Definition, analysis and application of a Climatic Severity Index aimed at zoning the Italian territory for summer air conditioning of buildings

The Italian territory is currently divided into climatic zones, based on a winter Climatic Severity Index, the Heating Degree Days, where bound values for primary energy need of buildings have been fixed in compliance with the European Directive 2002/91/CE. About summer air conditioning, the overall zoning of the Italian territory has not been identified yet, because of the lack of a summer Climatic Severity Index definition. Hence, a given building cannot be classified on the basis of its energy need and geographical position.
The definition of a Climatic Severity Index for the summer season is more complex with respect to the winter case: indeed, given the combined effect of the different climatic variables, the analysis of the energy performance of a building is more articulated and must be carried out at least on an hourly scale.
Thanks to a cluster analysis 20 Italian representative towns have been selected, characterized by different climatic profiles. Then, some benchmark buildings have been considered and, their cooling energy need has been assessed through a dynamic simulation software. The analysis of the results has highlighted the opportunity to express the energy need as a function of the observed climatic variables: this way, an index able to subdivide the Italian territory into summer climatic zones has been derived

Definizione, analisi e applicazione di un Indice di Severità Climatica alla zonizzazione del territorio italiano per la climatizzazione estiva degli edifici

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Il territorio italiano è attualmente suddiviso in zone climatiche sulla base di un Indice di Severità Climatica invernale, i Gradi Giorno, mediante il quale sono stati fissati dei limiti al fabbisogno di energia primaria degli edifici (in accordo con la Direttiva Europea 2002/91/CE). Riguardo la climatizzazione estiva non esiste ancora nessuna zonizzazione del territorio, a causa della mancanza di un indicatore di Severità Climatica estivo: di conseguenza, un determinato edificio non può essere classificato sulla base del fabbisogno energetico e della sua localizzazione geografica. La definizione di un Indice di severità Climatica per la stagione estiva risulta più complessa rispetto al caso invernale: infatti, considerando gli effetti combinati delle differenti variabili climatiche, l'analisi del fabbisogno energetico di un dato edificio risulta, in tal caso, più articolata e deve essere condotta su scala oraria. Attraverso una cluster analysis dei dati climatici di città italiane, ne sono state selezionate 20, ritenute rappresentative in quanto caratterizzate da profili climatici significativamente diversi dal punto di vista statistico. Successivamente, considerando alcune tipologie di edifici di riferimento, è stato valutato il fabbisogno energetico per la climatizzazione estiva, utilizzando un software di simulazione dinamica. L'analisi dei risultati ha evidenziato la possibilità di esprimere il fabbisogno energetico in funzione delle variabili climatiche osservate: ciò ha consentito di ricavare un Indice, in base al quale è possibile suddividere il territorio italiano in zone climatiche estive

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INTRODUCTION

In order to have some bound values for buildings' cooling energy need applied to the Italian legislation, in compliance with the European Directive 2002/91/CE, the Italian territory must be classified into summer climatic zones, based on a Summer Climatic Severity Index taking into account three climatic variables: temperature, absolute humidity and solar irradiation.

Previous works [1][2][3] have shown how to define a Climatic Severity Index which considers the interaction between a building, its air-conditioning plant (HVAC) and the site climatic profile. Indeed, for a generic building standing in a certain site, a function E_T of the variables of the site climatic profile is given and expresses the energy need of a building with a given volume V during a given time span T:

$$\frac{E_T}{V\,T} = f\left[\left(\Theta - \Theta_{ref}\right), \left(X - X_{ref}\right), \left(\Upsilon - \Upsilon_{ref}\right)\right] = \mathcal{E} \tag{1}$$

In general, Eq.(1) is non-linear with respect to the three independent variables; its linear term of a Taylor power series expansion, centered at the point $\{\Theta_0, X_0, Y_0\}$ is given by:

$$\mathcal{E} = A\,\Theta + B\,X + C\,\Upsilon - \left[A\,\Theta + B\,X + C\,\Upsilon\right]_{ref} \tag{2}$$

Equation (2) suggests the definition of the two characteristic vectors $\vec{V}_c$ (components Θ, X, Y) $\vec{V}_B$ (components A, B, C). The first one is the *climatic vector* and represents the outdoor climatic profile of the place where the building is located. Clearly the other vector must be connected with the geometric and thermophysical characteristics of the building (*building vector*).

