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IMPACT OF SOLAR IRRADIATION MODELS ON SIMULATED HOURLY ENERGY PERFORMANCE OF BUILDINGS

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ABSTRACT

This research work investigates the impact of the choice of solar irradiation models on the hourly energy needs, considering 72 simplified reference buildings in two European climates: Rome and Vienna. The full combination of 22 horizontal diffuse irradiance models and 12 irradiance models for tilted surfaces has been considered for the development of hourly solar irradiation profiles, used as input in building energy simulation (i.e., TRNSYS). The results highlight that the variability of input solar irradiation leads to different levels of uncertainty in energy model predictions also depending on the building characteristics.

INTRODUCTION

In Building Energy Simulation (*BES*) an accurate calculation of the solar irradiation incident on each surface of the envelope is essential in order to estimate solar heat gains or to perform daylight studies. In most of meteorological stations, only global solar irradiation on a horizontal plane is recorded and only some stations measure horizontal beam and diffuse components. Moreover, an even more limited number of stations monitor also the solar irradiation incident on tilted surfaces. For these reasons, a variety of mathematical and empirical models have been developed and proposed in the literature for both the subdivision of horizontal solar irradiation into beam and diffuse components (*horizontal diffuse irradiance models*) and for the estimation of irradiation on tilted surfaces (*irradiance models for tilted surfaces*).

Nevertheless, since these models have been developed from the experimental data of specific locations, none can provide the same reliability worldwide. This issue is well known in the literature and some authors assessed some models with experimental data for different locations with respect to those used in their definitions (Dervishi and Mahdavi, 2012). However, the uncertainty of *BES* output can be different, depending on either the building characteristics or the considered climatic conditions. As a consequence, changes on the building energy labelling, suboptimal definitions of the energy system controls and incorrect optimizations of the retrofit measures can arise (Prada *et al.*, 2015).

In this research work, the uncertainty on the predicted hourly energy performance due to the choice of solar irradiation models has been investigated. A set of 72 simplified reference buildings has been defined by changing insulation and thermal inertia of opaque components, windows' surface and orientation and kind of glazing, focusing on the solar heat gain coefficient (*SHGC*). 22 *horizontal diffuse irradiance models* have been coupled with 12 *irradiance models for tilted surfaces*, obtaining 264 combinations. The generated hourly profiles of solar irradiance have been used to perform *BES* with TRNSYS. Two European locations have been selected for this analysis: Rome, with a climate dominated by cooling demand, and Vienna, with a climate characterized by high heating demand. Finally, the uncertainty distributions of hourly heating and cooling energy needs have been discussed, also by means of statistical techniques, in order to correlate the differences of energy performance prediction to the building envelope features.

METHODS

The procedure adopted in this work consists of two steps. First, the hourly solar irradiation incident on vertical surface has been evaluated for each orientation and for any couple of models. Then, heating and cooling energy needs distributions have been calculated for each reference building and then analysed.

Solar irradiance models

In this research, 22 *horizontal diffuse irradiance models* have been selected. Firstly, the analysis has focused on the key-models presented in the literature, such as those by Orgill and Hollands (1977), Erbs *et al.* (1982), Muneer *et al.* (1984), Spencer (1982), Skartveit and Olseth (1987), the three models by Reindl *et al.* (1990a) and that by Boland *et al.* (2008). Some other models have been considered. These are based on the correlations of the previous researches, with some modifications introduced to adjust the correlations to specific climates and sky conditions (Hawlader, 1984; Maxwell, 1987; the three models by Perez *et al.*, 1992; the two models by Chendo and Maduekwe, 1994; Chandrasekaran and Kumar, 1994; Lam and Li, 1996; De Miguel *et al.*, 2001; Oliveira *et al.*, 2002; Karatasou *et al.*, 2003; Soares *et al.*, 2004).

As regards the *irradiance models for tilted surfaces*, 12 models, including both the isotropic and the anisotropic ones, have been considered: the models by Liu and Jordan (1960), Temps and Coulson (1977), Burgler (1977), Klucher (1978), Hay and Davies (1980), Skartveit and Olseth (1986), Reindl *et al.* (1990b), Ma and Iqbal (1983), Gueymard (1986), Perez *et al.* (1990) and the two models by Muneer (2006).

