Konferenzbeiträge / Atti / Proceedings

Building Simulation Applications BSA 2022

5th IBPSA-Italy Conference
Bozen-Bolzano, 29th June –1st July 2022

Edited by
Giovanni Pernigotto, Francesco Patuzzi,
Alessandro Prada, Vincenzo Corrado, Andrea Gasparella

bu,press
bozen
bolzano
university
press

Impact of Solar Radiation Modelling on the Simulated Building Energy Performance in the Climate of Bolzano, Italy

Giovanni Pernigotto – Free University of Bozen-Bolzano, Italy – giovanni.pernigotto@unibz.it
Alessandro Prada – University of Trento, Italy – alessandro.prada@unibz.it
Aleksandr Gevorgian – Free University of Bozen-Bolzano, Italy – aleksandr.gevorgian@natec.unibz.it
Andrea Gasparella – Free University of Bozen-Bolzano, Italy – andrea.gasparella@unibz.it

Abstract

We can mainly identify two groups of models in the literature to calculate solar irradiance incident on building envelope surfaces: *horizontal diffuse irradiance models*, to distinguish beam and diffuse horizontal components and *irradiance models for tilted surfaces*, to determine the irradiance incident on inclined surfaces. Due to the fact that solar irradiance data are different depending on location, climatic condition and topographic factors, there is no uniform solar irradiance model that can provide the same level of accuracy worldwide. Furthermore, this is even more critical in mountain areas, characterized by terrain complexity and the presence of specific local climatic conditions affecting solar radiation distribution.

In this research, the performance of 22 horizontal diffuse irradiance models and 12 irradiance models for tilted surfaces was assessed to check their suitability for application in mountain regions. The analysis was carried out in the Italian Alps, specifically, in the city of Bolzano, using as a reference the global solar irradiance data collected for both horizontal and vertical surfaces. Moreover, the energy needs for space heating and cooling of 48 simplified building configurations were simulated to quantify the impact of solar irradiance models on the simulated building energy performance.

1. Introduction

Nowadays, architects and engineers increasingly rely on building energy simulation tools to design more and more energy-efficient buildings. In this context, precise modeling of solar irradiance on building components is crucial, especially when simulating the thermal behavior of buildings. Various mathematical and empirical models have been developed and proposed in the literature in the last few decades, for both the subdivision of global horizontal solar irradiance into beam and diffuse components (horizontal diffuse irradiance models) and for estimating solar irradiance on tilted surfaces (irradiance models for tilted surfaces). Examples include isotropic models, as cited by (Duffie & Beckman, 1991), and anisotropic models (Gueymard, 1987; Klucher, 1979; Muneer & Kinghorn, 1997; Perez et al., 1990; Robledo & Soler, 1998). Comparisons and modifications to these models and their application to specific regions have also been undertaken (Behr, 1997; Remund et al., 2003).

Despite the availability of many models, these were primarily derived from flat regions, and their results are to some extent location-dependent. Indeed, accuracy issues might be found when these irradiance models are used in a mountain region, where orographic complexity may cause a wide variety of inclines, introduce shades and reflections influencing meteorological parameters and contributing to the formation of local climate conditions. In this case, the success in providing adequate solar irradiance information would depend on the model's accuracy and reliability of input parameters. As a consequence, these models should be validated in each location by comparing experimental data with the predicted ones (Loutzenhiser et al., 2007). Validation is indeed essential for quantifying output uncertainty, whose propagation in building performance simulation models can also depend on the building’s characteristics (Prada et al., 2015).

In this research, the accuracy of solar irradiance models on simulated building energy performance was investigated for a mountain climate, i.e., Bolzano, Italy. Specifically, 22 horizontal diffuse irradiance models were coupled with 12 irradiance models for tilted surfaces, obtaining 264 combinations. The different profiles of calculated solar irradiance incident on the building envelope surfaces were used as input in TRNSYS 18 for the simulation of the energy performances of a dataset of 48 simplified residential buildings. This set was defined by changing insulation level and thermal inertia of opaque components, window surface and orientation, and kind of glazing system, focusing on their solar heat gain coefficient (*SHGC*). Finally, minimum and maximum monthly and annual deviations in heating and cooling needs for the simulated dataset of 48 buildings were discussed, employing statistical analysis to correlate the differences in energy performance prediction to the building envelope features.

