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International High Performance Buildings Conference
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2016

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Solar Irradiance Modelling and Uncertainty on Building Hourly Profiles of Heating and Cooling Energy Needs

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ABSTRACT

Building energy simulations require a detailed characterization of the boundary conditions to solve the air heat balance problem. For dry and dew bulb temperatures and wind speed, measured hourly profiles can be easily included in weather files. On the contrary, beam and diffuse solar irradiance values incident on the building envelope are not directly available. This requires the adoption of solar irradiance models, which are often based on statistical correlations derived from empirical data. Since the samples of solar irradiance measurements used for the models development have been collected mostly in North America and European localities, no model can provide an adequate worldwide representativeness or be precisely defined as the best one. In this research we investigate the impact of the choice of solar irradiation models on simulated hourly energy needs in five European climates (Berlin, Vienna, Trento, Rome and Messina). 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) for a set of 72 simplified reference buildings. The results show that the variability of the estimation of solar irradiation leads to different levels of uncertainty in hourly energy model predictions, also depending on the building characteristics.

1. INTRODUCTION

Building Energy Simulation (*BES*) can be exploited for different purposes, ranging from energy to thermal and visual comfort analyses. Especially for multi-objective studies integrating and optimizing concurrent goals, the solar irradiation incident on the building envelope requires an accurate estimation. However, only global solar irradiation on a horizontal plane is usually recorded in most of meteorological stations and just in few cases horizontal beam and diffuse components are measured separately. Moreover, the solar irradiation incident on tilted planes is monitored rarely and only for some orientations of particular interest, such as for south-oriented surfaces. For all these reasons, empirical and mathematical models have been developed and included in *BES* codes. The variety of models proposed in the literature can be grouped into those aiming to distinguish the horizontal solar irradiation into beam and diffuse components (*horizontal diffuse irradiance models*) and those used to calculate the irradiation on tilted surfaces (*irradiance models for tilted surfaces*).

Every model has been developed trying to minimize the differences seen by contrasting with experimental data collected in specific locations. For this reason, constant and accurate reliability cannot be taken for granted by changing location and climate. In the literature, this issue is well-known and some research groups assessed the capabilities of some models by comparison with experimental data of locations different with respect to those used in their definitions in order to make some considerations about the best model for a given locality (Dervishi and Mahdavi, 2012). The uncertainty of *BES* output can be affected in different ways: some building characteristics can emphasize the inaccuracies of the solar irradiation models and some climatic conditions can be more sensitive to the selected model. Consequences concerns imprecisions of building energy labelling, unsuitable sizing of the energy system controls and incorrect optimizations of the retrofit measures (Prada *et al.*, 2015).

Further expanding previous analyses, in this research work we investigated the effect of the choice of solar irradiation models on the uncertainty of the predicted hourly energy performance. 22 *horizontal diffuse irradiance models* were coupled with 12 *irradiance models for tilted surfaces* in order to develop hourly profiles of solar irradiance for 5 European localities (Berlin, Vienna, Trento, Rome and Messina). The 264 alternatives were used as input in TRNSYS for the simulation of the hourly energy performances of a set of 72 simplified residential buildings, built varying parametrically insulation and thermal inertia of opaque components, windows surface and orientation and solar heat gain coefficient of glazing. The distributions of hourly heating and cooling energy needs along the year and for the different configurations in the sample were studied in order to identify the building features enhancing the uncertainty due to the solar irradiance modelling on short-term outputs.

2. METHODS

The procedure followed in the current research work is based on two phases. In the first one, the hourly solar irradiation profiles were elaborated in order to get all inputs necessary to run *BES*: for any couple of models, the irradiation was evaluated for each vertical surface and orientation. Then, for each building in the sample, the hourly distributions of heating and cooling energy needs were calculated and analyzed.

2.1 Solar irradiance models

In this research, we selected 22 *horizontal diffuse irradiance models* and 12 *irradiance models for tilted surfaces*. As regards the first group, the analysis included models presented in the literature as milestones, 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). Other models, based on the correlations of the previous researches, were considered as well. These further models often implement some modifications to those listed above in order 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 12 *irradiance models for tilted surfaces*, both isotropic and anisotropic models were 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).

2.2 Building configurations and climates

BES were repeated with any couple of solar models on a set of simplified buildings, with the aim of understanding the effects of solar irradiation estimation on the energy performance of buildings. The set of buildings was not defined to represent the actual European building stocks but to catch a sufficiently wide range of sensitivities to the external environment solicitations (Pernigotto *et al.*, 2014).

