor and base temperature are computed only when the outdoor temperature falls below the base temperature during the heating period. Conversely, in the case of *CDD*, the differences are calculated only when the outdoor temperature exceeds the base temperature during the cooling period.

In the literature, it is possible to find several ways of calculating the *DD* [1,31]:

- Mean Degree-Hours (MDH): calculated from the hourly temperature records (the Italian calculation method);
- daily maximum and minimum temperatures: e.g. the UK Meteorological Office equations which use mean daily temperature;
- direct calculation of monthly *DD* from mean monthly temperature and the monthly standard deviation; e.g. Hitchin's formula.

The MDH is the most rigorous and most mathematically precise method of calculating *DD*, and is defined as the ratio of the sum of hourly temperature differences to 24. In this version, only positive differences are summed; in the case of *HDD*, when the outdoor temperature exceeds the base temperature, the value of *DD* is null. Eq. (1) shows the general formula for *HDD*:

$$if\ (\theta_b - \theta_{o,j}) > 0 \quad \rightarrow \quad DD = \frac{\sum_{j=1}^{24} (\theta_b - \theta_{o,j})}{24} \tag{1}$$

where

DD is the daily degree-days for one day;
θ_b is the base temperature;
$\theta_{o,j}$ is the outdoor temperature in the *j*th hour.

The UK Meteorological Office Equations are sometime referred to as the "McVicker" or the "British Gas" formulas. Since 1928, this definition has been the standard method for calculating *DD* in the UK as an approximation of the integral:

$$DD = \int (dd)dt = \int (\theta_b - \theta_o)dt \tag{2}$$

for daily *DD* using daily maximum and minimum outdoor temperatures. The formulas were developed to be computed with a simple manual calculation using only a single (maximum and minimum) value for each day. Different formulations for different cases are shown in Table 1:

The mean daily temperature method is used in the USA, as defined by ASHRAE [36], and in Germany [37], where *DD* is calculated from:

$$\begin{aligned} &if\ \theta_{\max} < \theta_b \quad \rightarrow \quad dd = \theta_b - (\theta_{\max} + \theta_{\min})/2 \\ &if\ \theta_{\min} \geqslant \theta_b \quad \rightarrow \quad dd = (\theta_{\max} + \theta_{\min})/2 - \theta_b \end{aligned} \tag{3}$$

The adoption of mean daily temperature permits a simple definition and calculation of *DD*. As a consequence, this definition applies the reasonable assumption that heating systems do not operate on days when the average outdoor temperatures exceed the base one.

Furthermore, there have been a number of attempts to calculate degree-days from reduced weather data; for example, Thom [38,39] and Erbs [40] in the USA, based their work on the statistical analysis of truncated temperature distributions. Usually, these attempts are based on monthly mean temperature and on monthly standard deviation. Hitchin [41] proposed a relatively simple formula for *HDD* that has shown a good correlation with the UK climate.

Hitchin's formula states:

$$DD_m = \frac{N_m(\theta_b - \bar{\theta}_{o,m})}{1 - e^{-k(\theta_b - \bar{\theta}_{o,m})}} \tag{4}$$

Table 1
UK Meteorological Office equations for calculating daily heating degree-days.

Case	Condition	Daily heating degree-day
1	$\theta_{\max} < \theta_b$	$dd = \theta_b - (\theta_{\max} + \theta_{\min})/2$
2	$\theta_{\min} < \theta_b\ and\ (\theta_{\max} - \theta_b) < (\theta_b - \theta_{\min})$	$dd = (\theta_b - \theta_{\min})/2 - (\theta_{\max} - \theta_b)/4$
3	$\theta_{\max} > \theta_b;\ and\ (\theta_{\max} - \theta_b) > (\theta_b - \theta_{\min})$	$dd = (\theta_b - \theta_{\min})/4$
4	$\theta_{\min} \geqslant \theta_b$	$dd = 0$

where DD_m is the monthly degree-day value, N_m is the number of days in the month, $\bar{\theta}_{o,m}$ is the mean monthly temperature, k is a location specific constant given by$2.5/\sigma_{\theta}$, here $\sigma_{\theta}$is the standard deviation of the variation in temperature throughout the month.

Furthermore, ASHRAE recommends the method in [40] to estimate monthly degree-days. There are also reports of individual energy managers adopting their own techniques based on the kind of weather data that is available to them [23]. However, it should be noted that Eq. (1) should always be the preferred option if suitable hourly data and adequate data processing tools are available.

3. Method

As stated previously, the aim of this paper, which propose a simple new method for determining the energy demand of a building using only *DD,* is to highlight that a strong correlation between the building energy performance and *DD* is well founded if the same weather dataset is used. Following definitions and descriptions of the well-known methods for determining the *DD* (Section 2), considering the purpose of this paper and based on the particular situation of the Italian building energy-efficiency laws and standards currently in force, the authors describe an Italian case study, representing a methodology that can also be extended to other contexts (Section 4.1).

First, the energy performance of a non-residential building characterised by high-energy performance was evaluated. The energy demand regularity of non-residential buildings makes the energy assessment predictable. Indeed, studying the factors affecting the energy performance of office buildings and the energy characteristics of building constructions is essential for an improved understanding of energy policies, design principles, and operational strategies [42].

Thanks to the data obtained from the TRNSYS dynamic simulations [43], several correlations were constructed that are valid for buildings designed according to the energy requirements standards and laws in Italy. A total of 13 building models were simulated in five different climatic zones [44]. To represent the entire climate condition accurately, three cities from each climatic zone were considered, representing harsh, mild, and warm climates, respectively (Sections 4.2 and 4.3).

An in-depth analysis of the Italian procedure for determining the energy performance of a building indicated that, owing to the obsolescence of the old Italian technical standards UNI 10349: 1994 [45] and DPR 412/93 [44] based on climatic data prior to 1994, and in the absence of the Cooling Degree Day (*CDD*) values, the new version of the standard, UNI 10349, published in 2016 [46], should be used. The standard UNI 10349-1: 2016 contains monthly average data calculated from test reference years, developed by the Italian Thermo-technical Committee for 110 Italian locations, and recalculates the *HDD* and *CDD* values. However, at present, UNI 10349: 2016 calculates the *HDD* and *CDD* values without changing the previously stated heating or cooling periods for all Italian cities, and without making any distinction between the climate zones. For this reason, the current evaluation of the energy performance of Italian buildings is based on the old *HDD* and does not consider the *CDD*. Therefore, in this work, only the heating load was analysed.

To evaluate the correct correlation between the thermal energy requirement obtained from the validated simulation and *DD*, the following questions must be asked: is it advisable to use the *HDD* value from the old standard, or is it preferable to use that of the new standard? Furthermore, if a specific climate file has been used in a dynamic simulation that does not refer to either of the two standards, are the correlations between the *HDD* values, dictated by law, and the energy requirements, obtained from a generic simulation, correct?

To answer these questions, in this work, the simulation data were used to explore whether a direct correlation of a generic *HDD* with the simulated H_d, value, obtained from a generic software tool, could lead to unrealistic consumption estimates. To demonstrate this, the authors extrapolated several simple correlations between H_d and *HDD*, and then evaluated the reliability of these correlations for three different scenarios:

- the *HDD* relating to the old Italian standard [44–46] (Section 5.1);
- the *HDD* calculated based on the TMY (Section 5.2); and
- the *HDD* relating to the new Italian standard (Section 5.3).

Moreover, other correlations were developed by generalising the results, and considering the variability of the building energy performance within the climatic context and its shape. These new relationships enable the simplification of the evaluation of energy performance (Section 5.4) in any initial energy planning phase.

The obtained results underline the importance of the selection of weather data in evaluating the heating energy demand of a building. Furthermore, the high degree of correlation of each issued relationship clearly proves that *HDD* is a suitable index for assessing the building energy performance if it is truly representative of the climatic boundary conditions (Section 5.5).

The flow chart in Fig. 3 describes the proposed methodology for the evaluation of the heating energy demand of a building in detail, illustrating the procedure, scenario, and results.

4. Case study

In this section, following a generic indication of the Italian climate and identification of the Italian *HDDs*, a detailed case study on a non-residential building located in the Italian peninsula is described. As indicated previously, to generalise the results and represent the weather of the entire peninsula 13 different building models located in 15different Italian cities were constructed.

4.1. Italian climate context

The Italian region is between the 47th and 36th parallel north, located almost in the centre of the Northern Hemisphere temperate zone of the. From a general perspective, the Mediterranean Sea influences the Italian climate (Fig. 1).

The climate varies considerably from the north to the south of Italy. In the north, the climate is harsh, with very cold winters and very hot, humid summers. In Central Italy, the climate is milder with a shorter and less intense cold season than in the north but with long summer. In Southern Italy and the islands, winters are mild, while spring and autumn are characterised by temperatures that are reached only in summer in other regions of Italy [48]. In general, the summer can be quite hot in Italy, mainly in the south of the peninsula, with high nocturnal temperatures of 28 to 33 °C, and sometimes even 40 °C.

4.2. Definition of the Italian DD

In the evaluation of building energy requirements, in relation to meteorological conditions, the determination of DD is fundamental. Attention to energy saving and the subsequent release of the first relevant standards happened in 1974 after the first energy crisis.

Italy faced this problem by amending a law [49] and then updating art. 37 of the law [50], which for the first time stated the principle of modern energy saving concepts in terms of plant design and thermal insulation of buildings. This was the first time, the Italian *DDs* were tabulated in a decree [51]. For a given location and, a fixed reference indoor thermal comfort temperature T_r, the *DD* index is calculated according to:

$$DD = \sum_{i} (T_r - T_i) \tag{5}$$

where the sum is extended to all i days of the year in which the average external daily temperature T_i is lower than a second reference

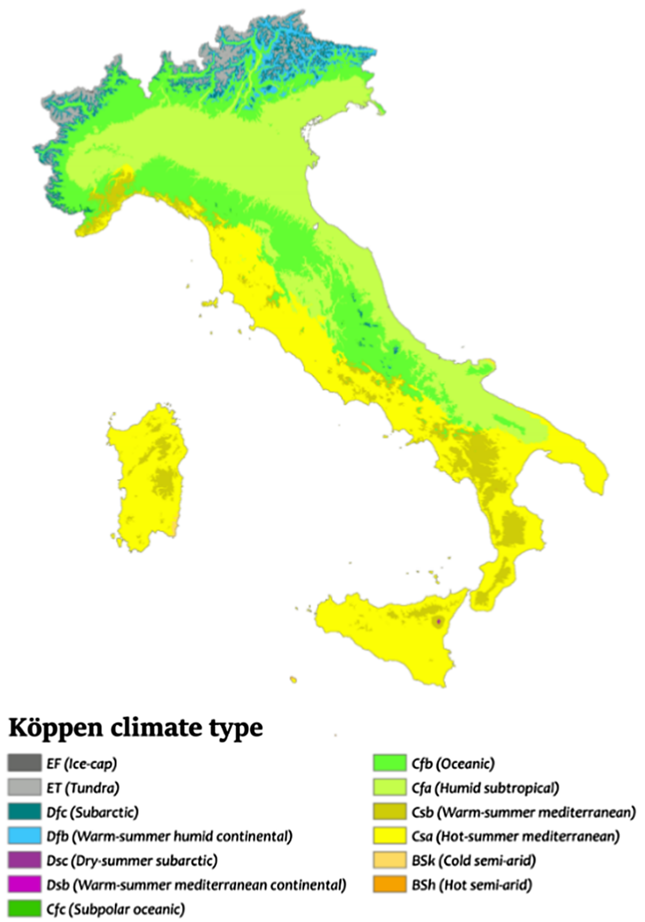


Fig. 1. Koppen climate map of Italy [47].

temperature T_s, conventionally fixed.

In order to calculate *DD*, for all Italian cities, it was necessary to have a reliable daily temperature measurement for a sufficiently long period (at least 7–10 years). This information was known only for some cities, and in [51] *DD* values have been established only for 103 locations where there were Italian Military Air Force weather stations. Then, employing a calculation method dictated by [51], it was possible to extend the calculation of *DD* to all areas of the Italian territory. In particular, the cities that do not fall in the list of 103 locations had a *DD* based on the following formula:

$$\Delta DD = \Delta h\frac{N_g}{100} \quad when \quad \Delta h > 100 \ m \tag{6}$$

where N_g is the number of days in the heating period of the reference location and Δh is the difference between the altitude of two compared cities.