2. Case Study

2.1 Location and Weather Station

Bolzano is a municipality in the Italian Alpine region (46.500° N, 11.350° E), located specifically in a basin where the Sarntal Valley, the Eisacktal Valley, and the Adige Valley meet. Almost 110,000 people live in this city on an area of about 30 km^2. Although the city centre is located at an altitude of 268 m, the municipality spreads from 232 m to more than 1600 m above sea level.

The weather station considered in this study is installed on the flat roof of the A2 Building at NOI TechPark in Bolzano (46.479° N, 11.331° E, about 25 m high), in the southern and industrial neighborhood of the city (Fig. 1).

As shown in Fig. 2, the weather station is equipped with 5 Delta-T SPN1 Sunshine Pyranometers able to measure both global and diffuse irradiance - one installed horizontally and four installed vertically towards the main cardinal directions. Furthermore, the weather station includes 5 LiCor Photometric Sensors (1 horizontal + 4 vertical, as for the SPN1 Sunshine Pyranometers) and an EKO ASI 16 sky camera (not used in this work). The 5 SPN1 Sunshine Pyranometers collect solar data with a 1-minute time discretization and the period considered in this analysis ranges from April 2021 to March 2022.

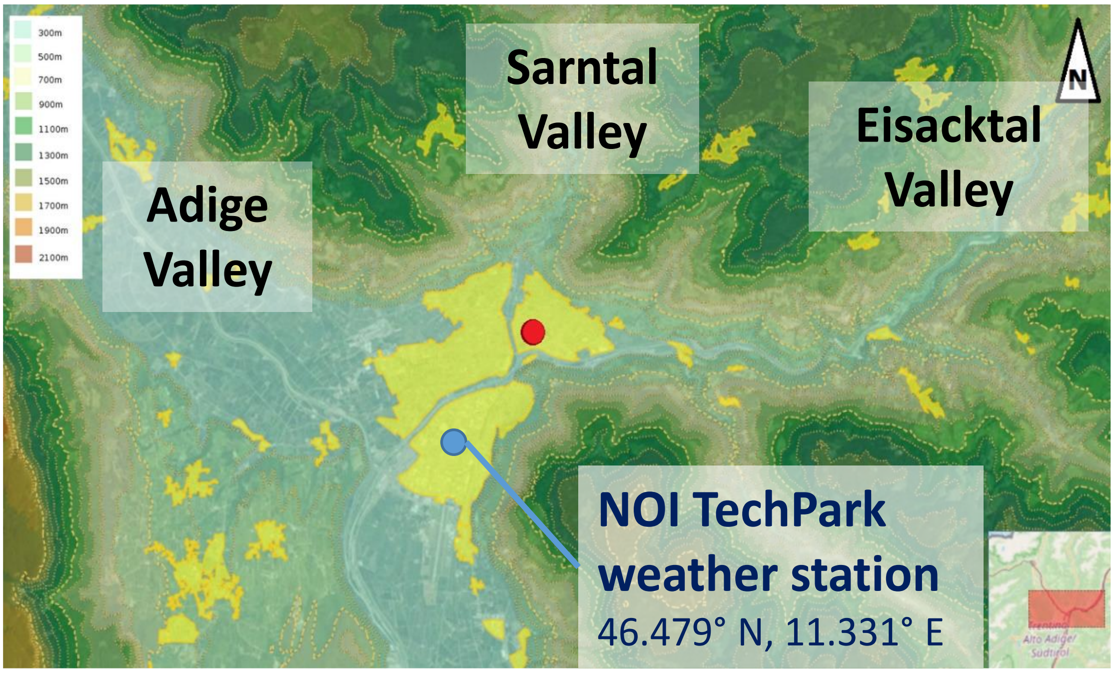

Fig. 1 – Basin of Bolzano: the different colors (light green to brown) indicate the altitude, while the yellow indicates the urban areas (map developed starting from Geobrowser Maps by the Autonomous Province of Bolzano). The red dot in the picture on the left indicates the University campus, while the blue dot highlights the position of the weather station at NOI TechPark considered in this research.