Each simplified building consists of a square thermal zone with a floor area of 100 m^2, an internal height of 3 m and the façades oriented towards the main cardinal directions. The floor is modelled as a crawl space and the thermal bridges are neglected. For each case, all windows are positioned on the same façade and the transparent area is 80 % of the whole window's area. Both sides of the vertical walls and the internal side of the roof have a solar absorptance of 0.3 while the external side of the roof and the internal side of the floor have 0.6.
All opaque components have the same composition, characterized by a two-layer structure with insulation on the external side and a massive layer whose thermal resistance is around 0.8 m^2 K W^{-1}. The insulating layer is polystyrene (thermal conductivity: 0.04 W m^{-1} K^{-1}; specific heat capacity: 1470 J kg^{-1} K^{-1}; density 40 kg m^{-3}) while the massive layer can be timber (thermal conductivity: 0.13 W m^{-1} K^{-1}; specific heat capacity: 1880 J kg^{-1} K^{-1}; density 399 kg m^{-3}; thickness: 0.10 m) or concrete (thermal conductivity: 0.37 W m^{-1} K^{-1}; specific heat capacity: 840 J kg^{-1} K^{-1}; density 1190 kg m^{-3}; thickness: 0.30 m). Windows are composed by a double-pane glazing with thermal transmittance of 1.1 W m^{-2} K^{-1} and a timber frame, whose transmittance is equal to 1.2 W m^{-2} K^{-1}.
Internal gains are assumed constant and equal to 4 W m^{-2}, half radiative and half convective, according to EN ISO 13790 (CEN, 2008) suggestions for residential dwellings. A constant ventilation rate of 0.3 air changes per hour are imposed in accordance with the Italian technical specification UNI/TS 11300-1:2014 (UNI, 2014). An ideal system provides all the power needed to maintain the zone internal air temperature between the heating and the cooling setpoints of 20 °C and 26 °C. In order to simplify the analysis of the results, heating and cooling seasons were delimited by 1st October and 31st March, independently of the climate.
Each building configuration differ for insulation level (5 cm or 15 cm of polystyrene, i.e., with thermal transmittances of the vertical walls of, 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 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 (14.56 or 29.12 m^2), orientation (east, south or west) and typology (*SHGCs* equal to 0.35, 0.49 or 0.61). Combining all the possible alternatives, the set of 72 simplified buildings was defined.
Five European locations were considered in this study: Berlin, Germany (Köppen classification: Cfb; heating degree-days with 18 °C as base temperature HDD_{18} = 3156 K d; cooling degree-days with 18 °C as base temperature CDD_{18} = 170 K d), Vienna, Austria (Köppen classification: Dfb; HDD_{18} = 3158 K d; CDD_{18} = 223 K d), Trento, Italy (Köppen classification: Cfa; HDD_{18} = 2610 K d; CDD_{18} = 391 K d), Rome, Italy (Köppen classification: Cfa; HDD_{18} = 1444 K d; CDD_{18} = 649 K d) and Messina, Italy (Köppen classification: Cfa; HDD_{18} = 758 K d; CDD_{18} = 1085 K d). The meteorological data of test reference year IWEC, developed by ASHRAE, were used as data source for all localities except Trento, for which the typical year presented in Pernigotto *et al.* (2014) was employed.

2.3 Analysis of hourly irradiation profiles and energy needs

The 264 series of incident hourly solar irradiation were analyzed in every climate and cardinal vertical orientations. For each hour during the daytime, the median of the 264 estimations was calculated and used as reference to determine the number of models within an acceptable range of error. Differently from the criteria adopted in our previous research (Prada *et al.*, 2014a; Prada *et al.*, 2014b; Pernigotto *et al.*, 2015), we chose the same reference threshold (i.e., 10 % deviation from the median) for the assessment of the variability of both solar irradiance and energy needs. Indeed, while for solar irradiance a 20 % error represents the difference often found between experimental data and models (Dervishi and Mahdavi, 2012), 10 % is the uncertainty expected from *BES* results according to the current state of the art of building simulation. The fraction of solar irradiation models within 10 % deviation from the median were calculated along all daytime hours belonging to both heating and cooling seasons. Then, their distribution functions were represented against the normalized daytime in order to allow for an easier comparison and, thus, to identify climates and orientations more sensitive to the model choice.
As regards the hourly energy needs, the implemented procedure is similar: for each climate, building and hour, 264 values were calculated and from them the hourly median was identified. When larger than a minimum of 0.1 kWh, the median was used as reference otherwise the series was neglected. As mentioned before, a threshold of 10 % deviation from the median was chosen to categorize each hour into four performance classes. An hour belongs to class "A" if more than 75 % of models ensure a deviation of heating or cooling demand within 10 % from the series median (i.e., more than 198 models), "B" if 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", if less than 25 % models are able to satisfy the 10 % deviation target (i.e., less than 66 models). The time-distributions of the four classes were analyzed, looking for correlations between climate and building characteristics in the propagation of the uncertainty due to the solar irradiation modelling. In particular, we focused on the distribution of hours belonging to class "A". The cumulative distribution functions were calculated and normalized with respect to the actual length of heating and cooling seasons (i.e., number of hours with heating and cooling load within a season) for the different building

configurations and climates, simplifying the comparison among the different cases. Finally, the normalized frequencies of class "A" during the entire actual heating or cooling seasons were calculated for each building.