Building configurations and climates

The effects of solar irradiation estimation on the energy performance of building has been assessed by repeating *BES* with any couple of solar models on a set of simplified buildings. These buildings are not necessarily representative of the European building stocks but they have been selected because of the wide range of sensitivities to the external environment solicitations and of their suitability for weather data analyses (Pernigotto *et al.*, 2014).

The base module consists of a single, square thermal zone with an area of 100 m^2 and an internal height of 3 m with the façades oriented towards the main cardinal directions. Thermal bridges are neglected and the floor is modelled as a crawl space. All the opaque components are modelled as a two-layer structure with insulation on the external side and with two alternatives for the massive layer (i.e., timber or concrete), whose thermal resistance is around 0.8 m^2 K W^{-1}. The insulating layer, polystyrene, has a thermal conductivity of 0.04 W m^{-1} K^{-1}, a specific heat capacity of 1470 J kg^{-1} K^{-1}, a density of 40 kg m^{-3}. The thermal conductivity, the specific heat capacity, the density and the thickness of the massive layers are, respectively, 0.13 W m^{-1} K^{-1}, 1880 J kg^{-1} K^{-1}, 399 kg m^{-3} and 0.10 m for the timber and 0.37 W m^{-1} K^{-1}, 840 J kg^{-1} K^{-1}, 1190 kg m^{-3} and 0.30 m for the concrete. The solar absorptance is 0.3 for both sides of the vertical walls and for the internal side of the roof, 0.6 for the external side of the roof and the internal side of the floor and 0 for the external side of the floor. The windows, positioned all on the same façade, consist of a double-pane glazing with a thermal transmittance, U_{gl}, equal to 1.1 W m^{-2} K^{-1} and a timber frame, whose transmittance, U_{fr}, is equal to 1.2 W m^{-2} K^{-1} and whose area is 20 % of the whole window area. The internal gains are assumed equal to 4 W m^{-2}, half radiative and half convective, as indicated by the EN ISO 13790 (CEN, 2008) for residential dwellings. A constant ventilation rate of 0.3 air changes per hour is considered, as suggested by the Italian technical specification UNI/TS 11300-1:2014 (UNI, 2014).

In each construction typology, the building configurations differ each other for insulation level (5 cm or 15 cm of polystyrene, i.e., with thermal transmittances of the vertical walls, U_{vw}, equal to, respectively, 0.45 W m^{-2} K^{-1} or 0.21 W m^{-2} K^{-1}), thermal inertia of the opaque components (area specific internal heat capacity κ_i equal to 75 kJ $m^{-2}K^{-1}$ for the timber structure and to 300 kJ m^{-2} K^{-1} for the concrete), size of windows (A_{win} = 14.56 m^2 or 29.12 m^2), orientation (East, South or West) and typology (*SHGCs* equal to 0.35, 0.49 or 0.61). This leads to a definition of a set of 72 simplified buildings, in accordance with a full factorial plan.

In each configuration, an ideal system has been used in order to provide all the power needed to maintain the zone internal air temperature between the heating and the cooling setpoints of 20 °C and 26 °C. Two locations have been considered: Rome, Italy (Köppen classification: Cfa; heating degree-days with 18 °C as base temperature HDD_{18} = 1444 K d; cooling degree-days with 18 °C as base temperature CDD_{18} = 649 K d) and Vienna, Austria (Köppen classification: Dfb; HDD_{18} = 3158 K d; CDD_{18} = 223 K d). In order to simplify the analysis of the results, for both locations the same heating and cooling seasons have been considered, delimited by 1st October and 31st March.

Analysis of the hourly needs

For every building configuration and climate, 264 series of hourly energy needs were calculated, from which an hourly median is identified. When its value is larger than a minimum of 0.1 kWh, the median is used as reference for the evaluation of the discrepancy given by the different solar irradiation models, otherwise the series is neglected. A threshold of 10 % of deviation from the median was assumed as the criterion to categorise each hour into four performance classes. A given hour belongs to class "A" when more than 75 % of models ensure a heating or cooling demand deviation within 10 % from the series median (i.e., more than 198 models), "B" when the percentage is between 50 % and 75 % (i.e., between 132 and 198), "C" between 25 % and 50 % (i.e., between 66 and 132) and "D", when less than 25 % models satisfy the 10 % deviation target (i.e., less than 66 models). The time-distributions of the four classes are analysed, considering their variations during the day and the season and the differences among the building configurations. Then, for each building configuration, the percentage annual occurrence of each category (i.e., the normalized frequency) is calculated with respect to the number of annual heating or cooling hours. In order to allow a direct and overall comparison between the buildings, comprehensive of the long-term performance, also the annual energy needs, calculated by summing the hourly median needs, have been normalized, with respect to the ones of the configuration with highest energy demand.