The application of this procedure led to a qualitative estimation of *DD* which affects its own reliability. In fact, this procedure presents some problems such as:

- the limited number of weather stations (103 locations or only about 1.3% of Italian municipalities);
- the reference temperature $T_s = 12\,^\circ\mathrm{C}$ chosen based on the technical design of the buildings and climate of a northern country (Germany), which are not representative of Italian climatic conditions;
- Eq. (6) which can be extended to the calculation of *DD* in all municipalities, but it is not always automatically applicable to all Italian regions.

The comparison of the *DD* value calculated employing 1970s data with the *DD* calculated with this procedure, led to deviations higher than 150%. In the 1980s, different methods of calculation were studied and analysed and a new procedure, currently in force, was adopted. In this case, reference data are based on a time series of 872 locations (10% of Italian municipalities).

It should be stressed that the calculation of *DD* must concern a fixed period of heating (or cooling). In the locations where there were weather stations, the *DD* was calculated using Eq. (5) in which the temperature T_r is equal to 20 °C. To define the heating period, it was assumed that it starts after 3 consecutive days of temperature $T_i < T_s = 12\,^\circ\mathrm{C}$ and ends when for 3 consecutive days the temperature $T_i > T_s = 12\,^\circ\mathrm{C}$; the time extension of the heating period has a minimum of 90 days (from December 1st to February 28th). For other locations, a linear regression procedure was adopted:

$$DD(h) = a + b\cdot h \tag{7}$$

where *h* is the altitude of the locations, *a* and *b* are the coefficients of linear regression related to climate information of the territory by the following formulae:

$$\begin{cases} a = \dfrac{(\sum_i DD_i\cdot\sum_i h_i^2 - \sum_i DD_i\cdot\sum_i h_i)}{\Delta} \\ b = \dfrac{(N\sum_i h_i\cdot DD_i - \sum_i h_i\cdot DD_i)}{\Delta} \\ \Delta = N\sum_i h_i^2 - (\sum_i h_i) \end{cases} \tag{8}$$

where

N = number of used locations;
h_i = altitude of the *i*th location;
DD_i = Degrees Day of the *i*th location.

The procedure described above has therefore led to the determination of *DD* for the Italian national territory [45,46]. In the last Italian standard, the *HDD* and *CDD* were calculated for all regional capital cities and for a heating period that can extend from 15th October to 14th April, and a cooling period that can extend from 15th April to 14th October. As this standard was recently issued, the Italian law decrees) have currently not been updated [52–55]. For this reason, this study takes into consideration only the data issued by the actual standard and the actual law decree.

According to the Italian national guidelines for building energy certification [56], the peninsula is characterized by different climatic zones, which theoretically have the same climate [52]. As indicated in Table 2, employing *HDD*, it is possible to identify six different climatic zones, where zone A represents the hottest and zone F represents the coolest. For each zone, the daily hours of heating system activity and the consequent yearly period has been published. Furthermore, based on this climatic zone classification, the current Italian law imposes transmittance limit vales for the design of high-performance buildings.

Table 2
Features of Italian Climatic Zones.

Climatic Zone	From *HDD*	To *HDD*	During of heating season		Daily hours
			From	To	
A	0	600	1st December	15th March	6
B	601	900	1st December	31st March	8
C	901	1400	15th November	31st March	10
D	1401	2100	1st November	15th April	12
E	2101	3000	15th October	15th April	14
F	3001	∞	No limit		

4.3. Building model

As the correct evaluation of *HDD* values influences the building heating demand, in the following, the authors describe the manner in which the results obtained by applying any numerical solution to the building thermal balance are strongly influenced by the *HDD* value, and hence, by the climatic database used. To this end, a detailed building thermal balance assessment was carried out by developing dynamic models in the TRNSYS environment [43]. A non-residential base model was designed, with high-energy performance, according to the national standard requirements. To generalise the results, the “ideal building” was varied with different shape factors ($0.24 < S/V < 0.9$) and heated volumes, thereby creating 13 different building models. Each model was simulated in different climate zones and characterised by specific internal gains [57]. Furthermore, three cities were selected for each zone, to take into account the maximum, minimum, and mean *HDD* values [58]. Table 3 presents the *HDD* values for the 15 selected locations according to actual Italian law [52].

Climatic zone A was not simulated, because it is not representative. In Italy, only two cities belong to this zone, with very similar *HDD* values: Lampedusa ($HDD = 568$) and Porto Empedocle ($HDD = 579$). Regarding the geometrical configurations, the shape factor influences the solar energy received by each location, as well as its total energy consumption [59]; indeed, the radiation hitting a building can increase the cooling energy requirements by up to 25% [60]. Moreover, the shape factor determines not only the total area of the facade and roof receiving solar radiation, but also the surface exposed to the outside, and thus, to energy losses [61]. The following building configurations were investigated, characterised by the geometrical dimensions listed in Table 4.

The building orientation is a very important parameter, which influences the passive solar design of buildings. Indeed, the intensity of the beam solar radiation received on the building facade is dependent on the wall azimuth and building orientation [62]. For these reasons, each model for each location was simulated eight times, with the building orientation varied by 45° each time, and all of the obtained results were averaged. In this manner, the mean energy performance of a building was evaluated as a function of the incident solar radiation calculated by averaging the eight simulation results.

For each model, the authors defined the stratigraphy of the walls, roofs, and floors, by ensuring that the transmittance values (*U-values*) conformed to the standard national limits (Table 5) [57]. In general, the external walls are characterised by a limestone block and a layer of polystyrene with plaster on the inner and outer surfaces; the floor has a concrete slab, a cement screed, and one polystyrene layer; and the roof consists of a cement slab, a cementitious screed, and a layer of polystyrene with a bituminous layer and an outer covering, which guarantees the structure permeability.

To develop the dynamic models in TRNSYS, the authors used TMY –second edition (TMY2) generated by the Meteonorm software [63]. All TMY2 files were calculated considering actual monitored data recorded from 2000 to 2009.

Table 4
Geometric characteristics of the investigated building models [57].

Case study	S/V [m^{-1}]	Width [m]	Depth [m]	Height [m]	Loss surface [m^2]	Heating surface [m^2]	Heated volume [m^3]
1	0.24	45	39	13.5	5797	7050	23,793
2	0.50	106	50	4.5	11,987	5293	23,793
3	0.90	118	8	3.16	2673	940	2970
4	0.35	15	30	13.5	2115	1800	6075
5	0.62	25	20	4.5	1405	500	2248
6	0.76	40	25	3.16	2411	1000	3160
7	0.4	25	15	10.5	1590	1125	3938
8	0.32	40	40	9	4640	3200	14,400
9	0.27	60	22	13.5	4854	5280	17,820
10	0.69	90	20	3.5	4370	1800	6300
11	0.70	45	60	3.2	6072	2700	8640
12	0.58	50	50	4	5800	2500	10,000
13	0.56	100	50	4	11,200	5000	20,000

As indicated in a previous study [57], the “ideal building” was built based on the European standard on energy consumption, EN ISO 13790: 2008 [64], implementing detailed information concerning:

- the thermophysical characteristics of the building envelope;
- solar gains;
- internal gains (users, equipment and lighting system); and
- a defined operating time of the heating system (eight hours per day for five days per week).

As demonstrated in previous works [57,58], the “ideal building” model was calibrated based on empirical data reported in the scientific literature. For example, Table 6 describes the weekly schedules regarding the utilisation of equipment, lighting system, and presence of office users.

Each daily schedule is described in Fig. 2; based on the time period, the load fractions used and number of users are reported.

In this model, the total floor surface has three different uses: offices (14%), meeting rooms (56%), and other uses (30%). The authors estimated that there are approximately 0.07 people per square metre of office space and 0.5 people per square metre of meeting room space [65,66]. Furthermore, the infiltration losses were determined according to Appendix C of [64]. Concerning the typical office equipment, a heat gain of 230 W per piece of equipment, with one piece for each office worker and one piece per 50 meeting people, was estimated; the presence of office workers with sedentary activity was also estimated (1 met).

5. Results and discussion

To evaluate the building energy performance in the same city, correlating the energy demand with the climate context, it is necessary to have knowledge of the weather data and the correct *HDD*.

The annual heating demand obtained from the dynamic models was used to validate the simple correlations that determine the H_d value, knowing only the *HDD* value or, more generally, knowing the contemporary *HDD* and *S/V*.

As explained in Fig. 3, simple correlations were developed using

Table 3
Selected Italian cities and DPR 412/94 *HDD* values.

Italian climatic zones									
B		C		D		E		F	
Location	*HDD*	Location	*HDD*	Location	*HDD*	Location	*HDD*	Location	*HDD*
Messina	707	Cagliari	990	Genova	1435	Trieste	2102	Cuneo	3012
Palermo	751	Bari	1185	Firenze	1821	Torino	2617	Cortina	4433
Crotone	899	Termoli	1350	Forlì	2087	Bolzano	2791	Sestriere	5165

Table 5

Limit and model thermal transmittance values used in TRNSYS models.

Climatic zone	A–B		C		D		E		F	
U value	limit	model	limit	model	Limit	model	limit	model	Limit	model
	[W/(m²·K)]									
U_{wall}	0.45	0.444	0.38	0.379	0.34	0.336	0.30	0.297	0.28	0.276
U_{roof}	0.38	0.377	0.36	0.353	0.30	0.303	0.25	0.249	0.23	0.234
U_{floor}	0.46	0.445	0.40	0.385	0.32	0.307	0.30	0.287	0.28	0.268
U_{window}	3.2	2.76	2.40	2.26	2.00	1.76	1.80	1.76	1.50	1.40

Table 6

Weekly schedules of equipment, lighting systems and attendance of office users.

Week day	Equipment Schedule	Lighting system Schedule	Users Schedule
Monday	equip. work day	lighting work day	people work day 1
Tuesday	equip. work day	lighting work day	people work day 2
Wednesday	equip. work day	lighting work day	people work day 1
Thursday	equip. work day	lighting work day	people work day 2
Friday	equip. work day	lighting work day	people work day 1
Saturday	equip. weekend	weekend	weekend
Sunday	equip. weekend	weekend	weekend

different weather data, and the results were compared to the simulated data, indicating the respective R^2 values.

Evidently, the three climate databases, determine three different types of *HDD* values for the same city, so the correlation degree will also vary. Specifically, in this work, the authors considered:

- *HDD* from 412/93 and UNI 10349:1994 (Section 5.1);
- *HDD* from TMY (Section 5.2); and
- *HDD* from UNI 10349: 2016 (Section 5.3).

The results, indicated by the high R^2 values underline the fact that correct evaluation of the building energy performance could be obtained with knowledge of only one or two well-known parameters, such as *HDD* and/or *S/V,* if the climate file used to determine the *HDD* is the same as that used for the energy evaluation.

5.1. Heating demand and HDD from 412/93 DPR

Based on the current Italian law and UNI TS 11300-1, 2 [53,54], the cities simulated in the case study are characterised by the *HDD* and climatic zone indicated in Table 3; furthermore, the results obtained from the dynamic simulations for each model, are presented in Table 7.

For each zone in the graphs from Figs. 4–8, the H_d versus *HDD* of the 13 models are plotted.

In general, for the same boundary conditions, it is expected that increasing the *HDD* value will increase the thermal energy requirements in each case study. Analysing the data trend for each climatic zone, except for climatic zones C and D, where it is possible to observe a regular growing trend, the thermal behaviour differs in other climatic zones:

- in climatic zone B, the models are characterised by a lower H_d for the average *HDD*;
- in climatic zone E, the models are characterised by a higher H_d for the average *HDD*; and
- in climatic zone F, certain models are characterised by a lower H_d for the average *HDD*.

The authors hypothesised a linear relationship between H_d and *HDD* as follows:

$$H_d = \alpha \cdot HDD + \beta \tag{9}$$

where α is a constant vale and β is a correction coefficient expressed in [kWh/m² year].