3. RESULTS AND DISCUSSION

3.1 Hourly solar irradiation profiles

As explained in the methods, the 264 hourly irradiation profiles were calculated, as well as the median for each daytime hour. Comparing each result with the median, the fractions of models within 10 % of deviation were calculated and represented in Figure 1, distinguishing "summer" and "winter season", respectively delimited by 1st October and 31st March. The normalization of the daytime hours allowed an easier comparison between the five localities, which are characterized by different total of daytime hours per season because of their latitudes. Indeed, during the so-called "summer season" we have 2882 daytime hours for Berlin, 2736 h for Vienna, 2537 h for Trento, 2671 h for Rome and 2656 h for Messina. During the "winter season", instead, there are 1763 daytime hours for Berlin, 1872 h for Vienna, 1725 h for Trento, 2000 h for Rome and 2005 h for Messina. Trento has the minimum number of daytime hours because of the orographic characteristics of the locality: thus, due to the mountains surrounding the city in the Adige Valley, actual times of dawn and dusk occur later and earlier.

Especially for the "summer season", it can be observed that south vertical orientation is the one showing the best agreement among the models: except for Trento, at least around 30 % of model are within 10 % deviation from the median. We registered at least 50 % of models respecting the chosen accuracy threshold for 92.3 % of hours in Berlin, 92.7 % in Vienna, 81.1 % in Trento, 86.5 % in Rome and 80 % in Messina. East and west vertical orientations have very similar trends in all localities excluding Trento and, in particular, for Berlin and Messina. For these two orientations, we found at least 50 % of solar models in good agreement for almost 49 % of summer daytime in Berlin, 46.2 % (east) and 52.2 % (west) in Vienna, 49.3 % (east) and 57.1 % (west) in Trento, 47.1 % (east) and 42.7 % (west) in Rome and almost 45 % in Messina. North vertical orientation is the most critical in all localities during the summer season: only 41.3 % of daytime for Berlin, 39.8 % for Vienna, 39.5 % for Trento and 35 % for both Rome and Messina are characterized by at least 50 % of solar irradiation models giving estimations within 10 % deviation from the median. The peculiar trends in Trento can be explained because of the orography issues, affecting the accuracy of the estimations on east and north-oriented vertical planes.

For the "winter season", the south-oriented vertical plane is remarkably better than the other cardinal orientations only for Messina. The performance of solar models for the south is very close to other vertical planes in the other localities and even worse for Berlin. The minimum of 50 % of models within 10 % distance from the median in case of South vertical orientation is reached for 53.1 % of winter daytime in Berlin, 65.9 % in Vienna, 69.4 % in Trento, 59.8 % in Rome and 63 % in Messina. East and west orientations are almost overlapped in every climate except Trento: around 73 % of winter daytime has at least 50 % of solar models in good agreement in Berlin, 69.3 % (east) and 67.5 % (west) in Vienna, 51 % (east) and 62.7 % (west) in Trento, 52.1 % (east) and 49 % (west) in Rome and around 45 % in Messina. While in Berlin and Vienna, the estimation of solar irradiation on north-oriented vertical planes is as good as for east and west orientations, in the other climates it is the most critical. The target of 50 % models within 10 % deviation from the median is ensured for 71.4 % of daytime in Berlin and 63.2 % in Vienna, but only for 41.3 % in Trento, 39.4 % in Rome and 33.1 % in Messina. Regarding Trento, also during the winter season the orographic effect on the models' accuracy can be observed: west and south vertical orientations on a hand and east and north on the other hand have similar trends but very different levels of uncertainty.

As a whole, we can recapitulate that the best agreement among hourly estimates of solar irradiation is found during the summer season for south-oriented vertical walls while the most uncertain estimations are generally found for north-oriented vertical planes during the winter season. We can conclude, consequently, that when the beam irradiation is prevailing, the uncertainty due to the choice of solar model is smaller while the opposite is true for irradiation mostly diffuse. Models' outputs for east and west vertical planes are generally characterized by similar performances except in case of regional orographic obstacles, as it is in Trento. In that case, large discrepancies can be found among solar irradiation values predicted by the different models.