It is then possible to write Eq.(2) as a dot product of the vectors previously defined:

$$\mathcal{E} = \vec{V}_B \cdot \vec{V}_C - \vec{V}_B \cdot \vec{V}_{C,ref} \tag{3}$$

To investigate the nature of the *building vector* components (A, B, C), we can perform an analysis of the energy and matter exchange between the building and the outdoor environment, considering the principle of effects superposition, according to the linearization of Eq.(1), derived through the Taylor power series expansion presented in Eq.(2).

The total cooling energy needed to preserve a range of indoor comfort conditions (temperature and humidity) in a building with a volume V during a time span T, in such hypothesis, is provided by the sum of three integral terms:

$$E_T = \int_T P dt = \int_T P_D dt + \int_T P_G dt + \int_T P_R dt \tag{4}$$

Expanding the three terms and introducing the geometric and thermophysical characteristics of the building, we obtain:

$$\begin{aligned} E_T = {} & U_{eq}\, S \int_T (\theta_i - \theta_e) dt + \rho\, n\, V\, c_p \int_T (\theta_i - \theta_e) d \\ & + \rho\, n\, V\, r_0 \int_T (x_i - x_e) dt - \hat{S}_R \int_T \left(I_0 - I_{0,ref}\right) dt \\ & \pm \gamma\, m_{eq}\, \bar{\theta}_i\, T \pm \delta\, M_{eq}\, \bar{\theta}_e\, T \end{aligned} \tag{5}$$

The last two terms in Eq.(5) take into account, on average, the building thermal inertia. Equation (5) can now be rewritten as:

$$\begin{aligned} \mathcal{E} = {} & \left(U_{eq}\frac{S}{V} + \rho\, n\, c_p \pm \delta \frac{M_{eq}}{V}\right)\Theta_e + \rho\, n\, r_0\, X_e + \frac{\hat{S}_R}{V}\Upsilon_e + \\ & - \left[\left(U_{eq}\frac{S}{V} + \rho\, n\, c_p \pm \gamma \frac{m_{eq}}{V}\right)\Theta_i + \rho\, n\, r_0\, X_i + \frac{\hat{S}_R}{V}\Upsilon_{ref}\right] \end{aligned} \tag{6}$$

Reflecting the structure of Eq.(2), Eq.(6) can be expressed in a denser way as:

$$\mathcal{E} = A\Theta_e + BX_e + C\Upsilon_e - \left[A'\Theta_i + BX_i + C\Upsilon_{ref}\right] \tag{7}$$

Alternatively, reflecting the structure of Eq.(3), Eq.(6) can be rewritten as:

$$\begin{aligned} \mathcal{E} & = \vec{V}_B \cdot \vec{V}_C - \vec{V}_B{}' \cdot \vec{V}_{C,ref} = \\ & = \left|\vec{V}_B\right|\left|\vec{V}_c\right| cos(\alpha - \beta) - \left|\vec{V}_B{}'\right|\left|\vec{V}_{c,ref}\right| cos\left(\alpha' - \beta_{ref}\right) \end{aligned} \tag{8}$$

Now, the meaning of all the vectors involved is known. In most cases we have noted that:

$$cos(\alpha - \beta) \cong cos\left(\alpha' - \beta_{ref}\right) \tag{9}$$

$$k(\mu) = \frac{\left|\vec{V}_B{}'\right|}{\left|\vec{V}_B\right|} \cong 1 \tag{10}$$

Climatic Severity Index (C henceforth) may be finally defined as:

$$C = \frac{\mathcal{E}}{\left|\vec{V}_B\right| cos(\alpha - \beta)} = \left|V_C\right| - k(\mu)\left|V_{C,ref}\right| \quad (11)$$

The defined *C* assesses the cooling energy need, normalized with respect to the characteristics of the building.
As a consequence, it is not affected by the characteristics of the building, with the slightly exception of the almost constant parameter β, while it is fully dependent (linearly) on the climatic variables. For these reasons, *C* could be an operative tool for a classification of the summer climatic zones of a given region.