Table 1 – Solar irradiance models

ID	Horizontal diffuse irradiance models	ID	Irradiance models for tilted surfaces
1	Erbs et al. (1982)	A	Liu & Jordan (1960)
2	Orgill & Hollands (1977)	B	Burgler (1977)
3	Reindl et al. (1990a) – Model 1	C	Temps & Coulson (1977)
4	Reindl et al. (1990a) – Model 2	D	Klucher (1978)
5	Reindl et al. (1990a) – Model 3	E	Hay & Davies (1980)
6	Lam & Li (1996)	F	Ma & Iqbal (1983)
7	Boland et al. (2008)	G	Skartveit & Olseth (1986)
8	Hawlader (1984)	H	Gueymard (1986)
9	De Miguel et al. (2001)	I	Reindl et al. (1990b)
10	Karatasou et al. (2003)	J	Perez et al. (1990)
11	Chandrasekaran & Kumar (1994)	K	Muneer (2006) – Model 1
12	Oliveira et al. (2002)	L	Muneer (2006) – Model 2
13	Soares et al. (2004)		
14	Muneer et al. (1984)		
15	Spencer (1982)		
16	Chendo & Maduekwe (1994) – Model 1		
17	Chendo & Maduekwe (1994) – Model 2		
18	Skartveit & Olseth (1987)		
19	Maxwell (1987)		
20	Perez et al. (1992) – Model 1		
21	Perez et al. (1992) – Model 2		
22	Perez et al. (1992) – Model 3		

Fig. 2 – Weather station installed at NOI TechPark in Bolzano

3. Simulation

3.1 Solar Irradiance Models

As a follow-up to previous research on this topic (Pernigotto et al., 2015, 2016 and 2022; Prada et al., 2014a and 2014b), we focused on the same set of 22 horizontal diffuse irradiance models and 12 irradiance models for tilted surfaces previously analyzed (Table 1). The two groups of irradiance models were combined, for a total of 264 alternatives.

3.2 Dataset of 48 Building Configurations

48 simplified buildings were used for the assessment of the impact of the solar irradiance models on the simulated energy needs for space heating and space cooling. All 48 configurations are characterized by the same geometry and have a single thermal zone, with a square floor area of 100 m^2, an internal height of 3 m, and the façades oriented towards the main cardinal directions. In each building, all windows are positioned on the same façade. 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 are made of a two-layer structure with insulating polystyrene on the external side and an internal massive layer, whose thermal resistance is about 0.8 m^2 K W^{-1}. The polystyrene has a thermal conductivity of 0.04 W m^{-1} K^{-1}, a density of 40 kg m^{-3}, and a specific heat capacity of 1470 J kg^{-1} K^{-1}. The massive layer can be either timber (thickness: 0.10 m; thermal conductivity: 0.13 W m^{-1} K^{-1}; density: 399 kg m^{-3}; specific heat capacity: 1880 J kg^{-1} K^{-1}) or concrete (thickness: 0.30 m; thermal conductivity: 0.37 W m^{-1} K^{-1}; density: 1190 kg m^{-3}; specific heat capacity: 840 J kg^{-1} K^{-1}). The window systems are composed of double-pane glazing with a U-value of 1.1 W m^{-2} K^{-1} and a timber frame (20 % of the window area) with a U-value of 1.2 W m^{-2} K^{-1}.

Internal gains and ventilation rate are kept constant, with values representative of residential buildings (UNI, 2014) and equal, respectively, to 4 W m^{-2}, half radiative and half convective, and to 0.3 air changes per hour (ACH). An ideal system maintains the internal air temperature between 20 °C and 26 °C, i.e., the heating and the cooling setpoints. Conventional limits of heating and cooling seasons for the climate of Bolzano were neglected, assuming ideal space heating and cooling available all year.

A summary of the variables considered in the set of 48 buildings is reported in Table 2. Further details about this dataset of buildings can be found in (Pernigotto et al., 2021).