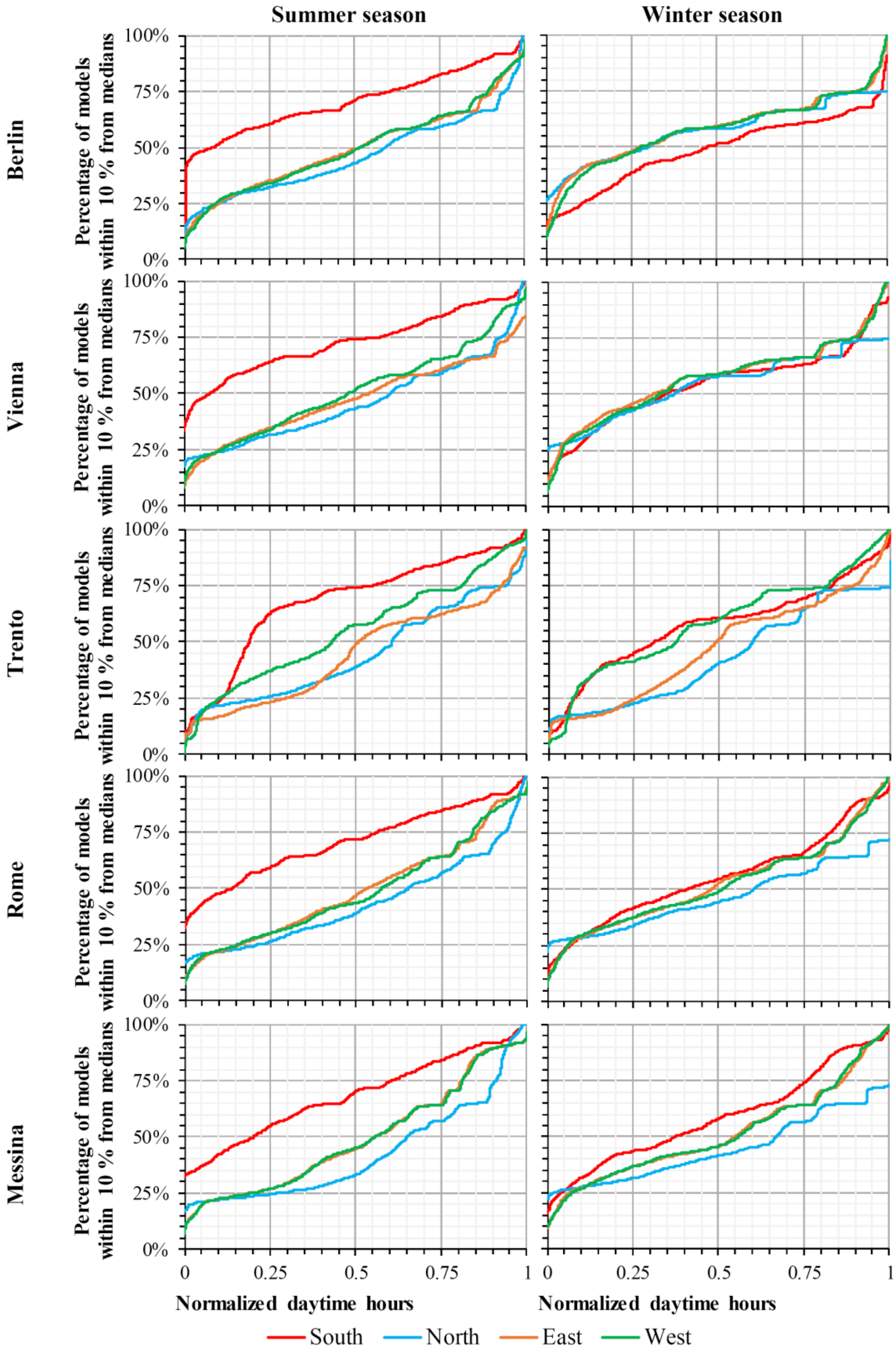

Figure 1: Percentage of models within 10 % deviations from the median for the four main cardinal vertical planes in the studied localities during the summer (left) and the winter (right) seasons.

3.2 Hourly energy needs profiles

The variability of solar irradiation predictions clearly affects the variability of hourly energy need predictions. For example, Figure 2 shows a comparison between the level of agreement found in hourly solar irradiation predictions for east and west-orientation vertical walls in Rome during the whole year and the variability of heating and cooling hourly energy needs for two building cases with a well-insulated timber structure and large windows with *SHGC* equal to 0.608 but different orientations. The daytime hours are divided into four groups depending on the amount of models whose solar irradiation estimations are within a 10 % deviation from the median: more than 75 % (very light grey), between 50 % and 75 % (light grey), between 25 % and 50 % (dark grey) or less than 25 % (very dark grey). Similarly, the graphs reporting the energy needs classes distinguish the time belonging to class "A" (very light grey), class "B" (light grey), class "C" (dark grey) and class "D" (very dark grey). As it can be seen, inaccuracies in solar irradiation calculations are specular moving from east to west vertical planes and the same trends can be recognized comparing the cooling need of the building with windows on the east façade to that with windows on the west façade. Indeed, while small impact can be observed for the heating needs, for the cooling ones the largest uncertainty is registered in the afternoon in case of east orientation and in the morning in case of west orientation, when the solar irradiation entering into the thermal zone is mostly diffuse.

