# Effect of Solar Radiation Model on the Predicted Energy Performance of Buildings

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## ABSTRACT

Building energy balance is strictly connected with incident solar irradiation, whose reliable estimation on envelope surfaces is essential for the evaluation of building solar gains. While diffuse and beam solar components on tilted surfaces are required, meteorological stations usually measure only global radiation on horizontal plane. In the literature, several diffuse irradiance and tilted surface irradiance models are reported, nevertheless, none is suitable for any locality. In this work, we assess the extent to which the choice of solar radiation models affects the predicted energy performance of a set of simplified reference buildings. By means of a full factorial plan, a set of 72 simplified residential buildings is defined by changing the main building features. A full combination of 22 horizontal diffuse irradiance models coupled with 12 irradiance models for tilted surfaces is implemented and used as a preprocessor of solar data used in TRNSYS. The results highlight that the variability of solar radiation in input induces different levels of uncertainty in energy models predictions. Besides, the dispersion of simulation outcomes shows interactions with the building features linked to the transmission of solar radiation inside the building, leading to different uncertainty propagations in *BES*.


## 1. INTRODUCTION

In building energy simulation (*BES*), a reliable estimation of solar irradiation incident on differently tilted and oriented surfaces, distinguishing diffuse and beam components, is essential in order to account for the solar heat gains or to evaluate daylighting issues. In most of meteorological stations, only global solar radiation on a horizontal plane is monitored and only some stations collect horizontal direct and diffuse components separately. Moreover, an even lower number of stations measure the solar radiation incident on tilted surface. For these reasons, a variety of mathematical and empirical models have been proposed in the literature for both the subdivision of horizontal solar radiation into direct and diffuse components (*horizontal diffuse irradiance models*) and for the calculation of irradiation on tilted surfaces (*irradiance models for tilted surfaces*). Nevertheless, since these models were developed starting from the experimental data of specific locations, none can provide results with the same worldwide reliability. This topic has been widely discussed in the literature and some authors assessed some models with experimental data for different locations with respect to those used for their definition. However, the propagation of the model uncertainty through *BES* has not been investigated in detail. The choice of a couple of solar models could lead to changes of the building energy labeling, incorrect optimizations of the retrofit, as well as suboptimal definitions of the energy system controls.

This research work investigates the extent to which the choice of solar radiation models affects the predicted energy performance of a set of simplified reference buildings, defined by changing the insulation and thermal inertia of opaque components, the windows surface and orientations and the kind of glazing, focusing on the solar heat gain coefficient (*SHGC*). A full combination of 22 *horizontal diffuse irradiance models* coupled with 12 *irradiance models for tilted surfaces*, for a total of 264 combinations, is implemented to calculate the hourly profiles of solar irradiance to use in the *BES*. The hourly *BESs* have been performed for different European locations representative of the five regions with different availability of annual solar radiation. Finally, the distribution of monthly heating and cooling energy needs and peak loads have been discussed by means of statistical techniques, in order to correlate the deviations of energy performance prediction to the building envelope characteristics.

## 2. METHOD

The procedure presented in this work consists of three main parts: (a) subdivision of the European region into homogeneous zones of available annual solar radiation and identification of reference cities; (b) evaluation of the solar radiation incident on vertical surface for each orientation and for any couple of models; (c) run of the *BES* and analysis of the heating and cooling energy needs and peak loads distributions.

### 2.1 Irradiance models

In this research, 22 *horizontal diffuse irradiance models* have been considered. Firstly, the analysis 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). Furthermore, we included also some models based on the correlations of the previous researches, with some modifications introduced by their authors to adjust the correlation 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*, we considered 12 models, including both the isotropic and the anisotropic ones: 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 Identification of solar classes

The first step of the analysis deals with the identification of European classes of solar radiation availability. The taxonomy analysis was performed by means of QGIS starting from PVGIS database (Šúri *et al.*, 2005). In this case, from the annual solar radiation recorded in the PVGIS database, we developed a continuous surface in order to characterize different European zones of the solar radiation availability. Firstly, the European territory has been ranked by identifying five intervals of annual global solar radiation incident on horizontal surface. Secondly, five cities (Berlin, Vienna, Trento, Rome and Messina) representative of each class have been chosen (Figure 1). Then, the meteorological data of test reference year IWEC, developed by ASHRAE, and the reference year of Trento presented in Pernigotto *et al.* (2014) are used.