TEST PROCEDURE OF INDEX C

In order to verify the workability and effectiveness of index *C*, an evaluation of the cooling energy need of buildings through a dynamic simulation software is necessary, changing the modulus of the two characteristic vectors, $[\vec{V}_B]$ and $[\vec{V}_C]$. Then, the derived values for *C* will be investigated.
Concerning the climatic vector $[\vec{V}_C]$, we have to consider *n* Italian sites where the cumulative climatic variables required by the developed framework, temperature, absolute humidity and solar irradiation on a horizontal surface, are available and officially acknowledged.
The Italian Standard UNI 10349 [4] meets the case: it reports for 101 Italian provincial capitals and month by month, the average air temperature, the average solar irradiation at ground level and the average partial steam pressure in the air. By processing such data, it is possible to evaluate the modulus of the climatic vector $[\vec{V}_C]$ for the 101 sites.
As regards the building vector $[\vec{V}_B]$, it is necessary to identify *m* building typologies, to be chosen among the national set of buildings: their geometric and thermophysical characteristics will lead to *m* different values of the building vector $[\vec{V}_B]$.

Sampling of test sites

From the population of the 101 towns surveyed in the Italian UNI 10349 Standard, a cluster analysis on the three standardized cumulative climatic variables has been implemented. Then, from each derived group, a unit has been selected, obtaining a representative sample of the population.
In order to consider also some units characterized by extreme values in our sample, a Ward's linkage clustering rule with a Euclidean dissimilarity measure has been adopted [5]. Table 1 shows the Duda-Hart stopping rule [5], followed to determine the optimal number of clusters: consequently, this choice has led to the size of our sample of Italian provincial capitals.
To identify the number of groups, we found one of the largest *J* values that corresponds to a low T_{pseudo}: 19 clusters have been singled out. Then a statistically representative sample of 20 Italian provincial capital has been built, adding an extra unit with average values for the analyzed variables to the 19 units from each derived group, in order to compare the results of the following simulations on it with respect to the ones from the 19 sampled towns.

Number of clusters	Duda-Hart statistics	
	J	T_{pseudo}
2	0.3917	121.14
3	0.3206	139.89
4	0.2976	94.43
5	0.2143	36.66
6	0.4014	28.34
7	0.2303	80.22
8	0.3496	40.92
9	0.2868	34.81
10	0.3188	17.10
11	0.2843	37.76
12	0.1794	64.03
13	0.2769	10.44
14	0.2251	13.77
15	0.2633	44.77
16	0.2425	24.99
17	0.2185	28.61
18	0.2132	33.22
19	0.2359	6.48
20	0.1764	9.34
21	0.2786	7.77
22	0.0103	96.56
23	0.1396	36.98
24	0.3403	19.39
25	0.1929	20.92

TABLE 1 Determination of the sample size
Source: authors' estimations

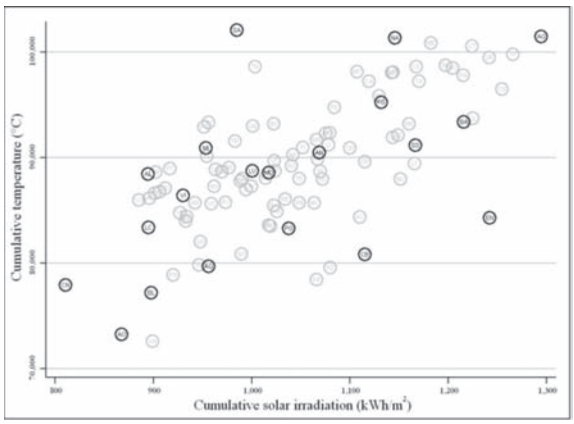

FIGURE 1 Distribution of the Italian provincial capitals
Source: authors' estimations