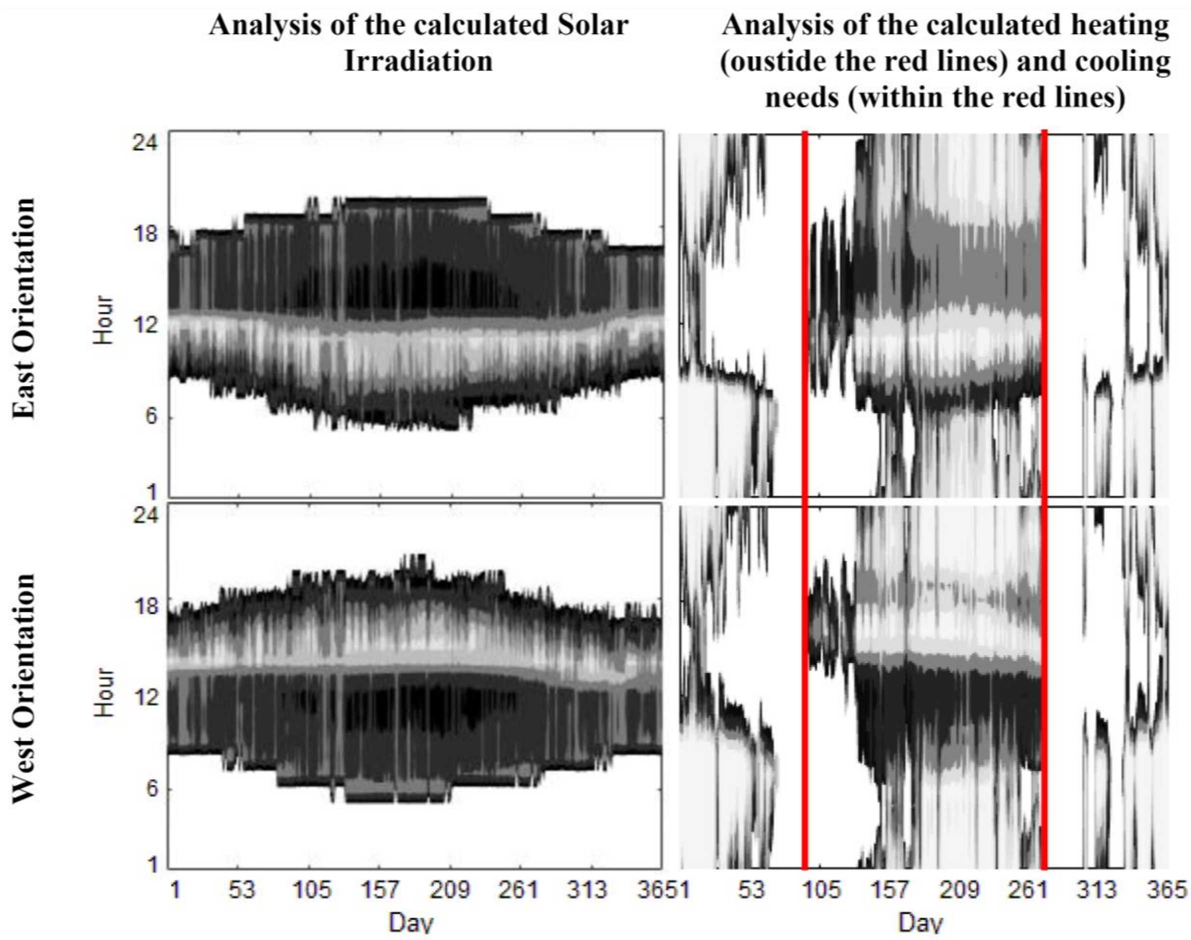

Figure 2: On the left, the density of solar models with normalized deviations lower than 10 % with respect to the medians are reported for Rome east and west orientations. On the right, the variability of the energy need predictions. Irradiation and energy values are categorized into the four performance based on the number of models respecting the 10 % deviation: more than 75 % (very light grey), between 50 % and 75 % (light grey), between 25 % and 50 % (dark grey) or less than 25 % (very dark grey).

3.3 Hourly cooling needs

In the five climates, the set of 72 buildings present different length of the actual cooling season. In Berlin, the fraction of summer hours with positive cooling load is only 10.7 %, as average, with a standard deviation of 9.4 %, ranging from a minimum of 0.2 % to a maximum of 34 %. As regard the other climates, in Vienna the average percentage of hours with cooling load is 28.9 % ± 11.2 % (ranging from 11.1 % to 55.5 %), in Trento 44.8 % ± 15.6 % (from 16.5 % to 86.7 %), in Rome 62.8 % ± 9.1 % (from 43.8 % to 81.5 %) and in Messina 76.5 % ± 6 % (from 64.5 % to 90.2 %). Lowering the latitude, the cooling needs increase as well as their occurrence during the season. The building configurations with the minimum number of cooling hours are different from location to location but common characteristics can be observed. As expected, a low value of *SHGC* (i.e., 0.351), small windows (i.e., 14.56 m^2) and poorly-insulated opaque component (i.e., 5 cm of polystyrene) help in reducing the frequency of the cooling loads. On the contrary, high *SHGC* (i.e., 0.608), large windows (i.e., 29.12 m^2) and well-insulated opaque component (i.e., 15 cm of polystyrene) lead to higher frequencies. Massive concrete walls are always present in case of maximum number of hours with cooling load while, for the configurations with minimum occurrence, concrete structures are found in colder climates and timber structures in the Mediterranean ones (i.e., Rome and Messina).