For each climate and separately for heating or cooling, the normalized frequencies of the four categories have been analysed through inferential statistics in order to identify linear correlations with the building characteristics and generalize the findings. For this purpose, the Pearson's product-moment index, r, has been chosen. Pearson's index varies from -1 to +1 and the sign indicates a direct (+) or negative (-) correlation. When $|r|$ =1, Pearson's index indicates a perfect linear correlation. Generally, a $|r|$ < 0.3

indicates a weak or even null linear correlation, between 0.3 and 0.7 a moderate and $|r| > 0.7$ a strong linear correlation. In addition to r, the p-value is computed, considering a significance level of 1 %. A not statistically significant p-value indicates the impossibility of discussing the linear relationship and generalizing the results with the desired significance level.

RESULTS AND DISCUSSION

Hourly heating needs

Large differences are found among the building configurations of the sample and between the two locations. As regards the number of hours with heating need and consequently evaluated, in Rome, it ranges from a minimum of 339 h (i.e., configuration with large South-oriented windows with high *SHGC* and well-insulated concrete walls) to a maximum of 3609 h (i.e., configuration with small West-oriented windows with low *SHGC* and poorly insulated concrete walls). The average value is 2524 h in the building sample. In Vienna, the minimum is 3156 h for a building configuration similar to the one found for Rome but with a timber structure, and the maximum is 4329 h, for the same configuration as for Rome. The average value is 3959 h.

The time-distributions of the four categories along the year are reported in Figure 1 for the building configurations described above. As a whole, the class "A" has the highest number of occurrences. The other classes are characterized by a lower magnitude. "C" and "D", in particular, occur for few hours when the heating need is close to zero. Typically, this happens at the beginning and at the end of the heating season and in morning and evening hours. In Rome, the category "A" shows a normalized frequency of 0.67 of the heating time as average for the set of building configurations, ranging from a minimum of 0.10 to a maximum of 0.95 - which correspond, respectively, to the case with the minimum total number of heating hours and to the one close to the maximum. In Vienna, with a climate dominated by heating needs, the results are different: as average, 0.91 of heating hours belong to the category "A", ranging from 0.63 to 0.99. Also in this climate, the lowest normalized frequency is found for a building configuration close to the minimum number of heating hours – specifically, the building with large South-oriented windows with high *SHGC* and well-insulated concrete walls – and the highest normalized frequency is for the case with the maximum number of heating hours. The uncertainty due the choice of the solar irradiation models depends strongly on the number of heating hours, which is function of climate and building characteristics. When the number of heating hours is low (e.g., for configurations in Rome with large South-oriented windows with high *SHGC* and well-insulated envelope) there is larger sensitivity to the solar irradiation models.