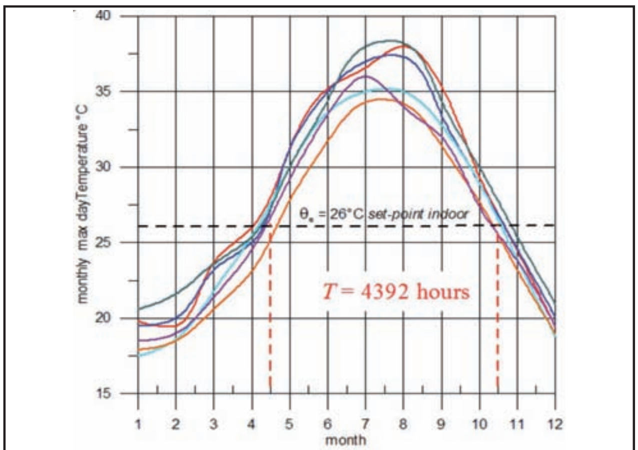

FIGURE 2 Maximum daily temperature of the six hottest Italian provincial capitals
Source: authors' estimations

Figure 1 shows the distribution of the Italian provincial capitals with respect to the cumulative solar irradiation and the cumulative temperature: sampled towns show a darker marker.

Time span *T* has been chosen from 15th April to 15th October in order to consider, also for the six hottest towns (Salerno, Agrigento, Messina, Naples, Catania and Trapani), all the hours of the year when the cooling demand might arise (Figure 2). In the subsequent simulations, the 26 °C set-point temperature for comfort climatic conditions has been assumed as the threshold corresponding to such energy need.

Choice of benchmark buildings

The computation of the energy need for cooling has been carried out on a benchmark building with a basic layout, that is a detached house single floor, with a flat roof and a brickwork load-bearing structure. A total glass surface, equal to 20% of the total vertical dissipative surface, has been assumed. Besides, the glass surface is asymmetrically distributed over the fronts of the building.

The benchmark building has been assessed under both the hypotheses of an envelope with thermal insulation (average thermal transmittance equal to 0.4 W/m^{2}K and triple glazing for the windows) and without thermal insulation (average thermal transmittance equal to 1.8 W/m^{2}K and single glazing). Under the two considered cases, the values of the overall envelope masses vary of about 15%, as reported in Table 2.

Characteristics	Thermal Insulation	NO Thermal Insulation
Net Values		
Height [m]	3	
Width [m]	10	
Depth [m]	15	
Floor [m^2]	150	
Ceiling [m^2]	150	
Doors, windows and shutters [m]	30	
Opaque vertical walls [m^2]	120	
Volume [m^3]	450	
Gross Values		
Envelope total surface [m^2]	524.5	495
Gross volume [m^3]	617.9	544.2
S/V	0.85	0.91

TABLE 2 Geometrical characteristics of the building
Source: authors' assumptions

Computation hypotheses and set-point

For the simulations, implemented thanks to the TRNsys 16 software, an ideal HVAC plant of unlimited power has been provided: it works when indoor temperature and/or humidity crosses the set-point values (26 °C and 60%, respectively). A daily non-stop plant activation is provided. Besides, the volume air change per hour has been set to 0.3 h^{-1}.

Different orientations of the benchmark building have been supposed, in order to explore the highest and lowest thermal irradiation load conditions (maximum and minimum exposure). As thermal insulation and orientation change, four configurations have been considered for a total of 80 runs of the TRNsys 16 code (4 configurations for 20 towns):

- Q_1 (No thermal insulation and maximum exposure);
- Q_2 (No thermal insulation and minimum exposure);
- Q_3 (Thermal insulation and maximum exposure);
- Q_4 (Thermal insulation and minimum exposure).

RESULTS OF THE SIMULATIONS

Results

Figure 3 depicts the simulation results for the 4 considered configurations and the 20 selected towns, in terms of the energy need for cooling E_T.

Figures 4 and 5 show the simulations concerning the two extreme configurations Q_1 and Q_4 in terms of the energy need $\mathcal{E}$ and the absolute value of the climatic vector of the towns $[\vec{V}_C]_{std}$, obtained from $[\vec{V}_C]$ with the standardization of its components with their average values on the Italian territory.