### 2.3 Test cases

The effects of solar radiation variability on the energy performance of building is studied by carrying out different *BES* with any couple of solar models on the set of 72 simplified buildings. These buildings are not representative of

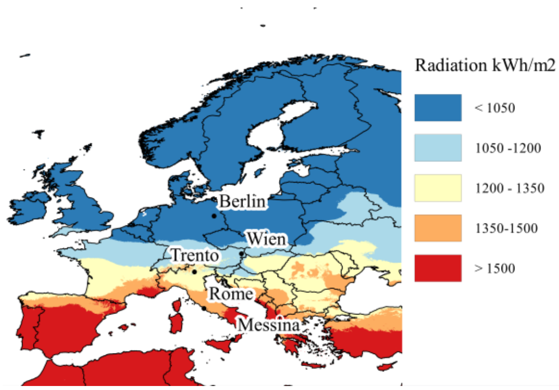


**Figure 1:** Annual solar radiation in Europe based on PVGIS data Šúri *et al.* (2005)

the European building stocks but they have been adopted because of their different sensitivities to the external environment solicitations and of their already-assessed 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 a height of 3 m with the façades facing the main cardinal directions. Thermal bridges are neglected and the floor is modelled with 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 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 $m^{-3}$ and two alternative thicknesses (0.05 m or 0.15 m). 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 (ACH) is considered, as suggested by the Italian technical specification UNI/TS 11300-1:2008 (UNI, 2008).
In each construction typology, the buildings 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 $\kappa_i$ 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 $m^2$) and orientations (East, South or West) and typology (*SHGCs* equal to 0.35, 0.49 or 0.61). In accordance with a full factorial plan, this leads to a definition of a set of 72 simplified buildings. In each building configuration, an ideal system has been used in order provide all the power needed to maintain the zone internal temperature between the set points of 20 °C and 26 °C.

## 3. RESULTS AND DISCUSSION

The *BESs* have been conducted for the five European locations starting from the hourly trend of solar radiation processed with each couple of radiation models. The monthly energy needs (both for cooling and heating) and the peak of heating and cooling demand of the set of reference buildings are analyzed. For each building and location, the absolute spread between maximum and minimum monthly results of the 264 *BESs* in term of either energy needs and peak loads for heating and cooling, is plotted against the medians of the distribution (Figure 2-5). This representation allows to highlight the extent of data dispersion and to note the presence of interactions with building.
Figure 2 shows that cooling needs are significantly affected by the choice of the solar models. In the summer months, two distinct linear trends characterized by two different percentages with respect to the medians are noted (respectively, a spread roughly equal to 50 % and 25 % of the medians). Thus, some building features are responsible for the different relative incidence of the spread on *BES* results. In contrast, in months with low cooling demand, a more compact distribution around a single straight line is identified for Trento, Rome and Messina. For those months, the cooling demands are given mainly from one of the two sub-groups of buildings and the

differences are not marked due to the lower values of the energy needs. Figure 3 shows that cooling peak loads are affected by changes in solar radiation estimation, as well. The graphs report a maximum spread roughly equal to 3 kW whereas an anomalous behavior for some results in Trento emerges. In fact, the dispersion of the solar radiation incident on vertical surfaces, especially on those oriented towards East and West, greatly increases due to orography effect on measured horizontal radiation that lead to incorrect evaluation of sky conditions (Prada *et al.*, 2014). Once again, in cities characterized by higher solar radiation availability, two different distinct trends can be recognized during the summer months and the alignment into the two groups seems more marked for the cooling needs. Also in this case, this behavior is less detectable in the months when solar radiation availability is reduced. For instance, it is not possible to identify clear trends for Vienna and Berlin and during the springs and autumn months in Rome, Messina and Trento.