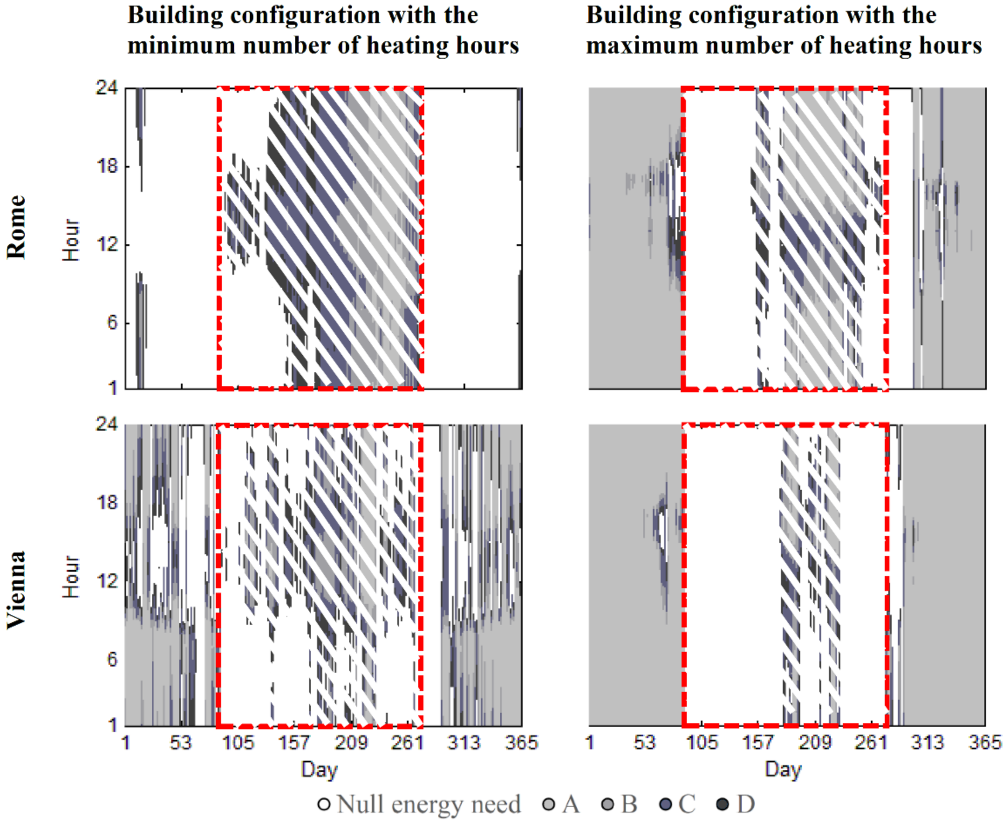

Figure 1 Time-distributions of the four deviation classes (A, B, C, D) for the building configurations with minimum and maximum number of heating hours in Rome and Vienna during the heating season. The cooling season, which is not considered in these graphs, corresponds to the striped area enclosed by the red dotted line.