Figure 3 reports the cumulative distribution functions of class “A” for the cooling needs of all buildings in the five climates with respect to the normalized time with positive cooling needs. Of all hours with load during the summer season, in Berlin only 11.3 % ± 9.1 %, as average, belongs to the best performing class, ranging from cases with no occurrences in class “A” to a highest frequency of 38.9 %. In Vienna the average is 36.4 % ± 7.9 % (from 20.1 % to 53.5 %) and, in Trento, 27.9 % ± 13.6 % (from 5.3 % to 50.9 %). As regard the Mediterranean localities, Rome has an average of 53.4 % ± 8.6 % (from 35.6 % to 74.5 %) and Messina 68.6 % ± 10.7 % (from 45.2 % to 91.5 %). It can be observed that climates with larger cooling needs have higher frequency of class “A”. However, looking at the building cases with the lowest frequencies in class “A”, all of them have large glazing with high *SHGC* and timber structures, except for Messina. On the contrary, the occurrence of class “A” hours on the total hours with cooling load is maximized when *SHGC* is low and windows are small; for those cases, it can be seen that in northern localities the structure is in concrete while in the Italian ones it is in timber.

In the right part of Figure 3, the seasonal frequencies of class “A” are reported for each building, distinguished by orientation of the windows. For the simulation in Berlin, the configurations with highest frequency of class “A” have often south-oriented windows, while those with lowest frequencies are often east-oriented, coherently with the findings on solar irradiation estimations. Similarly, in Trento the worst cases have east-oriented windows while the best ones have windows exposed towards south or west. For Rome and Messina, instead, many cases with windows in the southern façade are characterized by lower accuracy on the cooling need estimation even if south is the orientation with the best agreement among the solar models’ outputs. It can be concluded that for those climates where specific discrepancies have been identified among the results given by the different solar irradiation models (e.g., Trento) or where the cooling load is not particularly high (e.g., Berlin), a direct correlation between the accuracy of the solar inputs and that of the hourly cooling needs can be identified while for hotter climates (e.g., Rome and Messina) the interaction is more complex and the uncertainty propagation is more altered by the combined effect of the different building features.

3.4 Hourly heating needs

As regards the heating needs, many trends are opposite of those observed in the previous paragraph. As well-known, the actual heating season is longer in Berlin and shorter in Messina. Specifically, in Berlin the fraction of time of the winter season with heating load is 97.2 % ± 3.4 %, as average, and ranges from 84.8 % to 100 %, in Vienna we found an average of 90.6 % ± 6.4 % (from 72.2 % to 99.1 %), in Trento 79.3 % ± 16.2 % (from 38.8 % to 100 %), in Rome 57.8 % ± 7.8 % (from 7.8 % to 82.6 %) and in Messina 27.3 % ± 18.5 % (from 0 % to 63.7 %). The building configurations with the minimum number of heating hours are characterized by a high value of *SHGC*, large windows towards south and well-insulated opaque components, with concrete massive layers in the Italian localities and timber in Berlin and Vienna. Except for Berlin, all cases maximizing the hours with heating needs have low *SHGC*, small windows and poorly-insulated concrete opaque component.

In Figure 4 the cumulative distribution functions of class “A” are represented for the heating needs of all buildings in the five climates. Also this time they were compared to the normalized time with positive load. The majority of hours of the winter season with loads belongs to class “A” for Berlin (92.6 % ± 6.8 %, from 70.5 % to 99.9 %), Vienna (90.5 % ± 7.2 %, from 62.9 % to 98.9 %), Trento (77 % ± 12 %, from 30.2 % to 95.9 %) and Rome (66.5 % ± 21.1 %, from 9.7 % to 94.6 %) and for Messina their percentage is close to half of occurrences as average (46.8 % ± 23 %, from 0 % to 79.2 %). For all localities the same buildings are characterized by either the minimum frequency of class “A” or the maximum one. Respectively, the first is characterized by large south-oriented windows with high *SHGC* and well-insulated concrete walls while the latter has small east-oriented windows and poorly-insulated concrete walls. About the seasonal frequencies of class “A” for heating needs distinguished by orientation of the windows (right side of Figure 4), we can see similar behaviors in all locations except Trento and the best performances are registered for east and west orientation. In Trento, the locality with the most marked differences of accuracy in the solar irradiation estimation for the different orientations, cases with east-oriented windows appear to be the most robust to the choice of solar model and those with south or west-oriented windowed façades appear more influenced.