In Fig. 9, it is possible to observe the respective correlation coefficients R^2 of several case studies of climatic zones B and D; all results for all relationships in each zone are collected in Appendix A.

These results emphasise that it is important to establish a climatic index that is representative of the actual weather conditions considered in the simulation tool. Indeed, in this case, the climatic data implemented in the simulation tool differ with respect to the TMY used to determine the *HDD,* so the relationships between the heating demand obtained by the simulation tool and the *HDD* values dictated by the

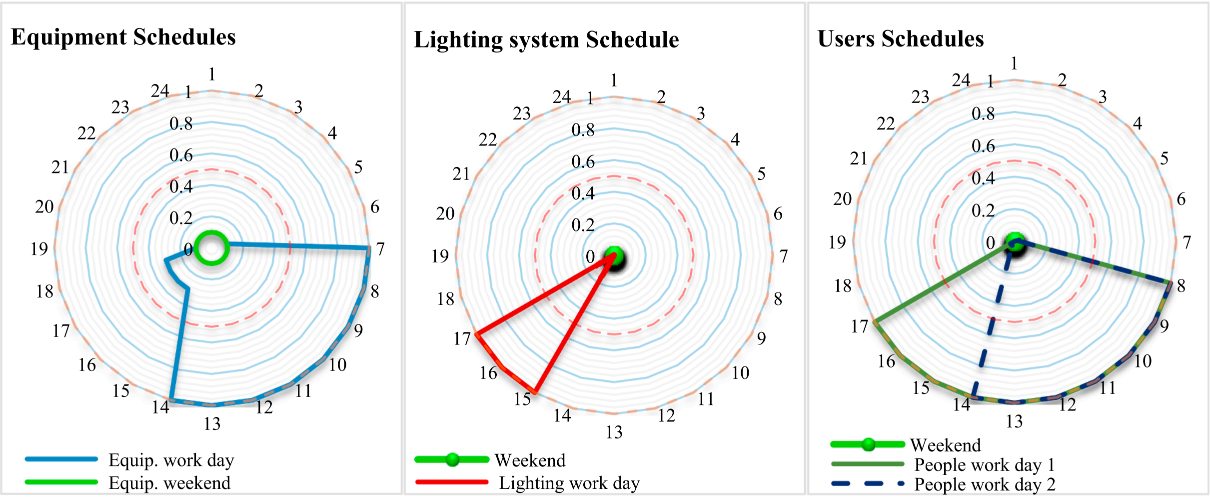


Fig. 2. Daily schedules: fraction of load used and of the number of people.

Table 7
Thermal heating energy demand in each location and for different *S*/*V*.

Climatic Zone	Location	*HDD* DPR 412/93	H_d models [kWh/(m^2·year)]												
			1	2	3	4	5	6	7	8	9	10	11	12	13
B	Messina	**707**	1.60	11.66	10.83	3.49	12.43	8.80	4.68	6.06	1.75	9.92	10.06	10.11	9.90
	Palermo	**751**	1.42	11.04	9.78	2.98	11.37	8.13	4.01	5.35	1.53	9.18	9.47	9.51	9.37
	Crotone	**899**	4.16	16.27	15.73	7.00	18.02	12.74	8.57	10.35	4.30	14.27	14.24	14.39	13.98
C	Cagliari	**990**	0.70	11.16	6.95	1.36	8.93	6.99	2.01	4.00	0.69	7.82	8.90	9.10	9.48
	Bari	**1185**	1.97	15.35	10.54	3.05	13.33	10.12	4.03	7.14	1.85	11.44	12.57	12.88	13.17
	Termoli	**1350**	4.35	18.93	15.83	6.48	19.01	13.78	8.01	11.15	4.28	15.49	15.93	16.44	16.34
D	Genova	**1435**	2.42	14.76	11.14	4.01	14.23	9.62	5.12	7.67	2.35	11.11	11.34	12.35	12.36
	Firenze	**1821**	2.90	17.06	12.48	4.33	16.19	11.20	5.56	9.03	2.71	12.89	13.30	14.39	14.44
	Forlì	**2087**	7.48	24.02	22.29	11.07	26.88	17.88	13.29	16.52	7.54	20.31	19.38	21.14	20.60
E	Trieste	**2102**	4.10	17.71	14.52	6.30	18.42	11.94	7.74	10.64	4.09	13.85	13.48	15.07	14.85
	Torino	**2617**	8.52	25.74	22.05	11.84	27.53	18.38	13.79	17.70	8.47	20.90	20.20	22.41	21.98
	Bolzano	**2791**	8.53	25.71	20.86	11.35	26.39	18.15	13.07	17.53	8.30	20.48	20.33	22.32	22.08
F	Cuneo	**3012**	3.64	19.21	11.20	4.31	15.92	11.19	5.26	10.19	3.11	13.10	14.02	15.61	16.10
	Cortina	**4433**	16.43	43.24	32.43	19.55	41.52	29.19	22.10	30.28	15.76	33.32	33.28	36.92	37.11
	Sestriere	**5165**	16.97	50.37	29.42	16.96	40.18	30.61	19.01	31.90	15.13	35.06	37.92	41.56	43.40

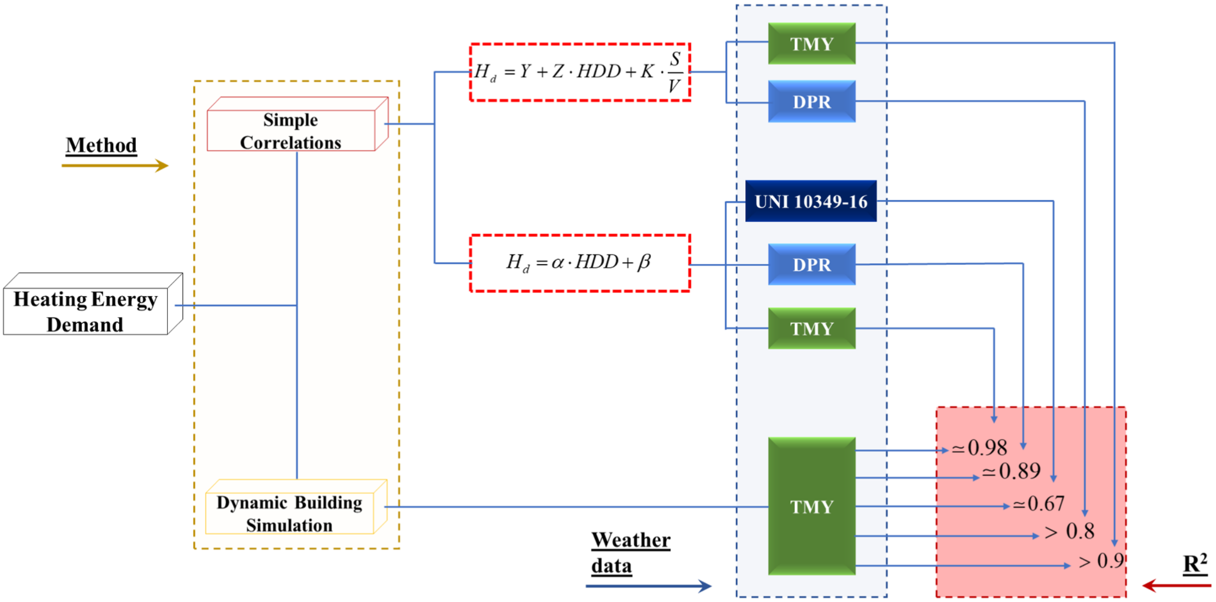


Fig. 3. Flow chart on the determination of heating energy demand.

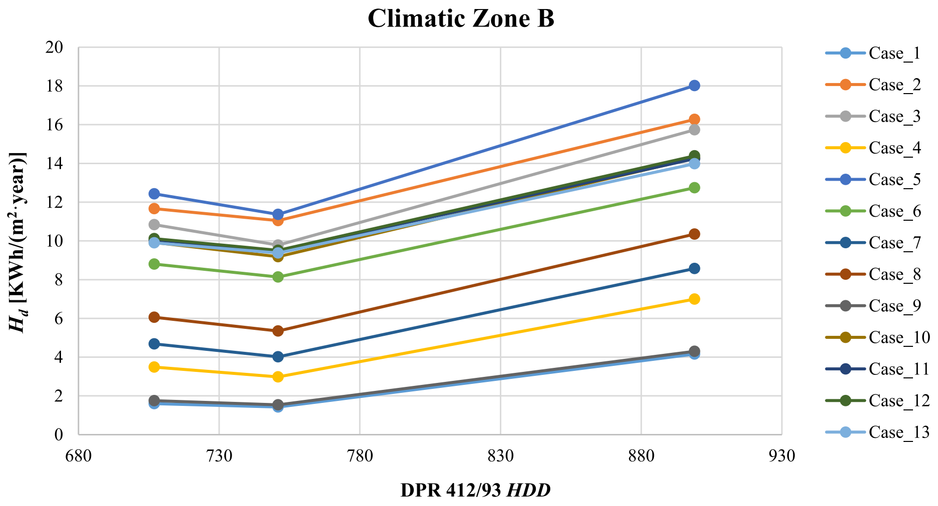


Fig. 4. Heating demand versus 412/93 DPR *HDD* of climatic zone B.

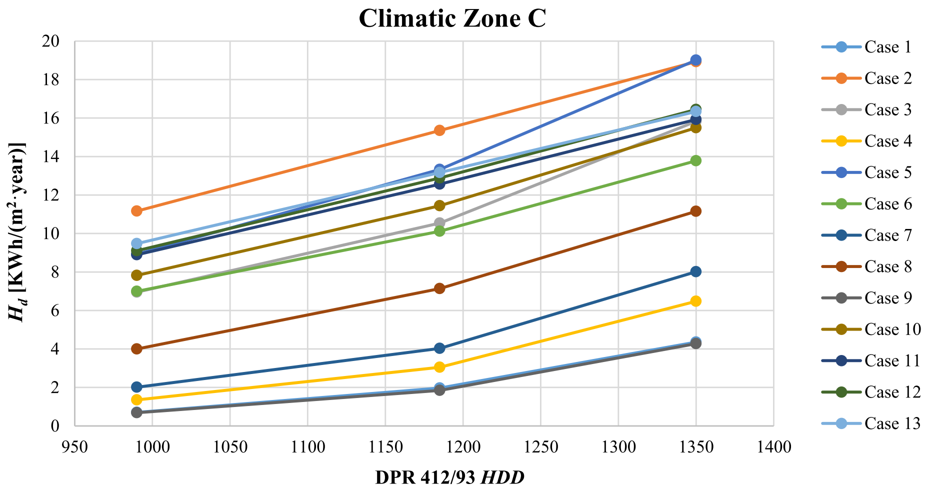


Fig. 5. Heating demand versus 412/93 DPR *HDD* of climatic zone C.

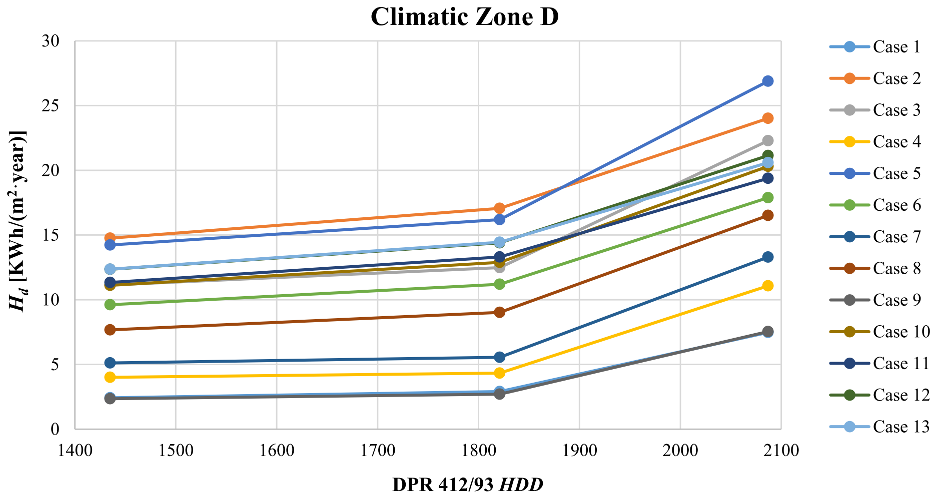


Fig. 6. Heating demand versus 412/93 DPR *HDD* of climatic zone D.