Table 2 – Variables describing the buildings in the dataset

Insulation thickness and U-value	Materials and thermal inertia c	Window size and WWR ratio	Window SHGC	Window orientation
5 cm (U = 0.45 W m^{-2} K^{-1})	Timber (c = 75 kJ m^{-2} K^{-1})	14.5 m^2 (WWR = 48.5 %)	0.35	East
15 cm (U = 0.21 W m^{-2} K^{-1})	Concrete (c = 300 kJ m^{-2} K^{-1})	29.1 m^2 (WWR = 97.1 %)	0.61	South
				West

3.3 Methodology

As a first step, focus was placed on the data collected by the SNP1 Sunshine Pyranometers of NOI TechPark weather station, performing a quality check to identify missing entries and outliers (e.g., values exceeding the solar constant and positive values before dawn and after dusk). Post-processed solar data, still with 1-minute time discretization, were further manipulated to obtain hourly profiles of solar irradiation, expressed in watt-hours per square meter in agreement with the typical convention adopted in weather data for building performance simulation (e.g., the EnergyPlus *.epw* weather files). Minor missing entries (i.e., one or few hours of missing solar irradiation data) were fixed by either linear or cyclic interpolation, depending on the length of the missing data series. Missing data entries longer than a day, on the other hand, were not fixed and simply discarded from the analysis.

In the second step, the capabilities of the 264 pairs of solar irradiance models were assessed using the measured solar data as a reference. Specifically, for each one of the 264 combinations of horizontal diffuse irradiance models and irradiance models for tilted surfaces, the hourly profiles of global solar horizontal irradiation of the selected period (April 2021 - March 2022) were used as inputs to determine the global and the diffuse solar irradiation on four vertical surfaces oriented towards the main cardinal directions. These estimated hourly profiles of global and diffuse solar irradiation were then compared to the measured ones, calculating for each orientation the Mean Absolute Error (MAE) in order to identify the best and the worst-performing pairs of models.

As regards the last step, the energy performances of the 48 reference building configurations were simulated in TRNSYS 18, using the best and the worst-performing pairs of solar irradiance models as inputs.

4. Result Analysis and Discussion

4.1 Step 1 – Quality Check on the Dataset of Solar Irradiation Measurements

Thanks to the quality check performed, it was found that, for the analyzed period (April 2021 – March 2022), the missing and wrong 1-minute entries had only minor impacts on the annual series, without continuous gaps longer than 1 hour. This ensured a robust basis for the comparisons performed in the next steps.

4.2 Step 2 – Comparison Between Simulated and Measured Solar Irradiation Values

4.2.1 Accuracy in the prediction of vertical diffuse solar irradiance

Table 3 shows the best and the worst-performing pairs of irradiance models, determined for each orientation according to the Mean Absolute Error (*MAE*) for the diffuse vertical irradiance values. It can be noticed that each orientation has a given pair of models optimizing the prediction of the diffuse vertical irradiance. Specifically, the pairs A10 (Liu & Jordan + Karatasou models) for the south orientation, A15 (Liu & Jordan + Spencer models) for the east one, H6 (Gueymard + Lam & Li models) for the north one, and B8 (Burgler + Hawlader models). The largest *MAE*s are found for east and west orientations, as expected, considering the geography of the location (Fig. 1). As regards the worst-performing pairs of models, for south and east orientations, the largest errors are found with the pair F20 (Ma & Iqbal + Perez Model 1) while D20 (Klucher + Perez Model 1) is the worst-performing pair for north and west orientations. *MAE* values are lower than about 15 Wh m^{-2} in case of the best-performing pairs and even larger than 70 Wh m^{-2} for the worst-performing ones.

Analyzing the horizontal diffuse irradiance models, which are most frequently found among the best-performing ones, we can list the Soares model for the south orientation, the Perez Model 1 for the east and the west orientations, and the Muneer model for the north. Some of these models, optimal for a given orientation, are the worst-performing ones for another. For instance, the Perez model 1 is the worst-performing for south and north orientations, the Soares model is the worst-performing model for the east one, and the Spencer model gives the worst estimates of vertical diffuse irradiance for the west orientation.