A clear linear relationship between the two considered variables has been observed for all configurations. The general expression has been modeled as:

$$\mathcal{E} = \frac{E_T}{T\,V} \cong a + b\left|\vec{V}_C\right| \tag{12}$$

Given the different characteristics of the buildings they are referred to, the estimated intercepts and slopes are not necessarily equal for all configurations.

Figure 6 shows the relative energy differences between the two cases Q_1 and Q_4, again as a function of the absolute value of the climatic vector of the towns $[\vec{V}_C]_{std}$.

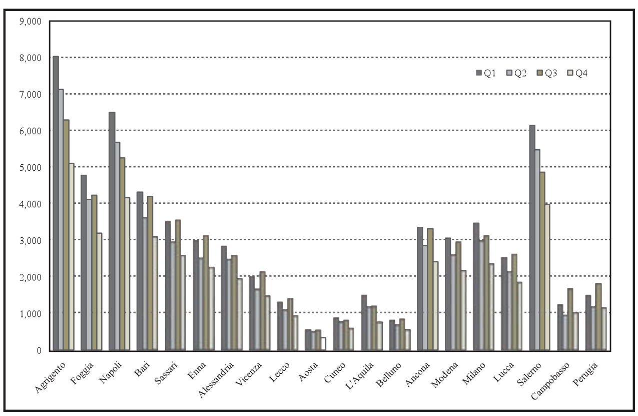

FIGURE 3 Energy need for cooling (kWh) of the 20 selected Italian provincial capitals
Source: authors' estimations

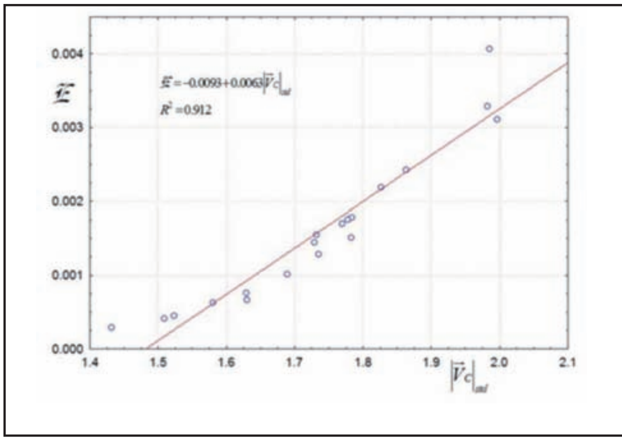

FIGURE 4 Energy need of the worst configuration Q_1
Source: authors' estimations

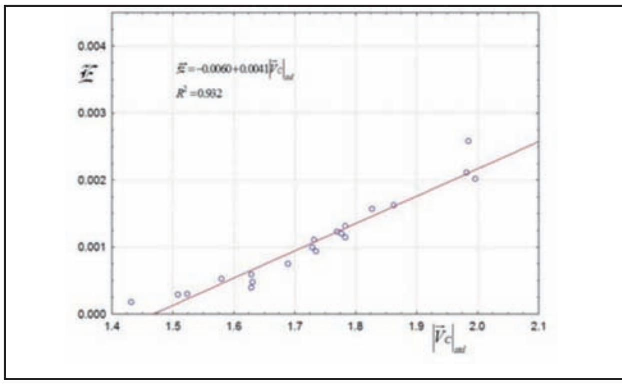

FIGURE 5 Energy need of the best configuration Q_4
Source: authors' estimations

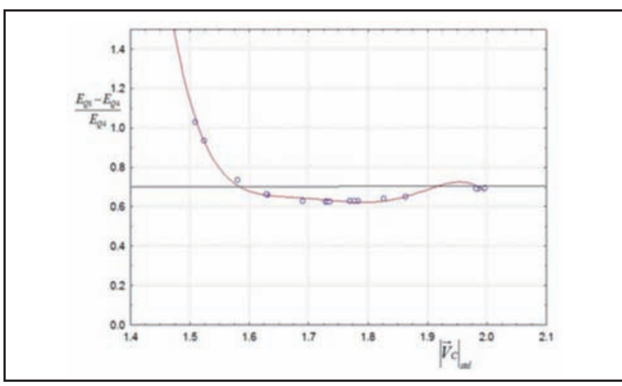

FIGURE 6 Relative difference of the energy need between configurations Q_1 and Q_4
Source: authors' estimations