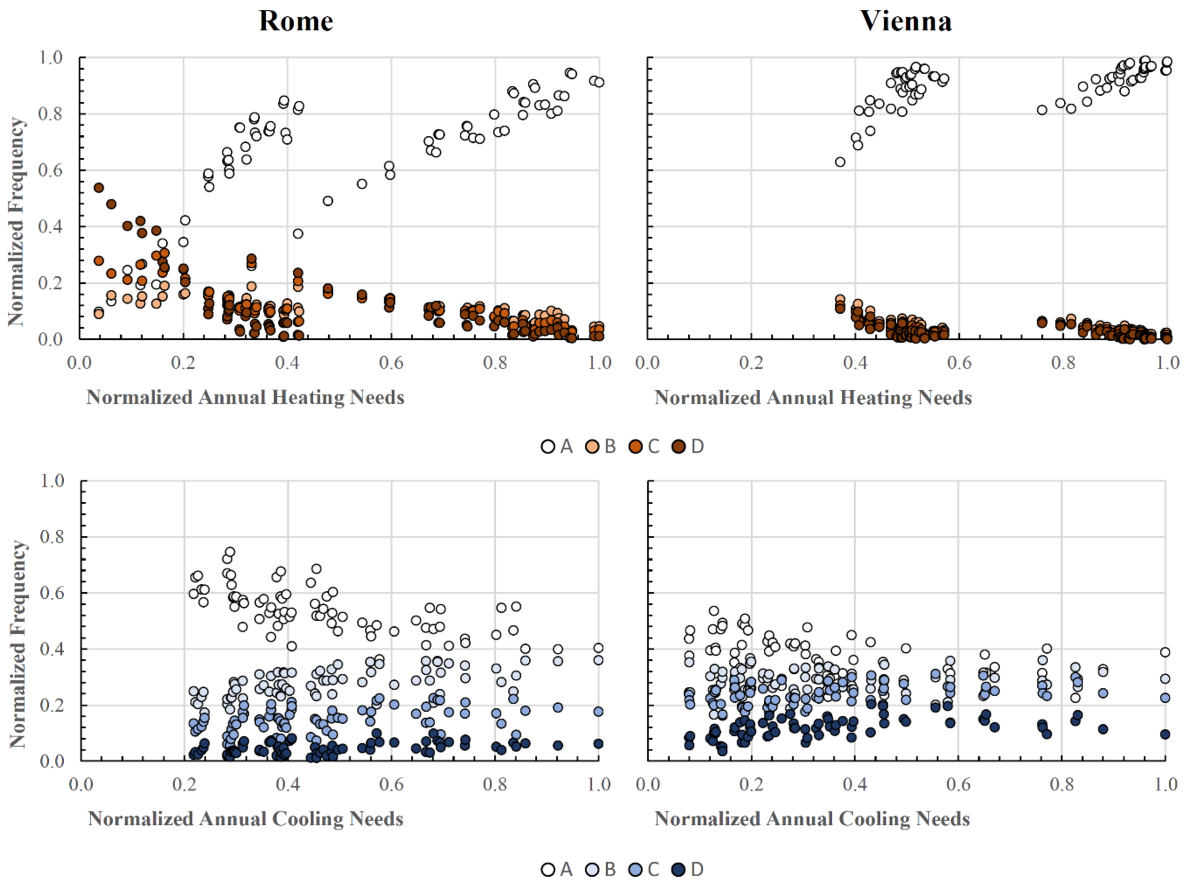

Figure 2 Normalized frequencies for the heating needs (top) and for the cooling needs (bottom) with respect to the normalized annual heating and cooling energy needs of the building configuration in Rome and Vienna.

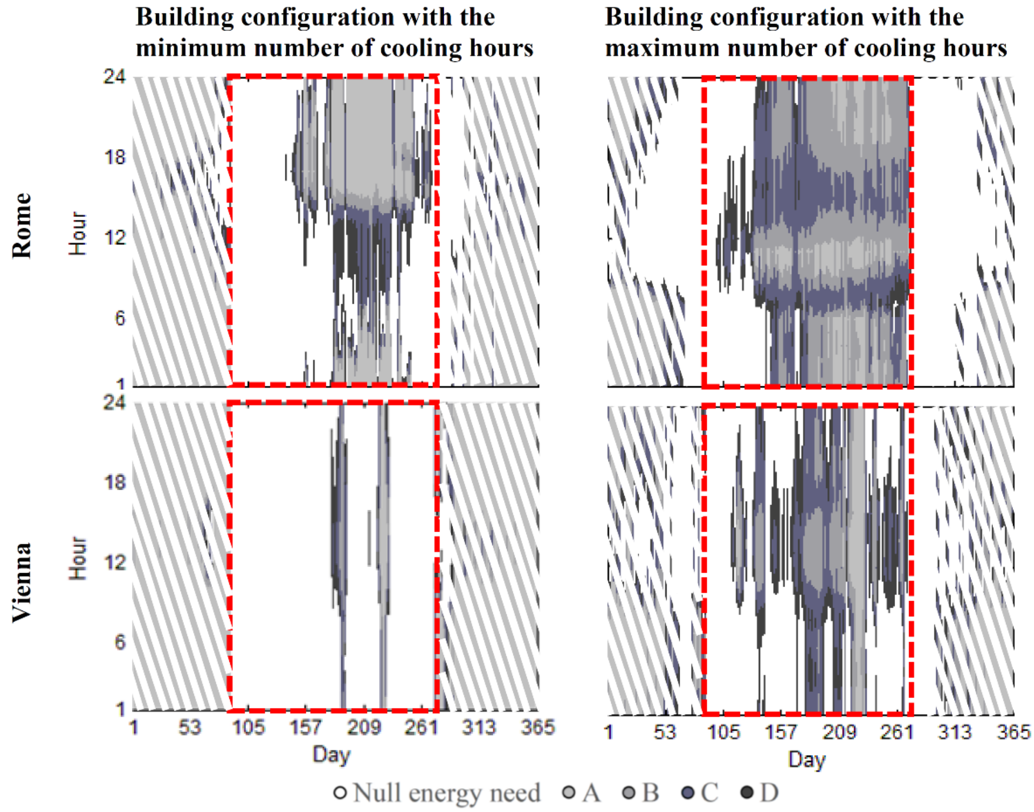

Figure 3 Time-distributions of the four deviation classes (A, B, C, D) for the building configurations with minimum and maximum number of cooling hours in Rome and Vienna during the cooling season. The striped area outside the red dotted lines corresponds to the heating season, which is not considered in these graphs.

As expected, a similar behaviour can be seen also comparing the normalized occurrences with the normalized annual heating needs (Figure 2 on the top). In Rome, the building configuration with the highest annual heating needs (i.e., 43.8 kWh m^{-2} yr^{-1}) has small West-oriented windows with low *SHGC* and poorly insulated timber walls. In Vienna, the configuration with the highest heating needs (i.e., 111.4 kWh m^{-2} yr^{-1}) has the same characteristics but East-oriented windows. In both climates, two different trends can be distinguished, according to the insulation level. The well-insulated buildings have normalized annual heating needs ranging from nearly 0 to 0.42 for Rome and between 0.37 and 0.57 for Vienna while the poorly insulated are larger than, respectively, 0.42 and 0.76. The normalized frequency of the category "A" is always larger than 0.6 in Vienna and, in particular, the poorly insulated buildings have frequencies always larger than 0.8. In Rome, on the contrary, some configurations with lower frequencies can be found. For each building, the frequency of category "A" is also a function of its windows properties: larger windows, higher *SHGC* and South orientation make the value drop and the frequencies of the other categories increase.