4.2.2 Accuracy in the prediction of vertical global solar irradiance

Table 4 shows the same analysis as in Section 4.2.1 considering *MAEs* calculated for the global solar irradiation on the vertical surfaces. As regards the best-performing models, G16 (Skartveit & Olseth + Chendo & Manduekwe Model 1), B20 (Burgler + Perez Model 1), H14 (Gueymard + Muneer) and B20 (Burgler + Perez Model 1) were identified, respectively, for south, east, north and west orientations. The pairs of worst-performing solar irradiance models were, instead, C20 (Temps & Coulson + Perez Model 1) for the south-oriented surface, F13 (Ma & Iqbal + Soares) for the east-oriented one, D20 (Klucher + Perez Model 1) for the north one, and F15 (Ma & Iqbal + Spencer) for the west one. As can be noted, when global solar irradiance is considered, the best- and worst-performing models are different to those found for the diffuse solar irradiance. Looking at the *MAEs*, larger values are generally observed compared to the previous analysis on the diffuse solar irradiance. Focusing on the best-performing models in global irradiance analysis, it can be seen that slightly larger *MAEs* are found for south and north-oriented vertical surfaces (i.e., respectively 24.8 versus 12.7 Wh m^{-2} and 9.8 versus 7.9 Wh m^{-2}). On the contrary, very large errors are observed for east and west orientations, with *MAEs* larger than 120 and 150 Wh m^{-2}. The same trends can be identified analyzing the results of the worst-performing models, with *MAEs* similar to those observed in the diffuse irradiance analysis for south and north orientations (i.e., 61.9 versus 75 Wh m^{-2} and 57.5 versus 61.6 Wh m^{-2}) and much larger for the east and west ones (i.e., 184.1 versus 71.8 Wh m^{-2} and 207.9 versus 58.6 Wh m^{-2}). On the whole, it can be concluded that a good level of accuracy can be obtained in the estimation of the incident global irradiance for south and north-oriented vertical walls, while larger errors are more frequently found for east and west orientations due to the presence of close natural obstacles.

As regards irradiance models for tilted surfaces, the Liu & Jordan model (south orientation), the Burgler Model (east and west orientations), and the Perez model (north orientation) can be seen as the most frequently found among the best-performing ones. Regardless of orientation, the worst-performing model most frequently encountered is the Ma & Iqbal model.

4.2.3 Comparison with another weather station

Table 5 reports the main findings of a former analysis (Pernigotto et al., 2022) focusing on another Bolzano weather station installed on top of one of the buildings of the university campus in the city center (46.498° N, 11.349° E) and performed over a three-year period (2018, 2019 and 2021). By comparing the *MAEs* reported in Table 4 with those in Table 5, it can be commented that larger errors are generally encountered in the prediction of solar irradiance in the location of the city center weather station. This is true for all vertical orientations except the eastern one. Indeed, studying the natural obstacles in the two locations, it can be seen that they are taller for the NOI TechPark weather station as far as the east orientation is concerned, while for the university weather station in the city center, they are more relevant for the west one. Again, each orientation has specific best and worst-performing pairs of solar irradiance models, which are typically different from those identified for the NOI TechPark weather station, except for the best-performing models for the west orientation and the worst-performing one for the north one.

Table 3 – Best and worst-performing pairs of solar irradiance models: diffuse irradiance

Best-performing pairs of irradiance models MAEs (Wh m^{-2})				Worst-performing pairs of irradiance models MAEs (Wh m^{-2})			
South	East	North	West	South	East	North	West
A10 Liu & Jordan + Karatasou	A15 Liu & Jordan + Spencer	H6 Gueymard + Lam & Li	B8 Burgler + Hawlader	F20 Ma & Iqbal + Perez Model 1	F20 Ma & Iqbal + Perez Model 1	D20 Klucher + Perez Model 1	D20 Klucher + Perez Model 1
12.7	15.1	7.9	14.8	75.0	71.8	66.1	58.6

Table 4 – Best and worst-performing pairs of solar irradiance models: global irradiance