The average difference for the energy need between the worst configuration Q_1 and the best one Q_4 is around 70%, confirming how building characteristics, orientation included, affect the total energy need.

Further elaborations

Index *C* can be assessed as:

$$C = \frac{\mathcal{E}}{b} \cong \left[\frac{a}{b} + \left|\vec{V}_C\right|\right] \qquad (13)$$

Estimated coefficients *a* and *b* are reported in Table 3.

Configuration	a	b	a/b
Q_1	-0.0093	0.0063	-1.476
Q_2	-0.0083	0.0056	-1.482
Q_3	-0.0071	0.0049	-1.449
Q_4	-0.0060	0.0041	-1.463

TABLE 3 Estimated coefficients

Source: authors' estimations

The meaning of the coefficients *b* and *a/b* can be derived from the comparison of Eq.(11) and Eq.(13). Indeed, coefficient *b* embodies the building characteristics $[\vec{V}_B]$ and its phase $\alpha(\beta$ is nearly constant for the 101 towns); *a/b* is proportional to $[\vec{V}_{C,ref}]$.
Figures 7 and 8 show the results derived by adopting Eq.(13) to assess the index *C*. The introduced normalization allows the convergence for the assessed values of the energy needed by buildings with different characteristics and orientations.

As a consequence, index *C* may be justly identified as the pursued Summer Climatic Severity Index, strongly dependent on the climatic parameters and slightly dependent on the building characteristics at the same time.

CLASSIFICATION OF THE ITALIAN TERRITORY

In general, a classification procedure of a continuous variable lies in the allocation of its values to a discrete scale made up of contiguous classes. Besides, the assessment of a continuous variable is affected by uncertainty, in the shape of oscillations around an average value and/or likely (measurement and/or computation) errors. All these matters lead to an evaluation of the confidence degree of the adopted classification, that is to an assessment of the probability of making no mistakes in the allocation to a class of a given value of a variable affected by uncertainty. This issue is more and more amplified for those values to be classified just close to the bounds of a class.
It can be shown [6] that, under such circumstances, the class span must be set on the basis of the expected variability with respect to the average. Besides, in order to reach a high confidence degree, the bound values of each class must be greater than (or at least equal to) twice as much the standard deviation of the variable.

The classification

As mentioned above, the original variables *C* and $[\vec{V}_C]_{std}$ may be considered as random variables. Their

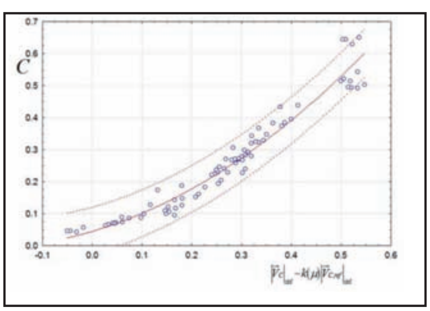

FIGURE 7 Interval of prediction (95% level) for the Climatic Severity Index C
Source: authors' estimations

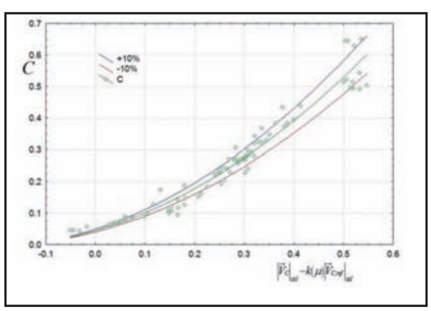

FIGURE 8 Range (±10%) of the Climatic Severity Index C
Source: authors' estimations