In winter months, the spreads of monthly heating needs (Figure 4) are aligned around lines with negative slope (i.e., the larger the monthly heating need, the lower the uncertainty due the solar irradiance models selection). However, also in this case, the dots can be split into two groups with similar slopes and for both of them the building configurations with the worst heating energy performance are characterized by low spread. In fact, the energy efficiency for space heating can be reached with two strategies - reducing the thermal losses and improving the utilization of solar and internal gains, and the buildings whose performance is more sensitive to the exploitation of solar contributions are more affected by the uncertainty. As expected, the influence of the radiation variability on the heating peaks (Figure 5) is limited and, in most of cases, the spread magnitude is lower than 0.5 kW. Since the heating peak loads are observed during the night hours, the solar radiation contributes weakly, mainly in building with high thermal capacitance in climates with a greater availability of solar radiation (i.e. Rome and Messina).

### 3.1 Statistical analysis

In order to assess in which month and locations the spread distribution is correlated linearly to the median distributions of the 264 *BES* outputs, we exploited Pearson's product-moment correlation coefficient, $r$. Furthermore, when linear relationship is not verified due to the different building behaviors in the sample – as seen in the graphs, we performed additional tests aimed at detecting the correlation between the spreads and building features. With a linear correlation between spreads and medians, the uncertainty caused by the choice of solar models can be approximated as a percentage of the energy performance. Moreover, the buildings, months and locations for which higher levels of inaccuracy are expected, can be identified. Pearson's index varies from -1 to +1 and the sign indicates a direct (+) or indirect (-) relationship. 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 some configurations, there are no energy needs or peak loads and, consequently, Pearson's coefficients have not been calculated. For the other cases, in addition to $r$, the p-value is computed considering a significance level of 1 %. Whatever $r$ value, a not statistically significant p-value indicates the impossibility of generalizing with the desired significance level and so we cannot state the linear relationship.

All spreads in cooling needs and peak loads have significant p-values while most of heating needs and peak loads during winter period are not significant. This means that, with different levels of approximation, the spreads for cooling needs and peaks assume linear trends with respect to the values of cooling needs and peaks. For the heating results, it is true only for small values of heating needs and peak loads. Considering cooling results, it can be seen that moving from colder to hotter months and from northern to southern locations (i.e., in cities with higher cooling demands), the linearity decreases – coherently with the graphs, in which two groups with different levels of spread are noted in summer months, especially for Messina and Rome. The lack of linear correlations in heating results reflects what found in the diagrams for the colder months, i.e., two separate groups of results for each location, distributed around two lines with similar slopes. Comparing buildings with similar cooling demand we have significantly different levels of uncertainty whereas, a much higher relative uncertainty can be encountered for heating in buildings with higher performances with respect to buildings with intermediate or low performances.

The distinctions of the results in the charts into separate groups and the low values or not-significant $|r|$ suggest a correlation between uncertainty introduced by the choice of solar irradiance models and buildings features. In order to find out these relationships, we selected only those months and locations with all buildings with positive medians of the results and $|r|$ lower than 0.7 (i.e., no strong linear correlation detected) and performed the analysis only for them, in order to have a more robust test.

As expected, the most correlated quantities are those involving the windows. The cooling spread (both needs and loads) have a strong correlation with the windows area and a moderate correlation with the *SHGC* and the south orientation. There is a weak correlation between the spread of the cooling peak loads and the thermal capacitance.

Looking at heating results, there are correlations, even if moderate, only between the spread of heating needs and the south orientation, and the windows area while for the heating peak loads only with the south orientation.