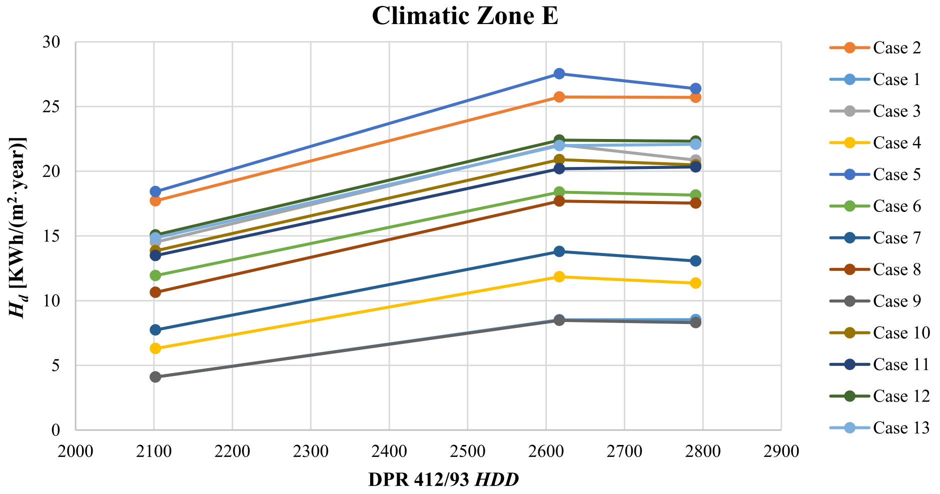


Fig. 7. Heating demand versus 412/93 DPR *HDD* of climatic zone E.

actual Italian laws are not really linked. For these reasons, to correlate the H_d simulated data with the respective climatic context accurately, the authors recalculated the *HDD* values, considering the TMY used in the building simulation tools.

5.2. Heating demand and HDD from TMY

TMY2 was used to develop the dynamic models in TRNSYS, considering actual monitored data recorded from 2000 to 2009. By applying the same procedure as in Section 4.2 (MDH), the *TMY-HDD*

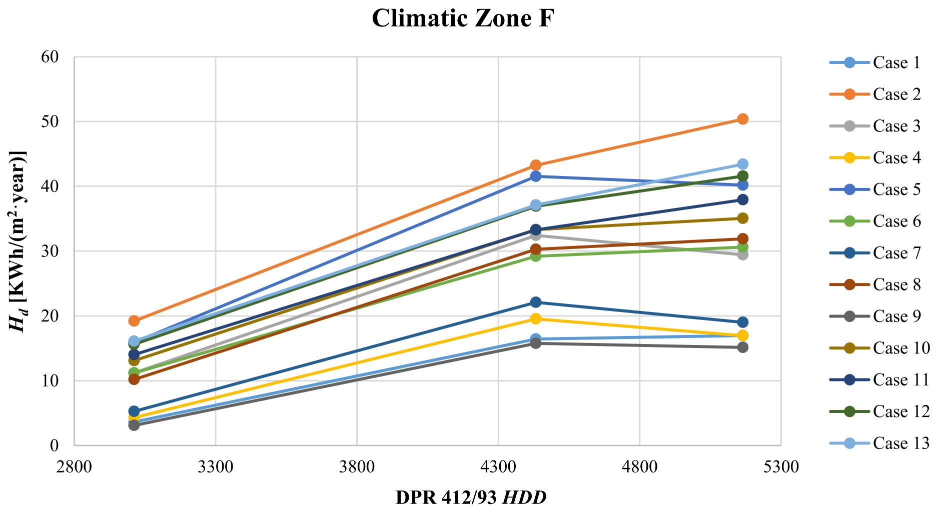


Fig. 8. Heating demand versus 412/93 DPR *HDD* of climatic zone F.

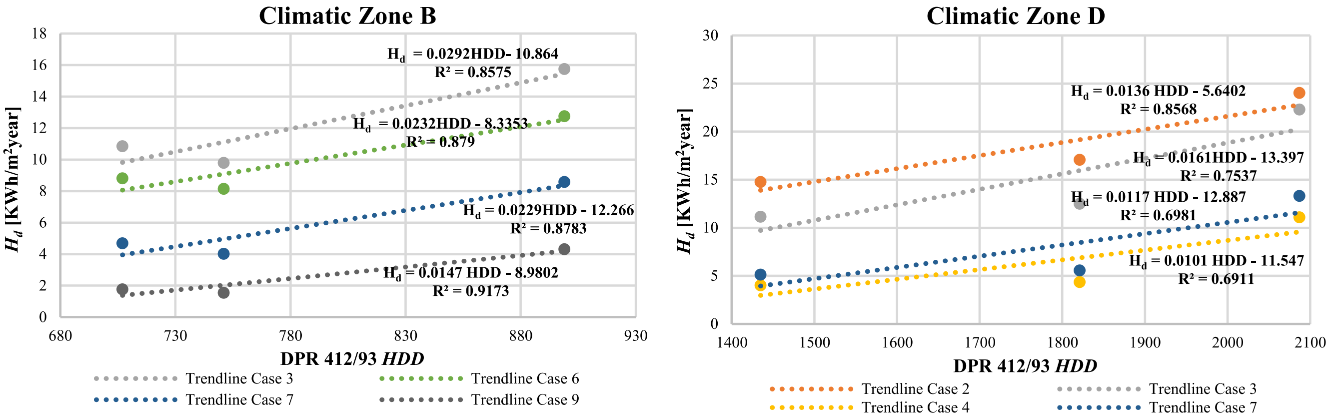


Fig. 9. Trend line examples of H_d function of 412/93 DPR *HDD* in climatic zone B and D.

Table 8
Selected Italian cities and *TMY-HDD* values.

Italian Climatic Zones									
B		C		D		E		F	
Location	*TMY-HDD*	Location	*TMY-HDD*	Location	*TMY-HDD*	Location	*TMY-HDD*	Location	*TMY-HDD*
Messina	673	Cagliari	1024	Genova	1417	**Trieste**	**1760**	**Cuneo**	**2213**
Palermo	656	**Bari**	**764**	Firenze	1598	Torino	2386	Cortina	4473
Crotone	**1012**	Termoli	1370	Forlì	1953	Bolzano	2384	Setriere	6804

Table 9
Selected Italian cities and *TMY-HDD* values.

Italian Climatic Zones									
B		C		D		E		F	
Location	*TMY-HDD*	Location	*TMY-HDD*	Location	*TMY-HDD*	Location	*TMY-HDD*	Location	*TMY-HDD*
Messina	673	**Crotone**	**1012**	Genova	1417	**Cuneo**	**2213**	Cortina	4473
Palermo	656	Cagliari	1024	Firenze	1598	Torino	2386	**Stelvio**	**6339**
Bari	**764**	Termoli	1370	Forlì	1953	Bolzano	2384	Setriere	6804

values for each location were calculated (Table 8):

Based on the distribution of the climatic zones presented in Table 1, it is possible to observe that, using the new updated weather data:

- Crotone, originally belonging to climatic zone B, now falls back to climatic zone C;
- Bari, originally belonging to climatic zone C, now falls back to climatic zone B;

Table 10
Thermal heating energy demand in some cities and for different S/V [kWh/(m^2 year)].

Climatic Zone	Location	TMY-*HDD*	H_d [kWh/m^2 ·year]												
			1	2	3	4	5	6	7	8	9	10	11	12	13
B	Bari	**764**	7.00	20.68	21.18	10.88	24.05	16.82	12.88	14.75	7.21	18.72	18.32	18.61	17.92
C	Crotone	**1012**	0.70	11.06	6.85	1.31	8.79	6.81	1.97	4.12	0.66	7.77	8.85	9.03	9.40
E	Cuneo	**2213**	5.14	21.69	15.33	6.78	20.36	14.03	8.14	12.81	4.73	16.11	16.57	18.28	18.40
F	Cortina	**4473**	16.43	43.27	32.43	19.55	41.52	29.36	22.10	30.28	15.76	33.32	33.28	36.92	37.12
	Stelvio	**6339**	17.86	50.32	32.67	19.27	43.24	31.74	21.77	33.11	16.40	36.26	37.96	41.85	43.22
	Sestriere	**6804**	16.97	52.08	29.60	16.96	40.37	30.75	19.01	31.99	15.13	35.44	38.40	42.38	44.58

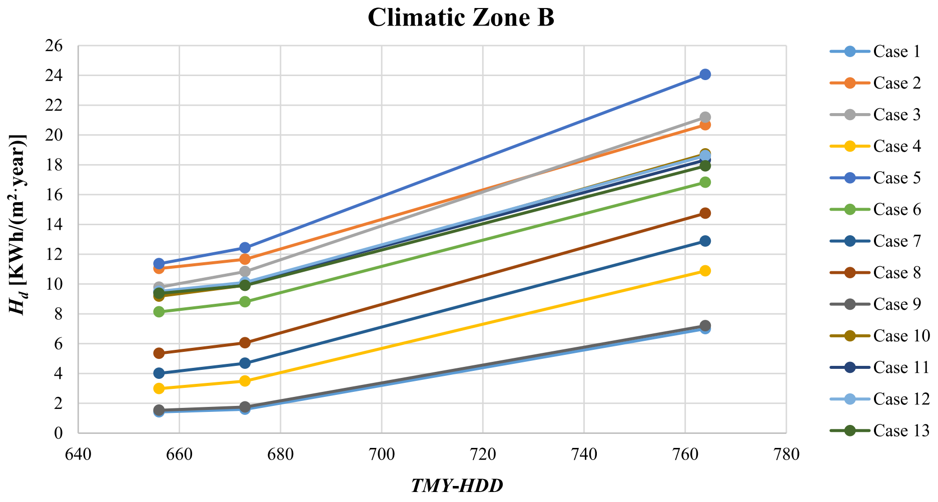


Fig. 10. Heating demand versus *TMY-HDD* of climatic zone B.

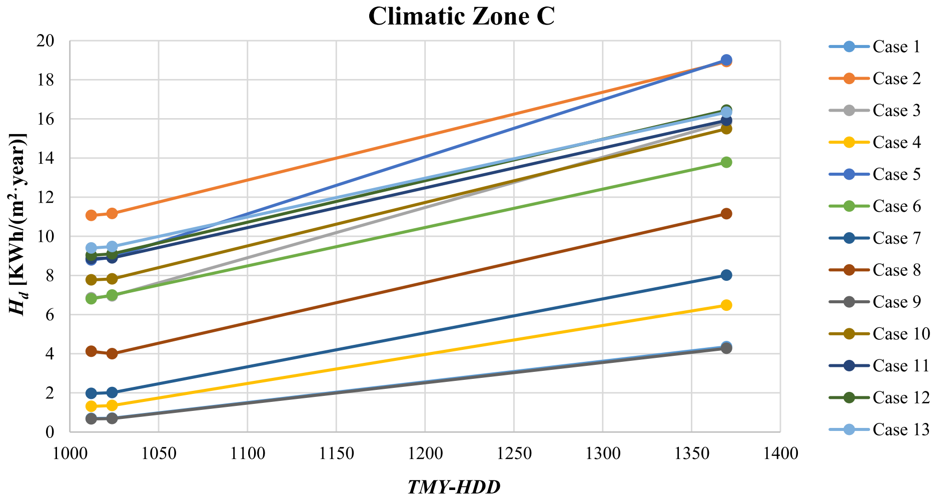


Fig. 11. Heating demand versus *TMY-HDD* of climatic zone C.

- Trieste, originally belonging to climatic zone E, now falls back to climatic zone D; and
- Cuneo, originally belonging to climatic zone F, now falls back to climatic zone E.

In general, it is possible to observe a generic reduction in *HDD* values, which is probably due to the general increase in average temperatures observed throughout the Italian peninsula in recent years.

To analyse the simulation results correctly, the cities listed in Table 9 were linked with new climatic zones; to consider an additional three cities in climatic zone F, another location, namely Stelvio, was added.