Hourly cooling needs

As far as the cooling needs, in Rome climate, the sample of buildings has an average number of cooling hours of 2754 h, with a minimum of 1923 h (i.e., the building configuration with small West-oriented windows with low *SHGC* and poorly insulated timber walls) and a maximum of 3576 h (i.e., the one with large West-oriented windows with high *SHGC* and well-insulated concrete walls). In Vienna, the average value is 1269 h, the minimum 486 h (i.e., the case with small South-oriented windows with low *SHGC* and poorly insulated concrete walls) and the maximum 2436 h (i.e., the building configuration with large South-oriented windows with high *SHGC* and well-insulated concrete walls).

Figure 3 illustrates the time-distributions of the four classes for the above-mentioned configurations. In contrast to the heating season, in the cooling one the normalized frequency of the category "A" is more limited, especially in Vienna. In Rome, even if the "A" class is still the most important, its magnitude is lower if compared to the findings of the heating season. In Vienna, in particular, it becomes comparable with the categories "B" and "C". The main building characteristic affecting the time-distribution of the categories is the windows' orientation, as showed for example in Figure 4. Considering the building configurations with East-oriented windows, categories "C" and "D" are more frequent at dawn and in the afternoon while they are more common in the morning for cases with West-oriented windows. The building configurations with South-oriented windows, instead, have a more homogeneous time-distribution of the categories during the daytime. For all orientations, categories "C" and "D" are more frequent at the beginning and at the end of the cooling season, especially in May and June for cases with South-oriented windows. These time-distributions are coherent with the findings of previous works (Prada *et al.*, 2014a), in which the authors assessed the effects of orientation on the agreement between the irradiation profiles of the different solar models.

For Rome, the average incidence of the category "A" is 0.53 of cooling hours, ranging from 0.36 (i.e., for the configuration with large East-oriented windows with high *SHGC* and poorly insulated timber walls) to 0.75 (i.e., for the configuration with small East-oriented windows with low *SHGC* and well-insulated concrete walls). The averages of the other groups are, respectively, 0.27 for "B", 0.15 for "C" and 0.05 for "D". For Vienna, the class "A" is smaller (0.36 as average) and "B" and "C" have similar sizes (respectively, 0.28 and 0.24). The category "A" ranges from a minimum of 0.20 (for the same case found for Rome) to a maximum of 0.54 (i.e., the configuration with small West-oriented windows with low *SHGC* and poorly insulated concrete walls).

Finally, the normalized frequencies are compared to the normalized annual cooling needs (Figure 2 on the bottom). In Rome climate, the configuration used for the normalization has an annual cooling need of 61.7 kWh m^{-2} yr^{-1}, large South-oriented windows with high *SHGC* and well-insulated timber walls. In Vienna, the building with the worst cooling performance is the same and it is characterized by 32.9 kWh m^{-2} yr^{-1}. Differently from the heating need analysis, it is not possible to distinguish clearly some groups of buildings in the comparison between normalized frequencies and normalized annual cooling energy needs. However, we can observe that those buildings with lower cooling needs, often characterized by small West-oriented windows with low *SHGC*, have higher frequencies for the "A".