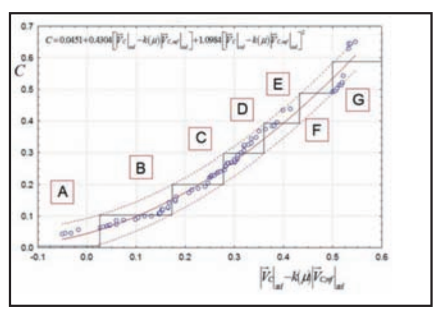

FIGURE 9 Interval of quantile-quantile prediction (95% level) for the Climatic Severity Index C

quantile functions *Q*, returning the value of the variable below which it would fall with a given probability, have been then considered. As shown in the *Q-Q* plot of Figure 9, the two variables share the same statistical distribution within intervals, which represent our pursued classes.
Seven classes have been singled out, made up of right-open intervals and marked by letters from A to G, reflecting an ascending order of the summer climatic severity, that is of the cooling energy need. Derived classes are reported in Table 4.

Class	Climatic vector range	Central value
A	< 0.025	0.015
B	0.025÷0.175	0.100
C	0.175÷0.276	0.200
D	0.276÷0.358	0.293
E	0.358÷0.430	0.391
F	0.430÷0.500	0.493
G	≥ 0.500	0.586

TABLE 4 Derived classes for the Climatic Severity Index C
Source: authors' estimations

The classification of the italian territory
Data needed for the computation of the climatic vector of only 101 Italian provincial capitals are, as afore-

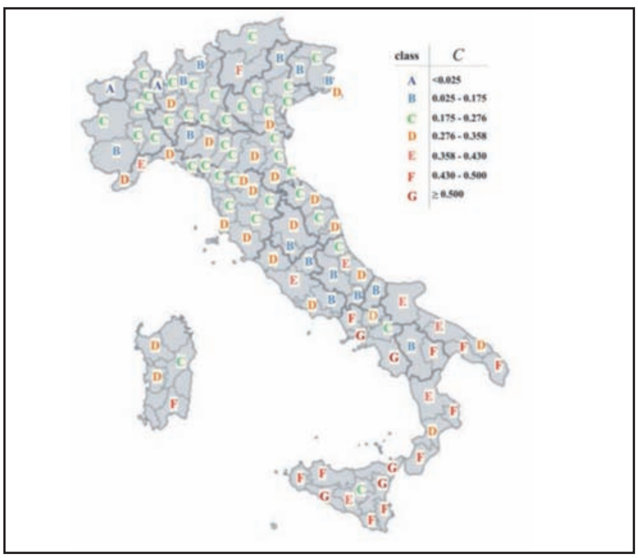

FIGURE 10 Class of Climatic Severity Index C of the Italian provincial capitals
Source: authors' estimations