Changing the *HDD* value and climatic zone alters, the heating periods and consequently the limit transmittance values. Table 10 presents the results obtained from the new dynamic simulations for each model, for only those cities with a changed climatic zone.

By plotting H_d versus new *HDD* indexes, it was possible to observe the following trends for each climatic zone (Figs. 10–14):

From the results, a more regular trend could be observed in each climatic zone with respect to the previous results (Figs. 4–8). Moreover, in this case, it was possible to determine linear correlations between the H_d and *HDD* values with higher correlation coefficients, R^2 (Fig. 15).

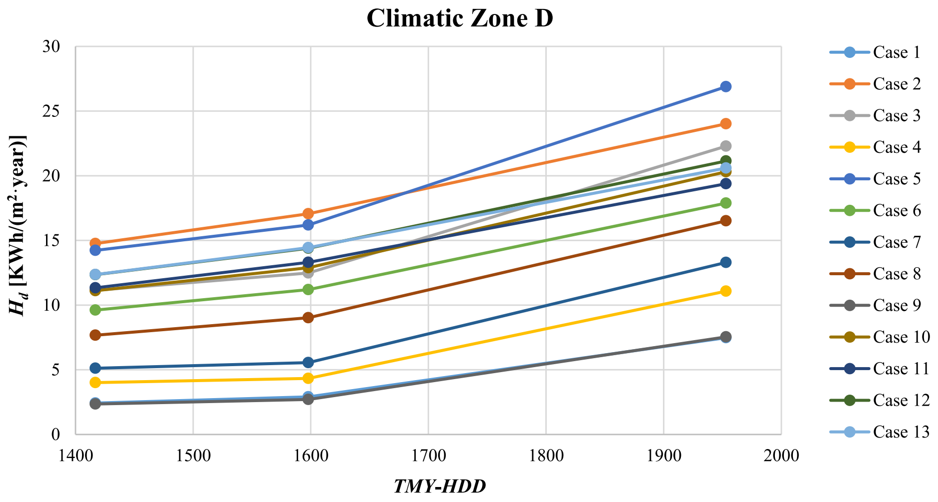


Fig. 12. Heating demand versus *TMY-HDD* of climatic zone D.

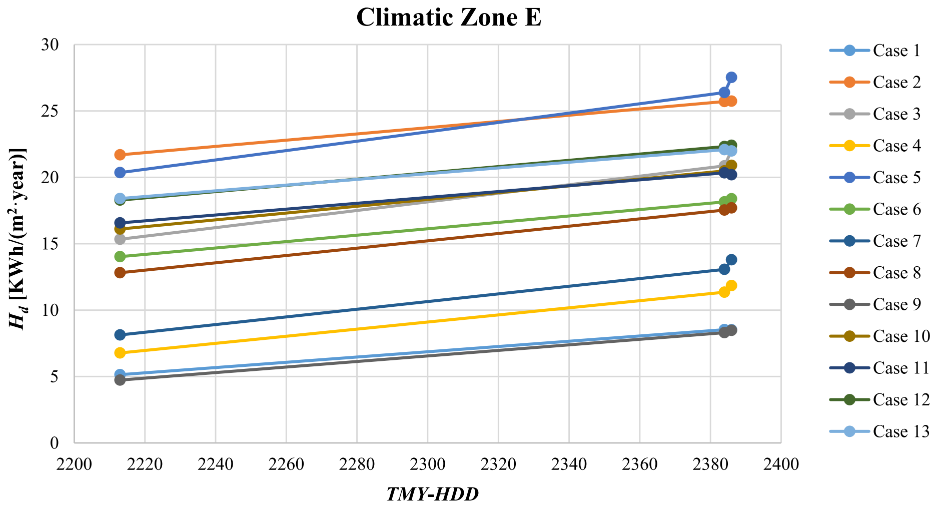


Fig. 13. Heating demand versus *TMY-HDD* of climatic zone E.

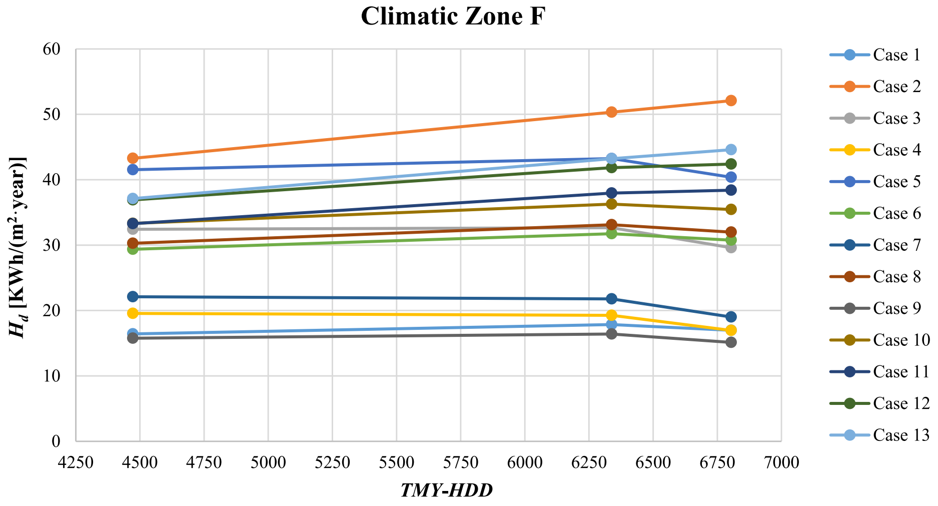


Fig. 14. Heating demand versus *TMY-HDD* of climatic zone F.

In Fig. 15, several trend-lines relating to the data from climatic zones B and D are illustrated. In these cases, it is possible to observe higher R^2 values with respect to Fig. 9 (all results are collected in Appendix B).

In contrast to the general trend, the H_d value was lower in relation to the maximum *HDD* value only in climatic zone F and for $S/V < 0.4$. These results confirmed the fact that the evaluation of the heating energy demand as a function of only a climatic parameter does not

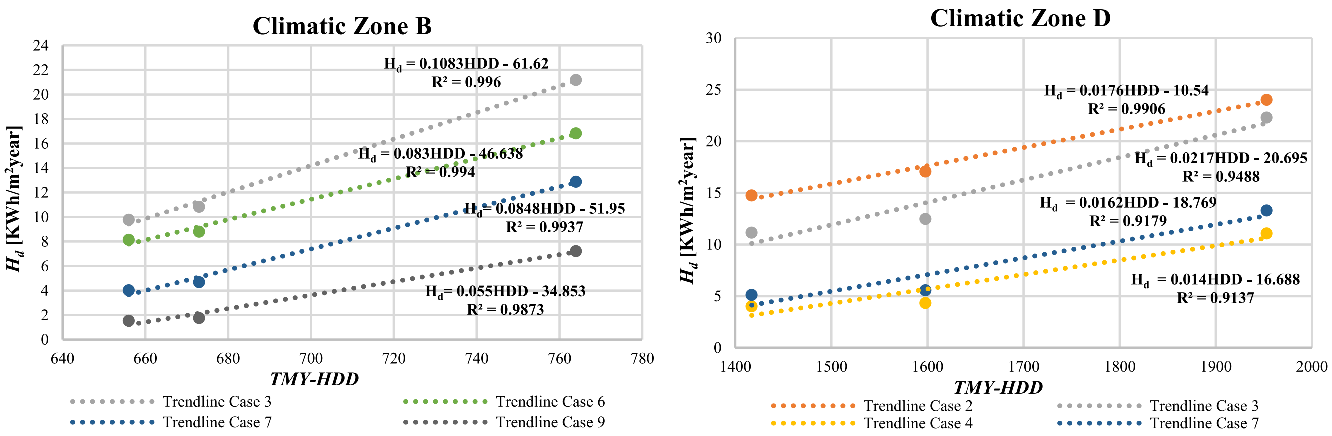


Fig. 15. Trend line examples of H_d function of *TMY-HDD* in climatic zone B and D.

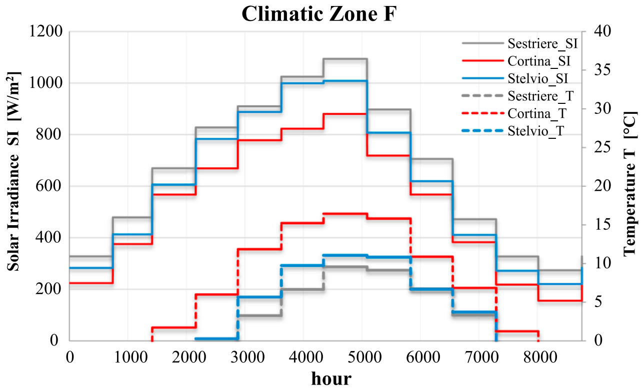


Fig. 16. Climatic data of cities belonging in climatic zone F.

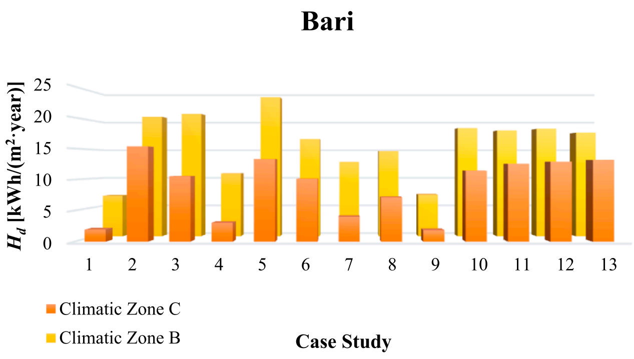


Fig. 17. Comparison between H_d calculated in climatic zone B and H_d calculated in climatic zone C for Bari.

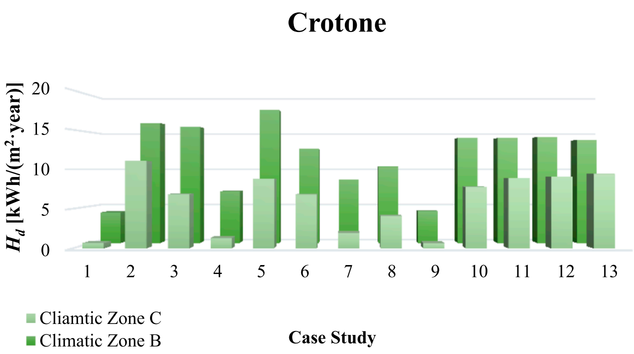


Fig. 18. Comparison between H_d calculated in climatic zone B and H_d calculated in climatic zone C for Crotone.

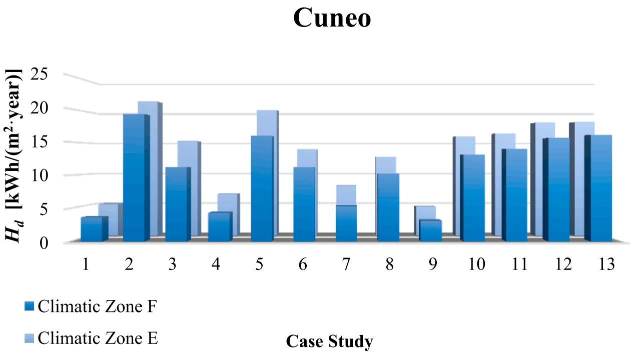


Fig. 19. Comparison between H_d calculated in climatic zone B and H_d calculated in climatic zone C for Cuneo.

Table 11
Selected Italian locations *10349: 2016-HDD*.

Location	*10349: 2016-HDD*
Palermo	1121
Messina	1262
Crotone	1264
Genova	1549
Termoli	**1555**
Cagliari	1584
Bari	1759
Firenze	1835
Trieste	1848
Forlì	2304
Bolzano	2346
Torino	2648
Cuneo	2919
Cortina	**4015**
Sestriere	**4430**

completely explain the building thermal balance. Indeed, by analysing the climatic data such as the temperature and solar irradiance relating to the locations belonging to climatic zone F, it is possible to observe the following graph (Fig. 16):

Although Cortina is characterised by the highest external average temperature, and thus, by a smaller *HDD* value than other cities, the H_d value is not always the smallest, because it is important to consider other boundary conditions such as the solar irradiance. Indeed, Cortina is characterised by a lower monthly solar irradiance than the other cities.