Best-performing pairs of irradiance models MAEs (Wh m^{-2})				Worst-performing pairs of irradiance models MAEs (Wh m^{-2})			
South	East	North	West	South	East	North	West
G16 Skartveit & Olseth + Chendo & Manduekwe Model 1	B20 Burgler + Perez Model 1	H14 Gueymard + Muneer	B20 Burgler + Perez Model 1	C20 Temps & Coulson + Perez Model 1	F13 Ma & Iqbal + Soares	D20 Klucher + Perez Model 1	F15 Ma & Iqbal + Spencer
24.8	121.7	9.8	150.2	61.9	184.1	57.5	207.9

Table 5 – Best and worst-performing pairs of solar irradiance models: global irradiance. Comparison with the analysis performed in Pernigotto et al. (2022) with respect to the UNIBZ weather station (46.498° N, 11.349° E) for the years 2018, 2019 and 2021

Best-performing pairs of irradiance models MAEs (Wh m^{-2})				Worst-performing pairs of irradiance models MAEs (Wh m^{-2})			
South	East	North	West	South	East	North	West
H18 Gueymard + Skartveit & Olseth	C20 Temps & Coulson + Perez Model 1	J18 Perez et al. + Skartveit & Olseth	B20 Burgler + Perez Model 1	I15 Reindl et al. + Spencer	F15 Ma & Iqbal + Spencer	D20 Klucher + Perez Model 1	F18 Ma & Iqbal + Skartveit & Olseth
43.8	79.3	26.1	165.3	67.4	130.6	79.9	384.1

4.3 Step 3 – Analysis of Building Energy Performance

Table 6 reports the minimum and the maximum deviations found by simulating the energy performances for the considered dataset of buildings with the different pairs of solar irradiance models. Specifically, considering the results described in Section 4.2, the following 7 pairs of models were selected for this analysis:

1. Burgler + Perez Model 1 (B20)
2. Temps & Coulson + Perez Model 1 (C20)
3. Klucher + Perez Model 1 (D20)
4. Ma & Iqbal + Soares (F13)
5. Ma & Iqbal + Spencer (F15)
6. Skartveit & Olseth + Chendo & Manduekwe Model 1 (G16)
7. Gueymard + Muneer (H14)

The largest heating need deviations are within 5 kWh m^{-2} m^{-1} and are registered in the coldest months of the year (i.e., January, December), as expected. As regards the whole simulated period, the largest heating need deviations range from 1.4 to 17.7 kWh m^{-2} a^{-1}. Higher sensitivity to the choice of solar irradiance models is often found in those configurations with poorly insulated massive walls (i.e., concrete structures with 5 centimeters of insulation), and large south-oriented windows with high *SHGC*.

The cooling needs are characterized by monthly deviations within or around 4 kWh m^{-2} m^{-1}, usually occurring during the summer (i.e., June). Considering the whole simulated period, cooling needs deviations range from 3 to 23 kWh m^{-2} a^{-1}. This time, the largest deviation occurs for building configuration with well-insulated lightweight walls (i.e., timber walls with 15 centimeters of insulation), and large west-oriented windows with high *SHGC*.

Table 6 – Minimum and maximum monthly deviations of heating and cooling needs for the simulated dataset of 48 buildings

	Heating need deviations [kWh m^{-2}]		Cooling need deviations [kWh m^{-2}]	
Time	min	max	Min	max
Jan 2022	0.3	4.8	0.0	3.8
Feb 2022	0.3	3.2	0.0	3.5
Mar 2022	0.0	1.8	0.0	3.3
Apr 2021	0.0	0.7	0.0	2.0
May 2021	0.0	0.1	0.0	3.4
Jun 2021	0.0	0.0	1.1	4.2
Jul 2021	0.0	0.0	0.9	3.9
Aug 2021	0.0	0.0	0.7	3.0
Sep 2021	0.0	0.0	0.3	2.3
Oct 2021	0.0	1.3	0.0	4.1
Nov 2021	0.2	3.5	0.0	2.3
Dec 2021	0.3	4.9	0.0	1.5
Period	1.4	17.7	3.1	22.9

Fig. 3 depicts the cumulative distribution functions of the annual energy needs for space heating and cooling simulated for the 48 buildings. As can be seen, a larger variability of the findings is recorded for the cooling needs, especially when the horizontal diffuse irradiance model 20 (i.e., the Perez Model 1) is involved.