4. CONCLUSIONS

In this work, we investigated how the choice of solar irradiation models can affect the reliability of *BES* for the calculation of hourly energy results. Hourly series from different models have been analyzed considering a tolerance level of 10 % of deviation from the hourly median. The fraction of solar models combinations leading to an acceptable deviation of hourly heating and cooling needs was estimated for a set of 72 simplified buildings and five European climates (Berlin, Vienna, Trento, Rome and Messina). We found that:

- Regarding the elaboration of solar irradiation, the best agreement is encountered when the beam irradiation is prevailing (e.g., during the summer season and for south-oriented vertical walls) while uncertainty is increased for irradiation mostly diffuse (e.g., for north-oriented vertical planes during the winter season). Large discrepancies can be detected in case of regional orographic obstacles (e.g., Trento).
- The hourly cooling needs simulated for buildings with small windows and low *SHGC* are less sensitive to the choice of the solar irradiance models, especially in hotter climates. Moreover, the windows' orientation can emphasize or reduce the effects of solar irradiation uncertainty, in particular in those climates where large discrepancies have been identified among the results given by the different solar irradiation models (e.g., Trento) or where the cooling load is not particularly high (e.g., Berlin).
- The hourly heating needs of buildings with large south-oriented windows, high *SHGC* and well-insulated concrete walls are more sensitive to the choice of the solar irradiance models, while those cases with small east-oriented windows and poorly-insulated concrete walls are more robust. Regarding the window's orientation, the best accuracy is registered for east and west in all localities except for in Trento, once again influenced by the local orography.

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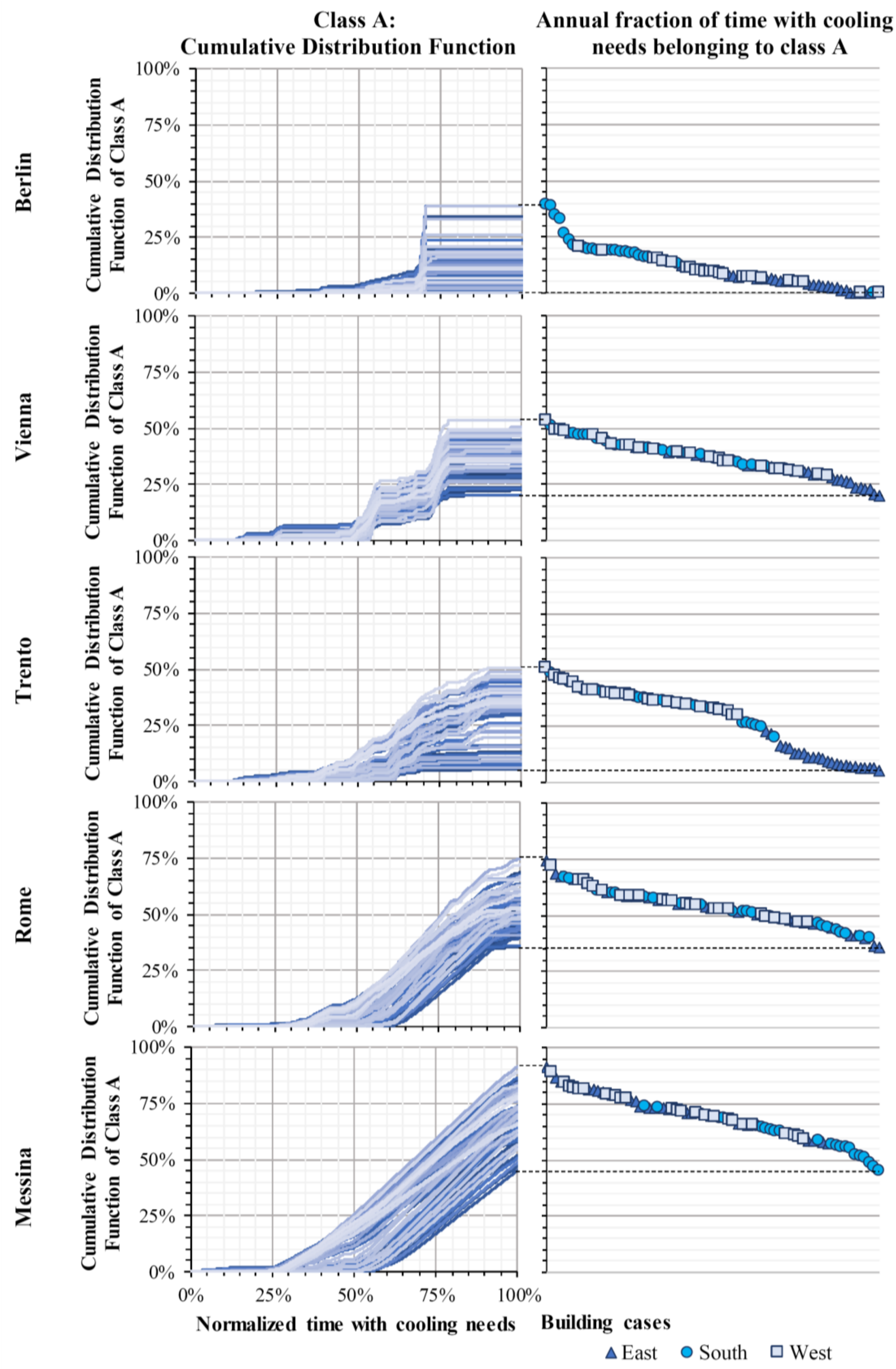