Furthermore, as indicated in Table 9, it is possible to change the dataset, *HDD* values, and even climatic zone, as for Bari, Crotone and Cuneo. The change in the climatic zone determines the variation in the

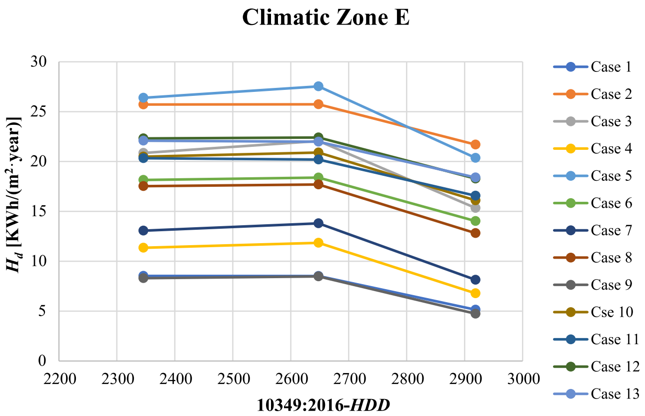


Fig. 20. Heating demand versus *10349:2016 HDD.*

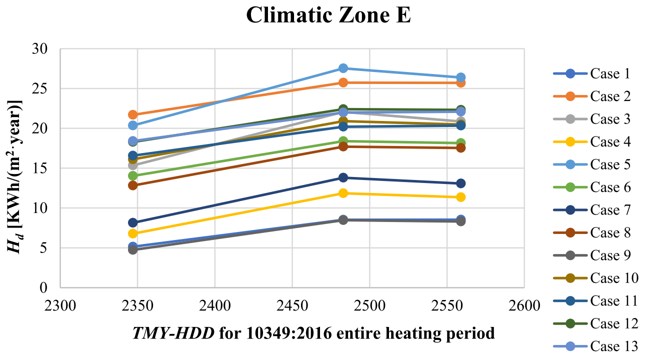


Fig. 21. Heating demand versus *TMY-HDD* for 10349:2016.

heating period and the thermal transmittance limit values.

Indeed, according to DPR412/93, Bari belongs in climatic zone C, while *TMY-HDD* places it in climatic zone B (Fig. 17). In this case, the change from a colder to a warmer climate class, determines a greater thermal energy demand, even though it reduces the operating heating period; contrary to common-sense expectations, this variation is attributable to the increase in the limit transmittance values, causing the building-plant system to be less thermo-insulated and resulting in greater thermal losses.

The same observation can be extended to the locations of Crotone (Fig. 18) and Cuneo (Fig. 19): the first location changes from a warmer (B) to a cooler (C) climate class, while the second changes from a colder (F) to a warmer (E) climate class.

The evaluation of H_d linked to DPR412/93-*HDD* is completely different from the evaluation of the same H_d linked to the *TMY-HDD* used in the simulation tool, particularly in those locations where the calculation of *HDD* leads to a change in the climatic class and thermo-physical design limits.

5.3. Heating demand and HDD from Italian standard 10349: 2016

The new Italian technical standard [46] collects updated *HDD* values from all Italian regional capital cities. The procedure is based on the calculation defined in [67], and the range for the heating period is from October 15th to April 14th (the heating period of climatic zone E). In this work, three of the 15 selected cities are not included in UNI 10349-3: 2016, namely: Termoli, Cortina, and Sestriere. By applying the *HDD* procedure indicated by UNI 10349-1: 2016 and using the representative TMY, the authors determined the *HDD* values for these three cities (see Table 11).

Unfortunately, in this case, the *HDD* values for all locations, were evaluated for the same heating period, making it impossible to identify the specific climatic zone for each city.

Only the cities of Torino, Cuneo, and Bolzano are characterised by *HDD* values that continue to belong in climate zone E, according to DPR 412/93 (2100 < *HDD* < 3000, Table 2). For this reason, considering the H_d designed and simulated in climate zone E and correlating these results with the 10349: 2016-*HDD* values, it is possible to obtain and evaluate the following results (Fig. 20).

In general, a decreasing trend of H_d can be observed, linked to an increase in the *HDD* value; these trends are unusual compared to case studies described previously, and are characterised by correlations with very low R^2 -values with the optimal value being 0.75 (Appendix C, Table C1). To conduct a generic comparison between these results and those demonstrated as possible before (Fig. 13), it is necessary for the *HDD* value to be calculated over the same heating period.

For this reason, based on the weather data of TMY2, generated by Meteonorm, the authors recalculated the *HDD* values for the three aforementioned cities, considering the heating period dictated by the 10349: 2016 technical standard. This assessment led to the determination of the following *HDD* values:

- Torino *HDD*: 2483 [K day];
- Bolzano *HDD*: 2559 [K day]; and
- Cuneo *HDD*: 2347 [K day].

These data were correlated with the H_d values of the 13 simulated buildings, obtaining the following trends:

In Fig. 21, an improvement can be observed in the trend of the H_d value for the increasing *HDD* with respect to the trend illustrated in Fig. 20. The correlations of H_d versus *TMY-HDD* calculated for the heating period from 15th October to 14th April are presented in Appendix C, Table C2.

However, despite the HDD calculation for the heating period provided by the new standard, using the TMY2 files and the trends shown in Fig. 21, being superior those illustrated in Fig. 20, these results are still far from those obtained in Fig. 13.

5.4. Heating demand correlations

As demonstrated in [58], a more extensive calculation of H_d should be a function of:

$$H_d = f\left(HDD;\ \frac{S}{V}\right). \tag{10}$$

Indeed, to evaluate the heating energy demand, it is necessary to consider simultaneously the *HDD* and *S/V* an important factor that strongly influences heat loss, heat gain and the heated volume.

The authors generalized the results looking for some correlations in which H_d is a function simultaneously of the *HDD* and *S/V* parameters [68]. In this research, more reliable linear relationships between H_d, *HDD* and *S/V* were developed with the following form:

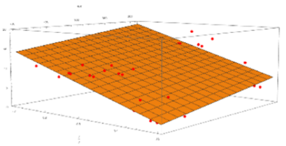
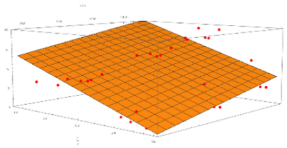
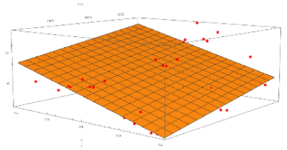
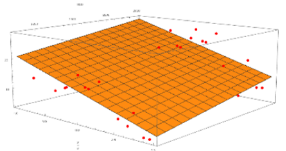
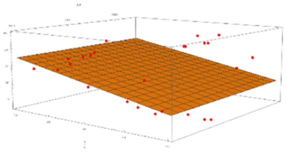
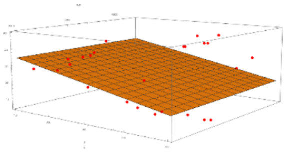
$$H_d = Y + Z{\cdot}HDD + K{\cdot}\frac{S}{V} \tag{11}$$

For each climatic zone, applying the last squared method, the values of *Y, Z* and *K* were determined; the results of the fitting procedure are shown in Tables 12 and 13, where for each climatic zone and for the entire Italian peninsula, the value of the three coefficients, the R^2 values and a graphic representation are provided.

In Table 12 the results related to the DPR 412/93 *HDD* are collected, while in Table 13 the results related to the *TMY-HDD* are summarised.

It is possible to determine the H_d of a building with a single equation and with a high correlation degree just knowing *HDD* and *S/V*. In particular, for the entire Italian peninsula, the correlation with *TMY-HDD* is characterized by an R^2 = 0.9 while the correlation determined by the DPR 412/93- *HDD* is characterized by an R^2 = 0.83.

Table 12
H_d function of DPR 412/93 *HDD* and *S/V*.

DPR 412/93-HDD			
Climatic zone	H_d equation form	H_d equation plan	R^2
B	H_d = -17.9785 + 0.0237916 *HDD* + 15.5132 *S/V*		0.94
C	H_d = -21.3214 + 0.0186898 *HDD* + 16.2852 *S/V*		0.91
D	H_d = -19.0741 + 0.0122947 *HDD* + 18.0579 *S/V*		0.92
E	H_d = -19.1646 + 0.0100572 *HDD* + 19.007 *S/V*		0.94
F	H_d = 10.1441 + 0.000455946 *HDD* + 23.7375 *S/V*		0.81
Italian Peninsula	H_d = -5.69106 + 0.00534053 *HDD* + 18.5202 *S/V*		**0.83**

5.5. Comparison and discussion

To provide an improved understanding the results obtained from each scenario, the equations and correlation values collected in the *Appendices* were compared. Table 14 displays the average R^2 values of the correlations for each zone, and the global average R^2 for each scenario. Evidently, as explained previously, only the values for climatic zone E are indicated for the *10349: 2016 HDD* scenario.

In all cases, the optimal results were related to the *TMY-HDD* scenario, demonstrating an R^2 value higher than 0.911. The same observations are valid for the results collected in Section 5.4, in which the correlations of H_d as a function of *HDD* and *S/V* are reported (Tables 12 and 13).

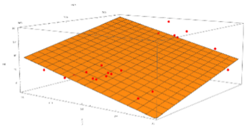
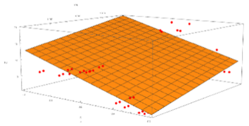
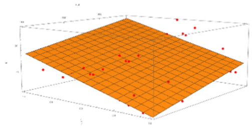
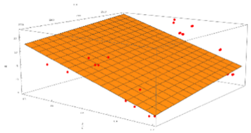
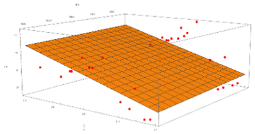
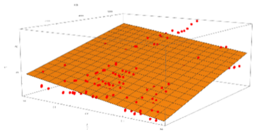
Moreover, in this case, the optimal correlations were obtained for the *TMY-HDD* scenario in which the R^2 value was higher than the R^2 value relating to the *DPR 412/93 HDD* scenario for each climatic zone.

Furthermore, the final mathematical solution enables the identification of the building energy performance in any Italian city and for any building shape; its simple form and high reliability accelerate the building energy evaluation phase, and its use does not require expert user knowledge. This methodology for determining these correlations and the previous considerations regarding the importance of the selection of correct weather data for calculating the climatic index can be extended to any country, climatic zone, and building type.

6. Conclusion

The energy performance of a building is strictly dependent on the climatic conditions. For this reason, in the literature, it is possible to identify several studies that have attempted to determine the energy demand as a function of weather indexes. The Heating Degree Days value for each considered location represents the most important climate severity index and can be used to evaluate the building energy performance. In general, a higher Heating Degree Days value indicates a higher thermal energy demand for maintaining comfort conditions. It is important to emphasise that the results emerging from a building thermal balance are necessarily correlated to the employed weather data. The assessment of the heating energy demand of a building, by means of the Heating Degree Day, is correct if the determination of the climate index is a function of the same weather data used during the

Table 13
H_d function of *TMY-HDD* and *S/V*.

TMY-HDD			
Climatic zone	H_d equation form	H_d equation plan	R^2
B	$H_d = -57.9013 + 0.0853618\ HDD + 16.402\ S/V$		0.95
C	$H_d = -21.568 + 0.0192865\ HDD + 14.9309\ S/V$		0.91
D	$H_d = -24.251 + 0.0163489\ HDD + 18.0579\ S/V$		0.93
E	$H_d = -55.0521 + 0.0263763\ HDD + 19.6228\ S/V$		0.94
F	$H_d = 10.9852 + 0.000931086\ HDD + 28.4968\ S/V$		0.93
Italian Peninsula	$H_d = -4.59104 + 0.00432513\ HDD + 19.5021\ S/V$		**0.90**

energy balance analysis.

In this work, the authors affirmed that a direct correlation of a generic Degree Days values with the simulated heating energy demand obtained from a generic software tool could lead to unrealistic consumption estimates. To demonstrate this, several simple correlations between the heating energy demand and the Heating Degree Days were extrapolated, evaluating the reliability of these correlations for three different scenarios. Based on the particular situation of the Italian building energy efficiency laws and standards currently in force, an Italian case study was analysed.