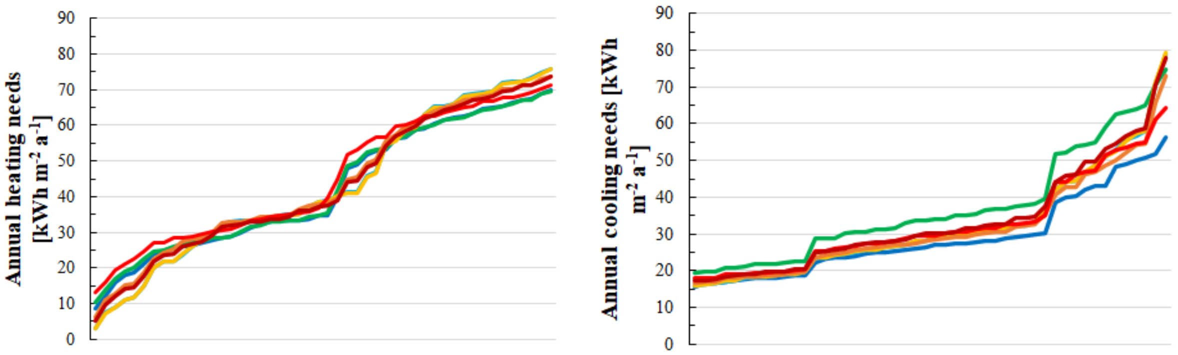

Fig. 3 - Cumulative distribution functions of the annual heating and cooling energy needs simulated for the 48 buildings with the following solar irradiance models: **B20** (Burgler + Perez Model 1), **C20** (Temps & Coulson + Perez Model 1), **D20** (Klucher + Perez Model 1), **F13** (Ma & Iqbal + Soares), **F15** (Ma & Iqbal + Spencer), **G16** (Skartveit & Olseth + Chendo & Manduekwe Model 1), and **H14** (Gueymard + Muneer)

5. Conclusion

This research assessed the capabilities of 22 horizontal diffuse irradiance models and 12 irradiance models for tilted surfaces for the calculation of the solar irradiance incident on the building envelope in mountain environments, which are characterized by complex irradiation patterns depending on the orography and the multiple terrain reflections. Solar irradiance calculated by all combinations of horizontal diffuse irradiance models and irradiance models for tilted surfaces were compared with diffuse and global irradiance measured in the Alpine location of Bolzano, Italy, during the period between April 2021 – March 2022 on four vertical surfaces oriented towards the main cardinal directions. Through the analysis of hourly Mean Absolute Errors, the best and the worst-performing pairs of models were first identified for each orientation and then used in TRNSYS simulations determine the energy needs for space heating and cooling for a dataset of 48 simplified buildings.

We found that:

- The performances of the pairs of solar irradiance models can be very different, depending on the orientation considered. In particular, the east and west orientations were found to be the most critical ones for the case study considered. Furthermore, varying accuracy can be expected for different locations in the same mountain valley or basin.
- None of the models in the literature was found able to ensure the same level of accuracy for all the four vertical cardinal orientations.
- The impact of the selection of solar irradiance models on the simulated energy performance is affected by the building's features.

Taking into consideration the main findings listed above, further developments of this research will involve testing potential modifications of the studied solar irradiance models to increase their capabilities when applied in mountain environments, in particular in the considered case study location of Bolzano, Italy.

Acknowledgement

This research was funded by the internal project of the Free University of Bozen-Bolzano "SOMNE - Bolzano Solar Irradiance Monitoring Network" (CUP: I56C18000930005; CRC Call 2018).

References

Behr, H. D. 1997. "Solar radiation on tilted south oriented surfaces: Validation of transfer-models." *Solar Energy* 61(6): 399-413. doi: https://doi.org/10.1016/S0038-092X(97)00081-9

Duffie, A. J., and W. A. Beckman. 1991. *Solar Engineering of Thermal Processes (*4th ed.). Wiley, Hoboken.