**Table 1:** Analysis of spread correlation with building features

| Spread | | *SHGC* | *Windows orientation* East | South | West | $A_{win}$ | $\kappa_i$ | $U_{vw}$ |
|---|---|---|---|---|---|---|---|---|
| **Cooling needs** | *r* | 0.50 | -0.20 | 0.40 | -0.20 | 0.74 | 0.00 | -0.03 |
| | *p-value* | <0.01 | 0.02 | <0.01 | 0.02 | <0.01 | 0.97 | 0.72 |
| **Cooling peak loads** | *r* | 0.43 | -0.21 | 0.43 | -0.23 | 0.70 | -0.20 | -0.01 |
| | *p-value* | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | 0.77 |
| **Heating needs** | *r* | 0.20 | -0.24 | 0.41 | -0.17 | 0.30 | 0.05 | 0.06 |
| | *p-value* | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | 0.02 | 0.01 |
| **Heating peak loads** | *r* | 0.17 | -0.14 | 0.31 | -0.18 | 0.25 | 0.15 | -0.08 |
| | *p-value* | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |

The thermal capacitance is slightly correlated to the spread of heating peak loads. Buildings with south oriented and large windows are subjected to larger uncertainty due to the selections of irradiance models. The cooling variations can be emphasized by high *SHGC* glazing. Hence, the buildings features induce different propagation of irradiance models uncertainty propagation and make difficult a generic quantification with respect to the expected values.

## 4. CONCLUSIONS

In this work, we investigated how the choice of solar radiation models can affect the reliability of *BES* results. This information is particularly useful for designers to understand the reliability of the *BES* results during the design phase of building. The level of uncertainty related to solar radiation is also useful to understand the calibration threshold of the as built building model for the post-occupancy verification of building performances. Additionally, the variability of results caused by solar model is useful for authorities to assess the risk of altering the building energy labeling and the verification of compliance to mandatory requirements, besides the importance of defining proper sets of reference weather data.
The results show similar behavior for the different locations with the exception of Trento where the orography induces higher variability of the model outputs in term of solar radiation estimations. The analysis on monthly heating needs and peaks highlights little interaction between results variability caused by the choice of models and building features. In fact, the statistical analysis demonstrates a poor correlation between median and spread for both heating peaks and needs, with Pearson's index generally lower than 0.3. Therefore, the percentage spread increases with decreasing heating demand and peak of heating. The choice of the radiation models has a greater impact on buildings with low heating needs and peaks, which better exploit the storage of solar heat gains to reduce demand. Hence, the uncertainty does not affect all building typologies in the same vein, but rather it becomes an issue for a specific subset of buildings. Additionally, this issue increases for well performing projects, which could happen for instance for nearly zero energy buildings. In contrast, proportionality between spreads and medians is noted for the cooling needs and peak loads during warmer months. Hence, the variability of the *BES* results can be estimated through *a priori* analysis both for cooling needs and peaks. The results also indicates two different levels of percentage spreads due to interactions with the building features. In fact, the statistical analysis reveals a linear correlation with the windows transmission characteristics of the solar radiation (*SHGC*) and, in particular, with window size and orientation. In conclusion, by studying in detail these correlations we can quantify a priori the reliability of the predicted cooling load for a given building based on its characteristics, especially for those climates without calibrated solar irradiance models or previous studies aimed at identifying the most accurate ones.