Following a review of the Degree Days extrapolation methods used globally, an in-depth analysis of the Italian procedure was carried out. Owing to the obsolescence of the old technical standard [44,45], based on climatic data collected before 1994, recent legislation [46] was enacted; this latest version updates the climatic data and recalculates the Heating Degree Days values only for all regional capital cities of Italy. However, [44] remains current, and determines the climatic zone and heating period of the entire Italian peninsula. The Heating Degree Days values indicated in [44] and [46] differ: in the former, the heating period is a function of the climatic zone, while in the latter, it is the same for the entire Italian peninsula. If users were to evaluate the energy performance of a building by means of simulation software such as TRNSYS, where the climate file differs from the weather data employed to deploy the law, the resulting evaluations would not be related to the Heating Degree Days indicated by the norm.

To achieve the aim of this study, the authors evaluated the correlation degree between the heating energy demand and Heating Degree Days by simulating the heating energy demand of 13 building models, located in 15 Italian cities. As expected, not only do different Heating Degree Days values induce variations, but so does a change in the pertaining climatic zone and the transmittance limits dictated by law for the building envelope design. The authors identified correlations between the heating energy demand versus the Degree Days dictated by the current law (DPR 412/93-*HDD)*, versus the Degree Days calculated with the Mean Degree Hours method based on the same climatic file used in the simulation tool (*TMY-HDD),* and finally versus the Degree Days dictated by the new standard (10349: 2016-*HDD)*. All results are

Table 14
Average and global R^2 correlation values for each zone.

	Climatic Zone					
Average R^2	B	C	D	E	F	Global
DPR 412/93 HDD	0.889	0.978	0.784	0.916	0.896	0.893
TMY-HDD	**0.993**	**1.000**	**0.960**	**0.994**	**0.911**	**0.972**
10349: 2016 HDD	–	–	–	0.673	–	0.673

presented in Appendices A–C.

A comparison of these results demonstrates that the optimal correlations are those relating to *TMY-HDD*, indicating that the correct evaluation of a building energy balance can only depend on a climatic index if the thermal needs and Heating Degree Days are calculated using the same weather data file. Indeed, the evaluation of the energy performance of a building by means of the correlation with a Heating Degree Days value dictated by a technical standard exhibits inferior correlation coefficient values; the simulated data from any software are based on a typical meteorological year, which is not the same as that used by the technical standard.

The same considerations are valid for the correlations proposed in Section 5.4, in which the heating energy demand is simultaneously a function of the building climatic context and shape factor. This final mathematical solution enables the identification of the building energy performance in any Italian city and for any shape of any building; its simple form and high reliability accelerates the building energy evaluation phase and its use does not require long computational time or expert users.

The presented methodology for the determination of these correlations and the previous considerations regarding the importance of the selection of correct weather data for the calculation of the climatic index can be extended to any country, climatic zone, and building type. Therefore, this work has highlighted critical issues in the field of energy performance assessment of buildings based on the use of climate indexes, and demonstrates the manner in which these can be overcome by means of the correct selection of climate files for their definition. The correct determination of these indexes, in relation to building energy requirements, can lead to the development of simplified alternative methods, such as the correlations proposed herein, which, owing to their high degree of reliability, can simplify the energy diagnosis phases and the selections of high-efficiency designs.

Appendix A

Correlation H_d versus 412/93 DPR HDD

See Tables A1–A5.

Table A1
Correlation H_d versus *HDD* for climatic zone B.

	City	Messina	Palermo	Crotone	H_d equation form	R^2
	HDD DPR 412/93	707	751	899		
	Case Study	H_d [kWh/m^2 year]				
Climatic zone B	1	1.60	1.42	4.16	**$H_d = 0.0146\ HDD - 9.1092$**	**0.925**
	2	11.66	11.04	16.27	**$H_d = 0.0269\ HDD - 8.1140$**	**0.896**
	3	10.83	9.78	15.73	**$H_d = 0.0292\ HDD - 10.864$**	**0.858**
	4	3.49	2.98	7.00	**$H_d = 0.0205\ HDD - 11.632$**	**0.891**
	5	12.43	11.37	18.02	**$H_d = 0.0331\ HDD - 12.090$**	**0.869**
	6	8.80	8.13	12.74	**$H_d = 0.0232\ HDD - 8.3353$**	**0.879**
	7	4.68	4.01	8.57	**$H_d = 0.0229\ HDD - 12.266$**	**0.878**
	8	6.06	5.35	10.35	**$H_d = 0.0253\ HDD - 12.603$**	**0.881**
	9	1.75	1.53	4.30	**$H_d = 0.0147\ HDD - 8.9802$**	**0.917**
	10	9.92	9.18	14.27	**$H_d = 0.0256\ HDD - 9.0186$**	**0.879**
	11	10.06	9.47	14.24	**$H_d = 0.0245\ HDD - 7.9533$**	**0.894**
	12	10.11	9.51	14.39	**$H_d = 0.0250\ HDD - 8.2861$**	**0.892**
	13	9.90	9.37	13.98	**$H_d = 0.0238\ HDD - 7.5828$**	**0.898**

Table A2
Correlation H_d versus *HDD* for climatic zone C.

	City	Cagliari	Bari	Termoli	H_d equation form	R^2
	HDD DPR 412/93	990	1185	1350		
	Case Study	H_d [kWh/m^2 year]				
Climatic zone C	1	0.70	1.97	4.35	**$H_d = 0.0100\ HDD - 9.4443$**	**0.951**
	2	11.16	15.35	18.93	**$H_d = 0.0216\ HDD - 10.195$**	**1.000**
	3	6.95	10.54	15.83	**$H_d = 0.0245\ HDD - 17.646$**	**0.975**
	4	1.36	3.05	6.48	**$H_d = 0.0141\ HDD - 12.897$**	**0.943**
	5	8.93	13.33	19.01	**$H_d = 0.0278\ HDD - 18.961$**	**0.985**
	6	6.99	10.12	13.78	**$H_d = 0.0188\ HDD - 11.742$**	**0.991**
	7	2.01	4.03	8.01	**$H_d = 0.0165\ HDD - 14.674$**	**0.945**
	8	4.00	7.14	11.15	**$H_d = 0.0198\ HDD - 15.788$**	**0.986**
	9	0.69	1.85	4.28	**$H_d = 0.0098\ HDD - 9.3020$**	**0.939**
	10	7.82	11.44	15.49	**$H_d = 0.0212\ HDD - 13.360$**	**0.994**
	11	8.90	12.57	15.93	**$H_d = 0.0195\ HDD - 10.456$**	**1.000**
	12	9.10	12.88	16.44	**$H_d = 0.0204\ HDD - 11.107$**	**0.999**
	13	9.48	13.17	16.34	**$H_d = 0.0191\ HDD - 9.4003$**	**1.000**

Table A3
Correlation H_d versus *HDD* for climatic zone D.

	City	Genova	Firenze	Forli	H_d equation form	R^2
	HDD DPR 412/93	1435	1821	2087		
	Case Study	H_d [kWh/m^2 year]				
Climatic zone D	1	2.42	2.90	7.48	$\boldsymbol{H_d = 0.0073\ HDD - 8.7064}$	**0.733**
	2	14.76	17.06	24.02	$\boldsymbol{H_d = 0.0136\ HDD - 5.6402}$	**0.857**
	3	11.14	12.48	22.29	$\boldsymbol{H_d = 0.0161\ HDD - 13.397}$	**0.754**
	4	4.01	4.33	11.07	$\boldsymbol{H_d = 0.0101\ HDD - 11.547}$	**0.691**
	5	14.23	16.19	26.88	$\boldsymbol{H_d = 0.0184\ HDD - 13.623}$	**0.783**
	6	9.62	11.20	17.88	$\boldsymbol{H_d = 0.0121\ HDD - 8.5819}$	**0.812**
	7	5.12	5.56	13.29	$\boldsymbol{H_d = 0.0117\ HDD - 12.887}$	**0.698**
	8	7.67	9.03	16.52	$\boldsymbol{H_d = 0.0128\ HDD - 11.802}$	**0.781**
	9	2.35	2.71	7.54	$\boldsymbol{H_d = 0.0075\ HDD - 9.0765}$	**0.711**
	10	11.11	12.89	20.31	$\boldsymbol{H_d = 0.0134\ HDD - 9.1357}$	**0.814**
	11	11.34	13.30	19.38	$\boldsymbol{H_d = 0.0118\ HDD - 6.3819}$	**0.853**
	12	12.35	14.39	21.14	$\boldsymbol{H_d = 0.0129\ HDD - 7.0055}$	**0.844**
	13	12.36	14.44	20.60	$\boldsymbol{H_d = 0.0121\ HDD - 5.7605}$	**0.859**

Table A4
Correlation H_d versus *HDD* for climatic zone E.

	City	Trieste	Torino	Bolzano	H_d equation form	R^2
	HDD DPR 412/93	2102	2617	2791		
	Case Study	H_d [kWh/m^2 year]				
Climatic zone E	1	4.10	8.52	8.53	$\boldsymbol{H_d = 0.0069\ HDD - 10.279}$	**0.942**
	2	17.71	25.74	25.71	$\boldsymbol{H_d = 0.0125\ HDD - 8.2802}$	**0.940**
	3	14.52	22.05	20.86	$\boldsymbol{H_d = 0.0104\ HDD - 6.9713}$	**0.853**
	4	6.30	11.84	11.35	$\boldsymbol{H_d = 0.0081\ HDD - 10.485}$	**0.898**
	5	18.42	27.53	26.39	$\boldsymbol{H_d = 0.0130\ HDD - 8.3171}$	**0.876**
	6	11.94	18.38	18.15	$\boldsymbol{H_d = 0.0098\ HDD - 8.4249}$	**0.925**
	7	7.74	13.79	13.07	$\boldsymbol{H_d = 0.0087\ HDD - 10.127}$	**0.879**
	8	10.64	17.70	17.53	$\boldsymbol{H_d = 0.0108\ HDD - 11.857}$	**0.931**
	9	4.09	8.47	8.30	$\boldsymbol{H_d = 0.0067\ HDD - 9.7049}$	**0.924**
	10	13.85	20.90	20.48	$\boldsymbol{H_d = 0.0105\ HDD - 7.9942}$	**0.914**
	11	13.48	20.20	20.33	$\boldsymbol{H_d = 0.0106\ HDD - 8.6540}$	**0.949**
	12	15.07	22.41	22.32	$\boldsymbol{H_d = 0.0114\ HDD - 8.5148}$	**0.936**
	13	14.85	21.98	22.08	$\boldsymbol{H_d = 0.0113\ HDD - 8.5729}$	**0.947**

Table A5
Correlation H_d versus *HDD* for climatic zone F.

	City	Cuneo	Cortina	Sestriere	H_d equation form	R^2
	HDD DPR 412/93	3012	4433	5165		
	Case Study	H_d [kWh/m^2 year]				
Climatic zone F	1	3.64	16.43	16.97	$\boldsymbol{H_d = 0.0066\ HDD - 15.291}$	**0.910**
	2	19.21	43.24	50.37	$\boldsymbol{H_d = 0.0148\ HDD - 24.610}$	**0.986**
	3	11.20	32.43	29.42	$\boldsymbol{H_d = 0.0093\ HDD - 14.916}$	**0.793**
	4	4.31	19.55	16.96	$\boldsymbol{H_d = 0.0065\ HDD - 13.855}$	**0.770**
	5	15.92	41.52	40.18	$\boldsymbol{H_d = 0.0122\ HDD - 18.685}$	**0.857**
	6	11.19	29.19	30.61	$\boldsymbol{H_d = 0.0095\ HDD - 16.326}$	**0.926**
	7	5.26	22.10	19.01	$\boldsymbol{H_d = 0.0071\ HDD - 14.512}$	**0.758**
	8	10.19	30.28	31.90	$\boldsymbol{H_d = 0.0106\ HDD - 20.578}$	**0.927**
	9	3.11	15.76	15.13	$\boldsymbol{H_d = 0.0060\ HDD - 14.039}$	**0.859**
	10	13.10	33.32	35.06	$\boldsymbol{H_d = 0.0107\ HDD - 18.024}$	**0.929**
	11	14.02	33.28	37.92	$\boldsymbol{H_d = 0.0114\ HDD - 19.657}$	**0.976**
	12	15.61	36.92	41.56	$\boldsymbol{H_d = 0.0125\ HDD - 20.980}$	**0.971**
	13	16.10	37.11	43.40	$\boldsymbol{H_d = 0.0130\ HDD - 22.284}$	**0.986**

Appendix B

Correlation H_d versus TMY-HDD

See Table B1–B5.