Gueymard, C. 1987. "An Anisotropic Solar Irradiance Model for Tilted Surfaces and Its Comparison with Selected Engineering Algorithms." *Solar Energy* 38(5): 367-386. doi: https://doi.org/10.1016/0038-092X(87)90009-0

Klucher, T. M. 1979. "Evaluation of models to predict insolation on tilted surfaces." *Solar Energy* 23(2): 111-114. doi: https://doi.org/10.1016/0038-092X(79)90110-5

Loutzenhiser, P. G., H. Manz, C. Felsmann, P. A. Strachan, T. Frank, and G. M. Maxwell. 2007. "Empirical validation of models to compute solar irradiance on inclined surfaces for building energy simulation." *Solar Energy* 81(2): 254-267. doi: https://doi.org/10.1016/j.solener.2006.03.009

Muneer, T., and D. Kinghorn. 1997. "Luminous efficacy of solar irradiance: Improved models." *International Journal of Lighting Research and Technology* 29(4): 185-191. doi: https://doi.org/10.1177/14771535970290040401

Perez, R., P. Ineichen, R. Seals, J. Michalsky, and R. Stewart. 1990. "Modeling Daylight Availability And Irradiance Components From Direct And Global Irradiance." *Solar Energy* 44(5): 271–289. doi: https://doi.org/10.1016/0038-092X(90)90055-H

Pernigotto, G., A. Prada, P. Baggio, A. Gasparella, and A. Mahdavi. 2015. "Impact of solar irradiation models on simulated hourly energy performance of buildings." In *Proceedings of Building Simulation 2015*, Hyderabad, India.

Pernigotto, G., A. Prada, P. Baggio, A. Gasparella, and A. Mahdavi. 2016. "Solar irradiance modelling and uncertainty on building hourly profiles of heating and cooling energy needs." In *Proceedings of the IV International High Performance Buildings Conference at Purdue*, West Lafayette, IN, U.S.

Pernigotto, G., A. Gasparella, and J.L.M. Hensen, 2021. "Assessment of a weather-based climate classification with building energy simulation." In *Proceedings of Building Simulation 2021*, Bruges, Belgium.

Pernigotto, G., A. Prada, and A. Gasparella, 2022. "Assessment Of The Accuracy Of Solar Irradiance Models In Mountain Locations: The Case Of Bolzano, Italy." In *Proceedings of the VII International High Performance Buildings Conference at Purdue*, West Lafayette, IN, U.S.

Prada, A., G. Pernigotto, A. Gasparella, and A. Mahdavi. 2014a. "Combined effects of diffuse fraction and tilted surface radiation models." In *Proceedings of ECPPM 2014 - 10th European Conference on Product & Process Modelling*, Vienna, Austria.

Prada, A., G. Pernigotto, P. Baggio, A. Gasparella, and A. Mahdavi. 2014b. "Effect of Solar Radiation Model on the Predicted Energy Performance of Buildings." In *Proceedings of the III International High Performance Buildings Conference at Purdue*, West Lafayette, IN, U.S.

Prada, A., G. Pernigotto, F. Cappelletti, and A. Gasparella. 2015. "Impact of solar irradiation models on building refurbishment measures from multi-objective optimization." In Proceedings of Building Simulation 2015, Hyderabad, India.

Robledo, L., and A. Soler. 1998. "Modeling Irradiance on Inclined Planes with an Anisotropic Model." *Energy* 23(3): 193-201. doi: https://doi.org/10.1016/S0360-5442(97)00083-2

Remund, J., W. Lucien, and J. Page. 2003. "Chain of algorithms to calculate advanced radiation parameters." In *Proceedings of ISES Solar World Congress*, Goteborg, Sweden.

UNI (Ente Nazionale Italiano di Normazione). 2014. *UNI/TS 11300-1:2014 – Energy performance of buildings Part 1: Evaluation of energy need for space heating and cooling*, Milan, Italy: UNI.