Statistical analysis

Looking at the heating need results (Table 1), the correlation scheme is the same for the four classes in both climates. The strongest linear relationship is found with the South-oriented windows, followed by the other orientations, the window's size and the thermal transmittance of the opaque envelope. South orientation of windows and their size have a negative relationship with the frequency of the category "A" while, for the thermal transmittance of the opaque envelope, the correlation is direct. For the other categories, instead, the opposite is true. The findings of both cities are similar but, in Vienna, the *SHGC* correlation index is slightly larger. For the cooling needs (Table 1), the correlations with each single building characteristics are less marked, as observed also before in the descriptive analysis. The windows' area is the most important variable and it has negative linear relationship with the normalized frequency of category "A" and positive for the others, as it can be seen also in Figure 4. *SHGC* has a similar behaviour but with minor magnitude. The orientation of windows and the parameters of the opaque envelope have not a clear trend of relationships in the different categories. In particular, as regards the orientation, this is probably because this parameter influences more the time-distribution and affects the value of the normalized frequency in interaction with the other variables describing the windows. As a whole, the inferential statistics confirm what has been already observed in the description of the results. The buildings with large South-oriented windows with high *SHGC* have hourly heating needs more sensitive to the choice of solar irradiation models. This can be a relevant issue for well-insulated configurations, for which the uncertainty has a larger relative impact. Regarding the hourly cooling needs, the size of the windows controls the impact of the choice of solar models, and, in interaction with the other windows' properties, *SHGC* and orientation, can maximize the uncertainty. These findings seem to be consistent with those of some previous works (Prada *et al.*, 2014b), focused on the spread of energy needs instead of the respect of a given tolerance and on a larger time-discretization (i.e., monthly).

CONCLUSION

In this work, we investigated how the choice of solar irradiation models from 264 alternatives present in the literature can affect the reliability of *BES* in the elaboration of hourly results. Considering a tolerance level of 10 % of deviation from the median, the fraction of solar models combinations leading to an acceptable deviation was estimated considering a set of simplified buildings and two European climates, Rome and Vienna. Regarding the hourly heating needs, for both locations and most of buildings, more than 75 % of the combinations of solar models lead to hourly heating needs within 10 % with respect to the median of the whole group of models. However, this fraction appears to be function of the length of the heating time, which is also dependent on the climate and the building characteristics. Buildings with large South-oriented windows with high *SHGC* are more sensitive to the choice of solar models, especially if they are well-insulated. Moreover, along the year, morning and evening hours, as well as days close to the beginning and to the end of the heating season have a large sensitivity. As concerns the hourly cooling needs, the impact of the choice of solar models is higher. Typically, less than half of the cooling hours are characterized by 75 % of solar irradiation models leading to satisfaction of the 10 % deviation criterion. The most influencing building variable in the uncertainty propagation is the windows' size, whose effect can be both enhanced by high *SHGC* and influenced by its orientation. In particular, the last variable affects significantly the time-distribution of the uncertainty: with East-oriented windows, the largest uncertainty is found in the afternoon while, with West-oriented ones, it is observed in the morning. In conclusion, this work allows to observe that:

- Even if for most of the time a large number of the assessed solar models bring to consistent estimations of the hourly needs, the uncertainty propagation is strongly influenced by building characteristics and varies along the year. For well-insulated buildings and for those maximizing the passive solar gains, the simulated hourly heating needs have the largest relative uncertainty, but the choice of solar models has an acceptable impact.
- For the simulation of the cooling needs, instead, the hourly output can be significantly different for more occurrences and, for each climate, the models with the best capabilities in modelling the local solar irradiation hourly profiles should be identified for the use in *BES*.