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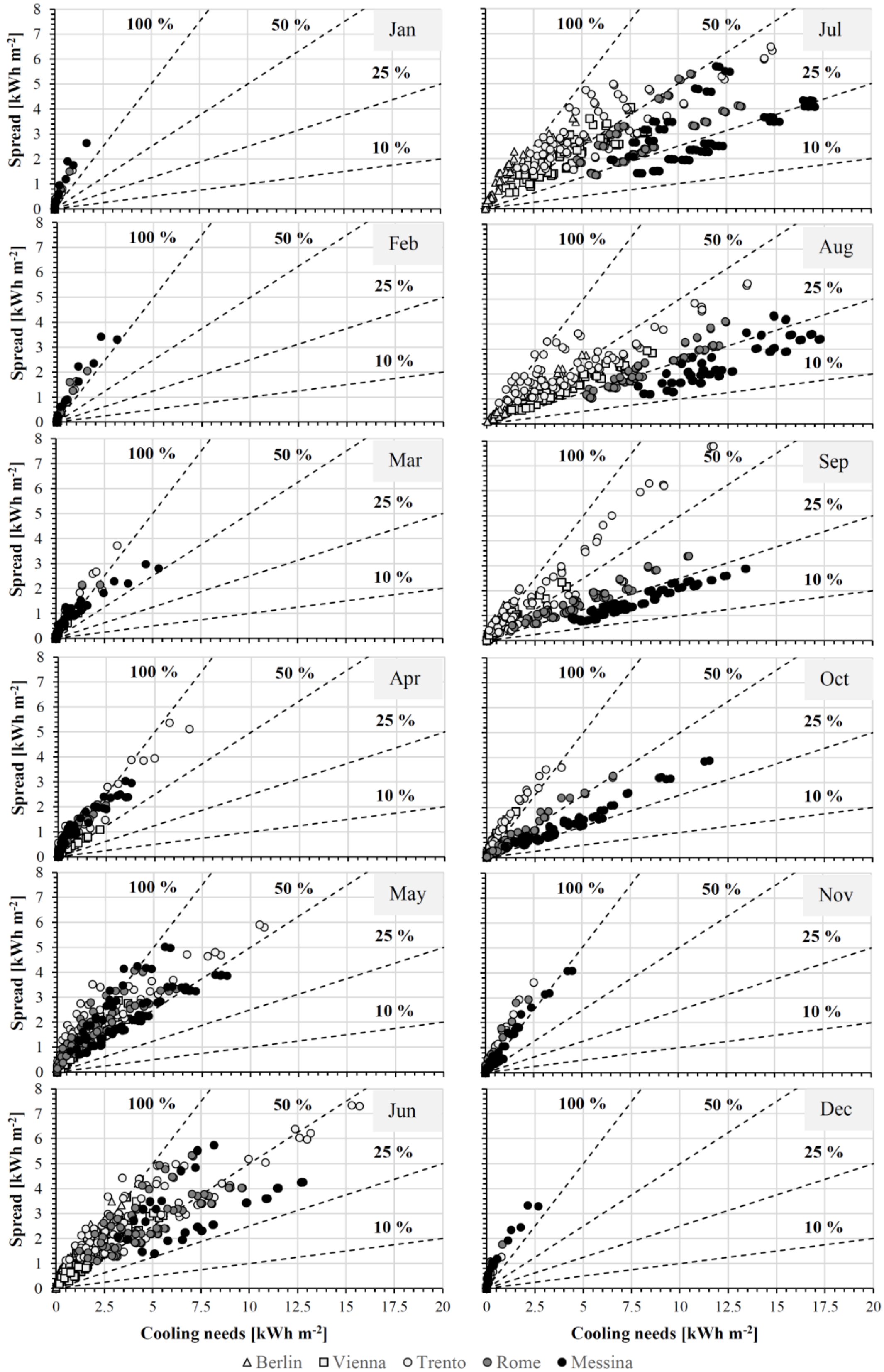