Table B1
Correlation H_d versus *HDD* for climatic zone B.

	City	Palermo	Messina	Bari	H_d equation form	R^2
	HDD Weather data	656	673	764		
		H_d [kWh/m^2 year]				
Climatic zone B	1	1.42	1.60	7.00	**H_d = 0.1209 HHD − 68.384**	**0.995**
	2	11.04	11.66	20.68	**H_d = 0.0925 HHD − 50.083**	**0.992**
	3	9.78	10.83	21.18	**H_d = 0.1083 HHD − 61.620**	**0.996**
	4	2.98	3.49	10.88	**H_d = 0.0758 HHD − 47.103**	**0.992**
	5	11.37	12.43	24.05	**H_d = 0.1209 HHD − 68.384**	**0.995**
	6	8.13	8.80	16.82	**H_d = 0.0830 HHD − 46.638**	**0.994**
	7	4.01	4.68	12.88	**H_d = 0.0848 HHD − 51.950**	**0.994**
	8	5.35	6.06	14.75	**H_d = 0.0898 HHD − 53.965**	**0.994**
	9	1.53	1.75	7.21	**H_d = 0.0550 HHD − 34.853**	**0.987**
	10	9.18	9.92	18.72	**H_d = 0.0911 HHD − 50.983**	**0.994**
	11	9.47	10.06	18.32	**H_d = 0.0848 HHD − 46.581**	**0.992**
	12	9.51	10.11	18.61	**H_d = 0.0873 HHD − 48.153**	**0.992**
	13	9.37	9.90	17.92	**H_d = 0.0821 HHD − 44.892**	**0.992**

Table B2
Correlation H_d versus *HDD* for climatic zone C.

	City *HDD* Weather data	Crotone 1012	Cagliari 1024	Termoli 1370	H_d equation form	R^2
	Case Study	H_d [kWh/m^2 year]				
Climatic zone C	1	0.70	0.70	4.35	**H_d = 0.0104 HHD − 9.8704**	**0.999**
	2	11.06	11.16	18.93	**H_d = 0.0222 HHD − 11.502**	**1**
	3	6.85	6.95	15.83	**H_d = 0.0254 HHD − 18.923**	**1**
	4	1.31	1.36	6.48	**H_d = 0.0146 HHD − 13.553**	**1**
	5	8.79	8.93	19.01	**H_d = 0.0289 HHD − 20.510**	**1**
	6	6.81	6.99	13.78	**H_d = 0.0196 HHD − 13.004**	**1**
	7	1.97	2.01	8.01	**H_d = 0.0171 HHD − 15.434**	**1**
	8	4.12	4.00	11.15	**H_d = 0.0201 HHD − 16.445**	**0.998**
	9	0.66	0.69	4.28	**H_d = 0.0102 HHD − 9.7363**	**0.999**
	10	7.77	7.82	15.49	**H_d = 0.0219 HHD − 14.467**	**0.999**
	11	8.85	8.90	15.93	**H_d = 0.0200 HHD − 11.518**	**0.999**
	12	9.03	9.10	16.44	**H_d = 0.0210 HHD − 12.266**	**1**
	13	9.40	9.48	16.34	**H_d = 0.0196 HHD − 10.530**	**1**

Table B3
Correlation H_d versus *HDD* for climatic zone D.

	City *HDD* Weather data	Genova 1417	Firenze 1598	Forli 1953	H_d equation form	R^2
	Case Study	H_d [kWh/m^2 year]				
Climatic zone D	1	2.42	2.90	7.48	**H_d = 0.0099 *HHD* − 12.138**	**0.938**
	2	14.76	17.06	24.02	**H_d = 0.0176 *HHD* − 10.540**	**0.991**
	3	11.14	12.48	22.29	**H_d = 0.0217 *HHD* − 20.695**	**0.949**
	4	4.01	4.33	11.07	**H_d = 0.0140 *HHD* − 16.688**	**0.914**
	5	14.23	16.19	26.88	**H_d = 0.0245 *HHD* − 21.471**	**0.963**
	6	9.62	11.20	17.88	**H_d = 0.0159 *HHD* − 13.418**	**0.976**
	7	5.12	5.56	13.29	**H_d = 0.0162 *HHD* − 18.769**	**0.918**
	8	7.67	9.03	16.52	**H_d = 0.0171 *HHD* − 17.309**	**0.962**
	9	2.35	2.71	7.54	**H_d = 0.0102 *HHD* − 12.734**	**0.925**
	10	11.11	12.89	20.31	**H_d = 0.0177 *HHD* − 14.499**	**0.976**
	11	11.34	13.30	19.38	**H_d = 0.0153 *HHD* − 10.676**	**0.990**
	12	12.35	14.39	21.14	**H_d = 0.0168 *HHD* − 11.797**	**0.987**
	13	12.36	14.44	20.60	**H_d = 0.0156 *HHD* − 10.085**	**0.991**

Table B4
Correlation H_d versus *HDD* for climatic zone E.

	City	Torino	Cuneo	Bolzano	H_d equation form	R^2
	HDD Weather data	2386	2213	2384		
	Case Study	H_d [kWh/m^2 year]				
Climatic zone E	1	8.52	5.14	8.53	**$H_d = 0.0197\ HHD - 38.453$**	**1**
	2	25.74	21.69	25.71	**$H_d = 0.0234\ HHD - 30.172$**	**1**
	3	22.05	15.33	20.86	**$H_d = 0.0356\ HHD - 63.545$**	**0.975**
	4	11.84	6.78	11.35	**$H_d = 0.0280\ HHD - 55.298$**	**0.994**
	5	27.53	20.36	26.39	**$H_d = 0.0384\ HHD - 64.712$**	**0.981**
	6	18.38	14.03	18.15	**$H_d = 0.0247\ HHD - 40.586$**	**0.999**
	7	13.79	8.14	13.07	**$H_d = 0.0308\ HHD - 60.080$**	**0.988**
	8	17.70	12.81	17.53	**$H_d = 0.0279\ HHD - 48.964$**	**1**
	9	8.47	4.73	8.30	**$H_d = 0.0212\ HHD - 42.288$**	**0.999**
	10	20.90	16.11	20.48	**$H_d = 0.0267\ HHD - 42.902$**	**0.995**
	11	20.20	16.57	20.33	**$H_d = 0.0215\ HHD - 30.979$**	**0.998**
	12	22.41	18.28	22.32	**$H_d = 0.0237\ HHD - 34.207$**	**1**
	13	21.98	18.40	22.08	**$H_d = 0.0211\ HHD - 28.290$**	**0.999**

Table B5
Correlation H_d versus *HDD* for climatic zone F.

	City	Cortina	Stelvio	Sestriere	H_d equation form	R^2
	HDD Weather data	4473	6339	6804		
	Case Study	H_d [kWh/m^2 year]				
Climatic zone F	1	16.43	17.86	16.97	**No reliable correlation**	**–**
	2	43.27	50.32	52.08	**$H_d = 0.0038\ HHD + 26.364$**	**1**
	3	32.43	32.67	29.60	**No reliable correlation**	**–**
	4	19.55	19.27	16.96	**No reliable correlation**	**–**
	5	41.52	43.24	40.37	**No reliable correlation**	**–**
	6	29.36	31.74	30.75	**$H_d = 0.0008\ HDD + 25.983$**	**0.667**
	7	22.10	21.77	19.01	**No reliable correlation**	**–**
	8	30.28	33.11	31.99	**$H_d = 0.001\ HDD + 26.164$**	**0.687**
	9	15.76	16.40	15.13	**No reliable correlation**	**–**
	10	33.32	36.26	35.44	**$H_d = 0.0011\ HDD + 28.543$**	**0.799**
	11	33.28	37.96	38.40	**$H_d = 0.0023\ HDD + 23.127$**	**0.987**
	12	36.92	41.85	42.38	**$H_d = 0.0024\ HDD + 26.122$**	**0.990**
	13	37.12	43.22	44.58	**$H_d = 0.0032\ HDD + 22.72$**	**1**

Appendix C

Correlation H_d versus HDD value dictated by UNI 10349-3:2016 and HDD value calculated using the weather data and considering the heating period dictated by the same technical standard

See Table C1–C2.

Table C1
Correlation H_d versus *HDD* dictated by the technical standard UNI 10349-3:2016.

	City	Torino	Cuneo	Bolzano	H_d equation form	R^2
	HDD UNI 2016	2648	2919	2346		
	Case Study	H_d [kWh/m^2 year]				
Climatic zone E	1	8.52	5.14	8.53	**$H_d = -0.0058\ HDD + 22.722$**	**0.725**
	2	25.74	21.69	25.71	**$H_d = -0.0069\ HDD + 42.521$**	**0.717**
	3	22.05	15.33	20.86	**$H_d = -0.0094\ HDD + 44.152$**	**0.563**
	4	11.84	6.78	11.35	**$H_d = -0.0078\ HDD + 30.568$**	**0.641**
	5	27.53	20.36	26.39	**$H_d = -0.0103\ HDD + 51.803$**	**0.582**
	6	18.38	14.03	18.15	**$H_d = -0.0071\ HDD + 35.450$**	**0.679**
	7	13.79	8.14	13.07	**$H_d = -0.0084\ HDD + 33.816$**	**0.611**
	8	17.70	12.81	17.53	**$H_d = -0.0081\ HDD + 37.299$**	**0.696**
	9	8.47	4.73	8.30	**$H_d = -0.0061\ HDD + 23.254$**	**0.686**
	10	20.90	16.11	20.48	**$H_d = -0.0075\ HDD + 38.860$**	**0.650**
	11	20.20	16.57	20.33	**$H_d = -0.0065\ HDD + 36.063$**	**0.751**
	12	22.41	18.28	22.32	**$H_d = -0.0069\ HDD + 39.204$**	**0.705**
	13	21.98	18.40	22.08	**$H_d = -0.0063\ HDD + 37.463$**	**0.744**

Table C2

Correlation H_d versus *HDD* calculated using the weather data and considering an heating period from 15 October to 14 April.

	City	Torino	Cuneo	Bolzano	H_d equation form	R^2
	HDD Weather data	2483	2347	2559		
	Case Study	H_d [kWh/m^2 year]				
Climatic zone E	1	8.52	5.14	8.53	**$H_d = 0.0171\ HDD - 34.608$**	**0.877**
	2	25.74	21.69	25.71	**$H_d = 0.0202\ HDD - 25.435$**	**0.871**
	3	22.05	15.33	20.86	**$H_d = 0.0288\ HDD - 51.520$**	**0.745**
	4	11.84	6.78	11.35	**$H_d = 0.0234\ HDD - 47.709$**	**0.811**
	5	27.53	20.36	26.39	**$H_d = 0.0313\ HDD - 52.366$**	**0.761**
	6	18.38	14.03	18.15	**$H_d = 0.0209\ HDD - 34.742$**	**0.842**
	7	13.79	8.14	13.07	**$H_d = 0.0254\ HDD - 50.960$**	**0.787**
	8	17.70	12.81	17.53	**$H_d = 0.0239\ HDD - 42.772$**	**0.855**
	9	8.47	4.73	8.30	**$H_d = 0.0181\ HDD - 37.381$**	**0.847**
	10	20.90	16.11	20.48	**$H_d = 0.0224\ HDD - 35.916$**	**0.819**
	11	20.20	16.57	20.33	**$H_d = 0.0188\ HDD - 27.310$**	**0.895**
	12	22.41	18.28	22.32	**$H_d = 0.0204\ HDD - 29.144$**	**0.862**
	13	21.98	18.40	22.08	**$H_d = 0.0184\ HDD - 24.546$**	**0.890**

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