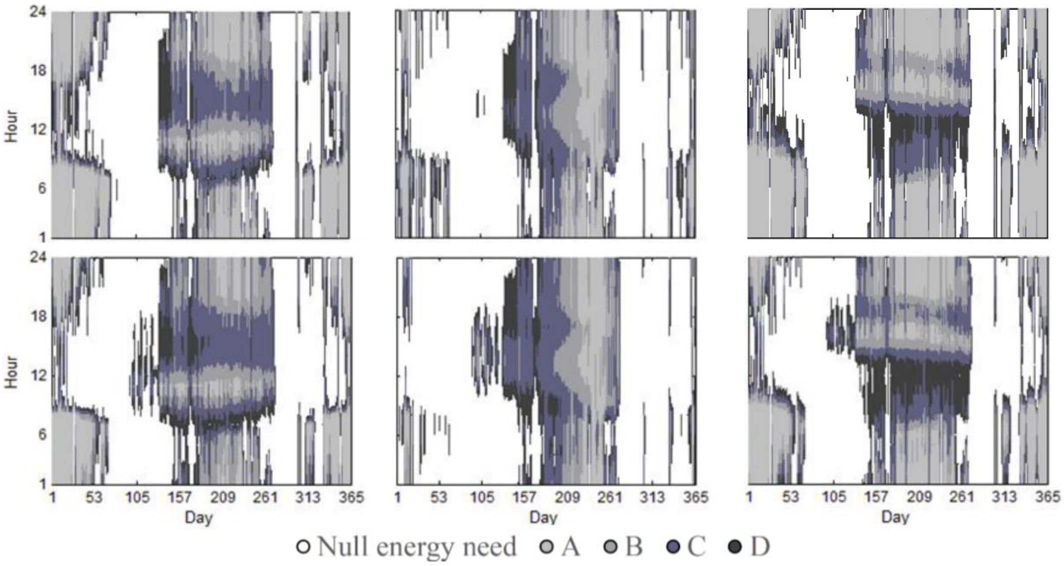

Figure 4 Time-distributions of the four deviation classes (A, B, C, D) for the building configurations with small (on the top) and large windows (on the bottom) with high SHGC, well-insulated timber walls in Rome climate: East (left), South (centre) and West-oriented windows (right).

Table 1

Pearson' product-moment indexes. In grey the linear relationship with index larger than 0.3 and statistically significant p-value. SHGC indicates the solar heat gain coefficient, A_{win} the window area, κ_i the specific internal heat capacity and U_{vw} the thermal transmittance of walls.

Normalized Frequency				*SHGC*	*Windows orientation*			A_{win}	κ_i	U_{vw}
					East	*South*	*West*			
Heating needs	*Rome*	*A*	*r*	-0.26	0.37	-0.72	0.35	-0.36	-0.06	0.41
			p-value	0.03	< 0.01	< 0.01	< 0.01	< 0.01	0.61	< 0.01
		B	*r*	0.27	-0.25	0.47	-0.22	0.42	-0.03	-0.47
			p-value	0.02	0.03	< 0.01	0.07	< 0.01	0.79	< 0.01
		C	*r*	0.25	-0.37	0.69	-0.33	0.31	0.10	-0.45
			p-value	0.03	< 0.01	< 0.01	< 0.01	< 0.01	0.39	< 0.01
		D	*r*	0.23	-0.36	0.72	-0.36	0.31	0.06	-0.31
			p-value	0.06	< 0.01	< 0.01	< 0.01	< 0.01	0.64	< 0.01
	Vienna	*A*	*r*	-0.31	0.36	-0.67	0.30	-0.43	0.05	0.38
			p-value	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.65	< 0.01
		B	*r*	0.33	-0.35	0.61	-0.27	0.45	-0.06	-0.43
			p-value	< 0.01	< 0.01	< 0.01	0.02	< 0.01	0.63	< 0.01
		C	*r*	0.31	-0.37	0.67	-0.30	0.42	-0.03	-0.39
			p-value	< 0.01	< 0.01	< 0.01	0.01	< 0.01	0.79	< 0.01
		D	*r*	0.27	-0.37	0.71	-0.34	0.41	-0.07	-0.31
			p-value	0.02	< 0.01	< 0.01	< 0.01	< 0.01	0.57	< 0.01
Cooling needs	*Rome*	*A*	*r*	-0.37	-0.07	-0.16	0.23	-0.68	0.32	-0.23
			p-value	< 0.01	0.54	0.20	0.05	< 0.01	< 0.01	0.06
		B	*r*	0.30	0.33	0.19	-0.52	0.52	0.12	-0.14
			p-value	0.01	< 0.01	0.11	< 0.01	< 0.01	0.34	0.23
		C	*r*	0.29	-0.19	0.07	0.12	0.51	-0.50	0.42
			p-value	0.01	0.11	0.54	0.32	< 0.01	< 0.01	< 0.01
		D	*r*	0.21	-0.12	0.02	0.10	0.48	-0.56	0.44
			p-value	0.08	0.33	0.86	0.43	< 0.01	< 0.01	< 0.01
	Vienna	*A*	*r*	-0.35	-0.54	0.31	0.23	-0.62	-0.14	-0.09
			p-value	< 0.01	< 0.01	< 0.01	0.05	< 0.01	0.26	0.45
		B	*r*	0.10	0.73	-0.21	-0.52	0.12	0.39	-0.31
			p-value	0.39	< 0.01	0.08	< 0.01	0.31	< 0.01	< 0.01
		C	*r*	0.28	0.33	-0.17	-0.16	0.61	0.07	0.23
			p-value	0.02	< 0.01	0.15	0.19	< 0.01	0.56	0.05
		D	*r*	0.37	-0.03	-0.25	0.28	0.61	-0.25	0.34
			p-value	< 0.01	0.80	0.04	0.02	< 0.01	0.04	< 0.01

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