**Figure 2:** Distribution of spread in monthly cooling needs

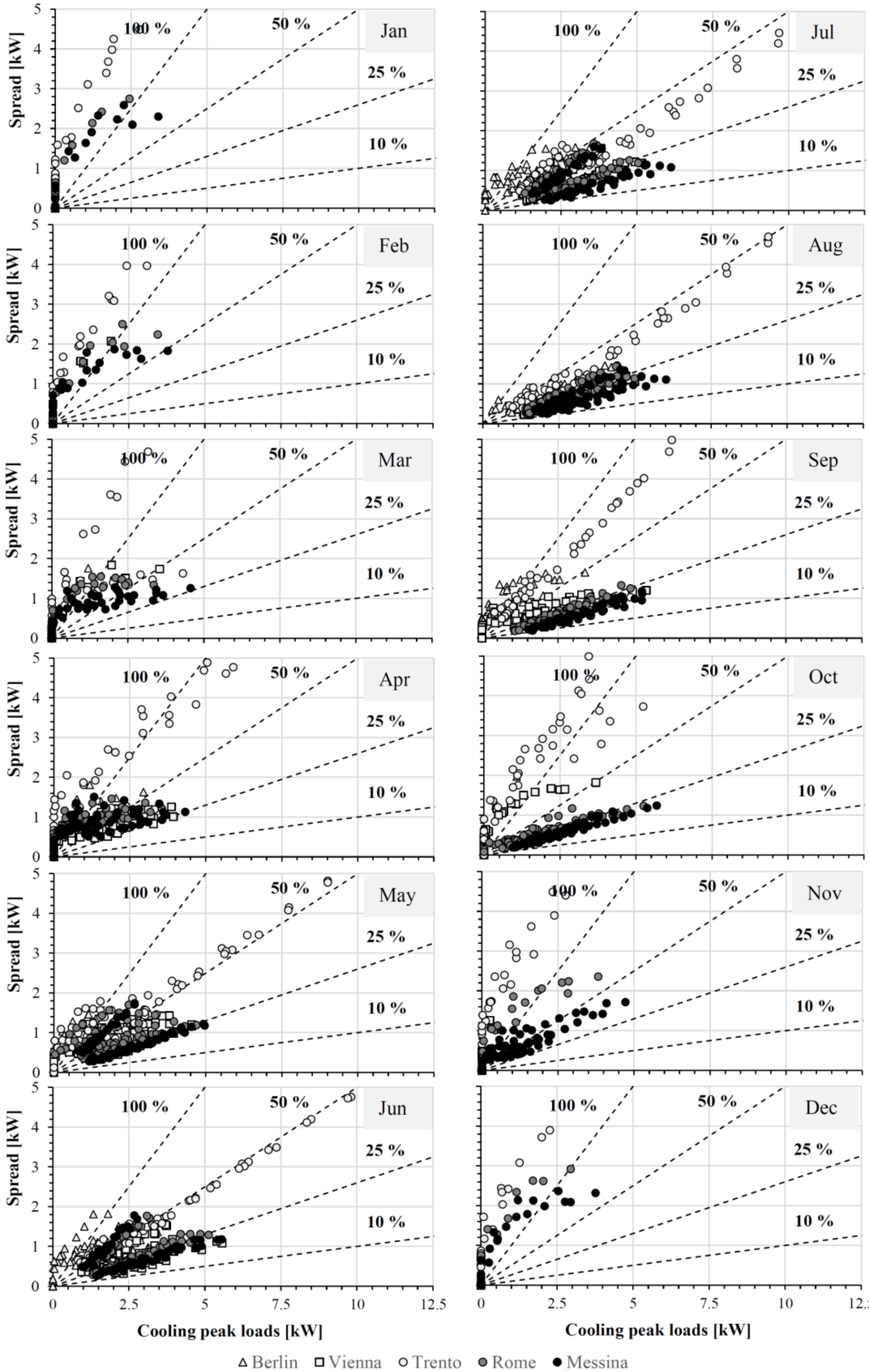


**Figure 3:** Distribution