Figure 3: Cumulative distribution functions (on the left) and seasonal frequencies (on the right, distinguished by window orientation) of hours with cooling needs belonging to class "A" with respect to the normalized hours with cooling load during the summer season, for each building configuration and climate.

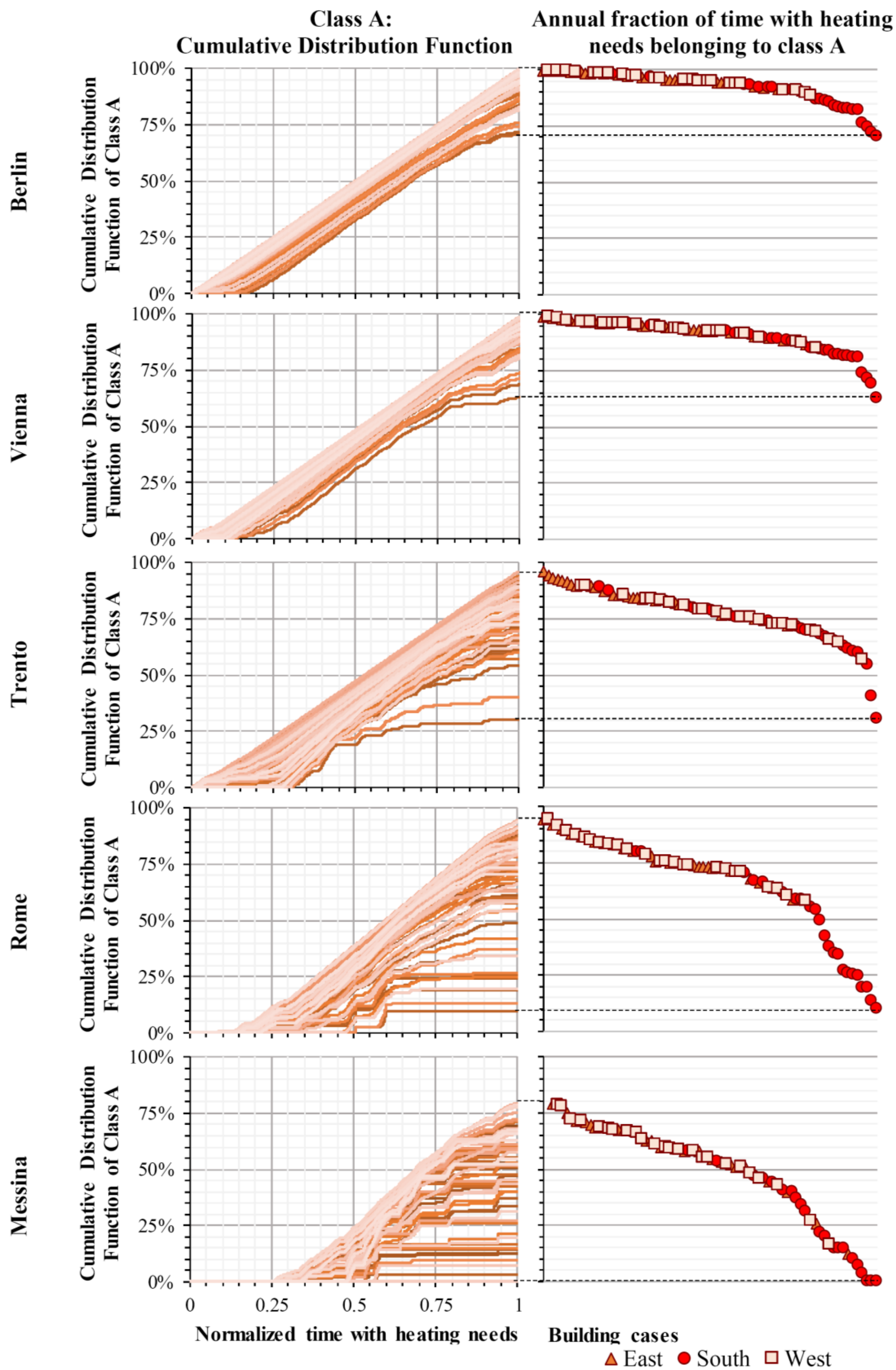

Figure 4: Cumulative distribution functions (on the left) and seasonal frequencies (on the right, distinguished by window orientation) of hours with heating needs belonging to class "A" with respect to the normalized hours with heating load during the winter season, for each building configuration and climate.