Town	$[\vec{V}_C]$	Class	Town	$[\vec{V}_C]$	Class
Agrigento	0.519	G	Massa	0.256	C
Alessandria	0.263	C	Matera	0.453	F
Ancona	0.303	D	Naples	0.516	G
Aosta	-0.034	A	Novara	0.241	C
Ascoli Piceno	0.300	D	Nuoro	0.255	C
L'Aquila	0.092	B	Oristano	0.332	D
Arezzo	0.210	C	Palermo	0.447	F
Asti	0.218	C	Piacenza	0.167	B
Avellino	0.184	C	Padua	0.228	C
Bari	0.360	E	Pescara	0.387	E
Bergamo	0.237	C	Perugia	0.163	B
Belluno	0.043	B	Pisa	0.269	C
Benevento	0.327	D	Pordenone	0.076	B
Bologna	0.357	D	Prato	0.351	D
Brindisi	0.357	D	Parma	0.292	D
Brescia	0.275	C	Pesaro Urbino	0.194	C
Bolzano	0.176	C	Pistoia	0.274	C
Cagliari	0.436	F	Pavia	0.211	C
Campobasso	0.114	B	Potenza	0.090	B
Caserta	0.463	F	Ravenna	0.205	C
Chieti	0.312	D	Reggio Calabria	0.466	F
Caltanissetta	0.367	E	Reggio Emilia	0.217	C
Cuneo	0.058	B	Ragusa	0.461	F
Como	0.215	C	Rieti	0.095	B
Cremona	0.255	C	Rome	0.408	E
Cosenza	0.422	E	Rimini	0.210	C
Catania	0.501	G	Rovigo	0.279	D
Catanzaro	0.336	D	Salerno	0.530	G
Enna	0.182	C	Siena	0.235	C
Ferrara	0.251	C	Sondrio	0.115	B
Foggia	0.397	E	La Spezia	0.270	C
Florence	0.313	D	Siracusa	0.480	F
Forlì	0.340	D	Sassari	0.317	D
Frosinone	0.068	B	Savona	0.360	E
Genoa	0.353	D	Taranto	0.436	F
Gorizia	0.139	B	Teramo	0.255	C
Grosseto	0.287	D	Trento	0.463	F
Imperia	0.339	D	Turin	0.185	C
Isernia	0.169	B	Trapani	0.486	F
Crotone	0.452	F	Terni	0.325	D
Lecco	0.165	B	Trieste	0.296	D
Lodi	0.273	C	Treviso	0.241	C
Lecce	0.452	F	Udine	0.230	C
Leghorn	0.318	D	Varese	-0.047	A
Latina	0.284	D	Verbania	0.192	C
Lucca	0.269	C	Vercelli	0.209	C
Macerata	0.210	C	Venice	0.254	C
Messina	0.507	G	Vicenza	0.224	C
Milan	0.312	D	Verona	0.267	C
Mantova	0.268	C	Viterbo	0.289	D
Modena	0.266	C			

TABLE 5 Classification of the Italian provincial capitals according to the Climatic Severity Index C
Source: authors' estimations

mentioned, now available and acknowledged by current Italian Standard (UNI 10349). Table 5 shows the results for the adopted classification, applied to Italian provincial capitals.
Figure 10 depicts the Italian provincial capitals according to their derived class for index *C*.

CONCLUDING REMARKS AND FURTHER DEVELOPMENTS

The proposed index *C* defines a relative scale thanks to which the energy need for cooling, normalized with respect to the building characteristics, may be assessed.
Some concluding remarks may be drawn:

1) A comparison with the currently adopted index concerning the winter air conditioning, that is the Heating Degree Day, is direct: remembering that it does not take into account neither the irradiation nor the air humidity effects, it provides a normalized measure of the heating energy need, establishing a relative scale. In this case, the normalization factor, that is the absolute value of the building vector $[\vec{V}_B]$, is reduced to the winter predominant component: the transmittance of the building envelope.
2) The suggested classification lies on climatic data of a number of different towns: if data are not accurately interpolated and/or their measurements are not congruent with respect to different areas of the territory, the consequent classification may result misleading. Hence, the need of an appropriate update and harmonization of data arises.
3) Another crucial and consequent development of the present work stems from the matter that index *C* is symmetrical with respect to the air conditioning season. Indeed, it is effective both for the summer and the winter cases.
4) As a consequence of the previous point, a classification of the Italian territory for the winter season also seems to be desirable on the basis of the developed index *C*. This way, the shortcomings of the currently adopted Heating Degree Day system might be gathered in, with particular attention to those towns where the free contribution of solar irradiation is remarkable.

CONCLUSIONS

Through a numerical experiment, implemented thanks to a dynamic computation TRNsys 16 code, the energy need for cooling buildings has been evaluated, considering different configurations for transmittance, mass and orientation of the benchmark building.
Then, the developed framework for the derivation of the Summer Climatic Severity Index has been applied to a sample of 20 Italian provincial capitals, chosen to represent the population of 101 towns for which climatic data were available and acknowledged by the current Italian Standard (UNI 10349). It has been proved that it was a statistically representative sample.
Results of the numerical experiment have been used for the classification of 101 Italian provincial capitals on the basis of the derived Summer Climatic Severity Index.
This first applicative step warmly suggests a follow-up of the work, and the extension of the developed framework to the winter case.

ACKNOWLEDGEMENTS

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