of spread in monthly cooling peaks

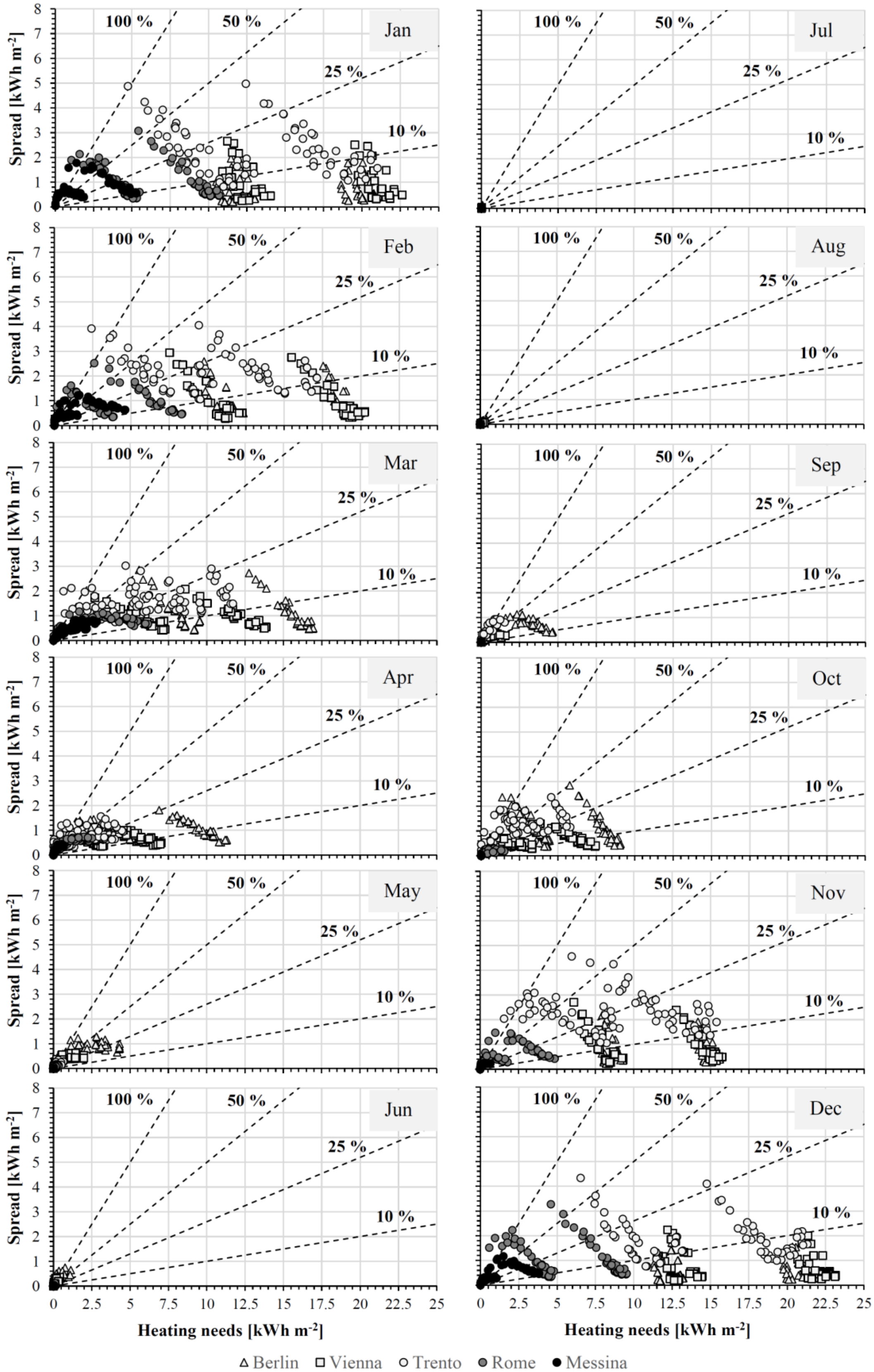


**Figure 4:** Distribution of spread in monthly heating needs

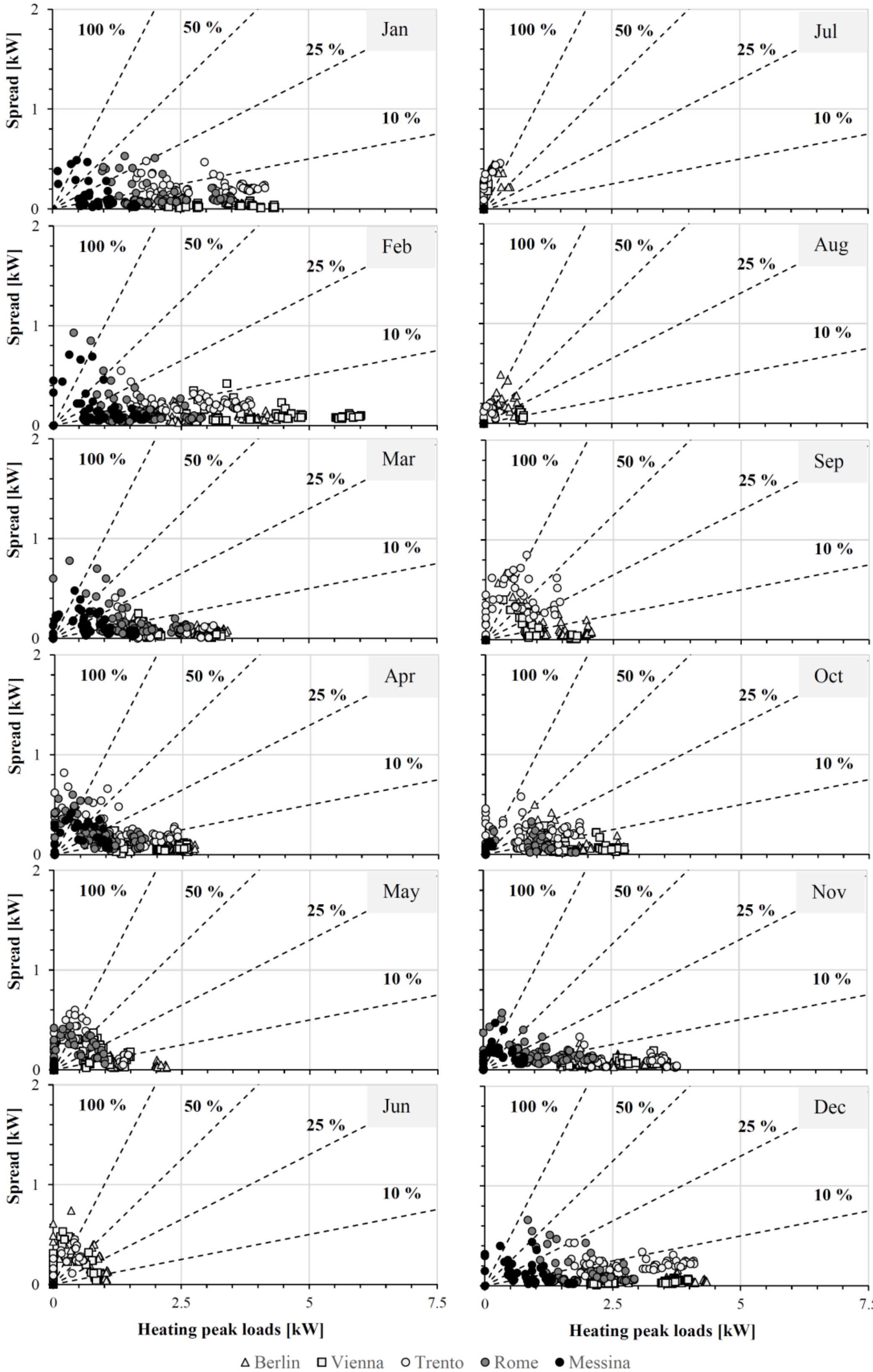


**Figure 5:** Distribution of spread in monthly heating peaks