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Validation of the Window Model of the Modelica Buildings Library

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VALIDATION OF THE WINDOW MODEL OF THE MODELICA BUILDINGS LIBRARY

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ABSTRACT

This paper describes the validation of the window model of the free open-source Modelica Buildings library. This paper starts by describing the physical modeling assumptions of the window model. The window model can be used to calculate the thermal and angular properties of glazing systems. It can also be used for steady-state simulation of heat transfer mechanism in glazing systems. We present simulation results obtained by comparing the window model with WINDOW 6 the well established simulation tool for steady-state heat transfer in glazing systems. We also present results obtained by comparing the window model with measurements carried out in a test cell at the Lawrence Berkeley National Laboratory.

INTRODUCTION

To accelerate innovation leading to cost-effective very low energy systems for new and existing buildings, the Lawrence Berkeley National Laboratory has been developing a free and open source Modelica Buildings library for building energy and control systems (Wetter et al. 2011a). The library contains more than 200 component models for HVAC systems, controls and airflow network. They can be used for analysis of the operation of existing building systems, fast prototyping of innovative systems, and development of advanced controls.

Recently, we implemented window and room models into the Buildings library to extend its capability to whole building energy simulation (Wetter et al. 2011b). This paper presents the validation of the window model. The first part of this paper describes the main physical assumptions of the window model. The second part of the paper validates the window model using both WINDOW 6 and experimental data. The results show that the window model of the Buildings library version 1.0 build 2 provides similar results as WINDOW 6 and experimental data.

PHYSICAL WINDOW MODEL

The models used in the Modelica window model of the Buildings library version 1.0 build 2 are similar to the equations used in WINDOW 6 (Robin et al. 2011) and are described in TARCOG 2006 (TARCOG 2006). The model computes the heat balance between the exterior surface and the room-facing surface for a window system. The current version of the Modelica implementation can handle an infinite number of glazing layers. In addition, it can have an exterior or an interior shade, but not both, or it can have no shade. The convective and radiative heat transfer between the window system and the outside or the room is computed by the models *ExteriorHeatTransfer* and *InteriorHeatTransfer*.

The *window* model has three main sub models that implement the relevant heat balances:

1. The model *frame* computes one-dimensional heat conduction through the frame.
2. The model *glaUns* computes the heat balance of the part of the glass that is unshaded. For example, if the shade signal is u=0.2, then this model accounts for 80% of the glass that is not behind the shade or blind.
3. The model *glaSha* computes the heat balance of the part of the glass that is shaded. For example, if u=0.2, then this model accounts for the 20% of the glass that is behind the shade or blind. If the parameter *glaSys* specifies that the window has no exterior and no interior shade, then the model glaSha will be removed.

The models *glaUns* and *glaSha* compute the solar radiation that is absorbed by each glass pane and the solar radiation that is transmitted through the window as a function of the solar incidence angle. They then compute a heat balance that takes into account heat conduction through the glass, heat convection through the gas layer, and infrared radiation from the exterior and the room through the glass and gas layers. The infrared radiative heat exchange is computed using a radiosity balance. Heat conduction through the frame is computed using a heat flow path that is parallel to the glazing system, i.e., there is no heat exchange between the frame and the glazing layer.

It is important to notice that there are differences in the calculation of glass properties between the Buildings library and the WINDOW 6 program. To calculate the angular transmittance, reflectance and absorptance of a glazing system, WINDOW 6 first calculates these values at distinct wave lengths using transmittance and reflectance at zero incidence angle for that wave length. It then weights the calculated angular transmittance, reflectance and absorptance over the entire spectrum. This approach requires a library that contains glass property at various wave lengths. The window model in the Buildings library version 1.0 build 2 only uses the spectrally averaged transmittance and reflectance of glass at zero incidence angle and does not count their differences over the spectrum of wave lengths. As a result, there are differences in prediction between the current Modelica window model and WINDOW 6. These differences will be shown in the next section.

Comparative model validation with WINDOW 6

The following section describes the validation of the Modelica window model through comparisons with WINDOW 6.
As a first validation step, the angular properties of five different glazing systems are calculated using the Modelica window model and results are compared with the results of WINDOW 6.
1. The first system (sys1) is a single pane glazing system with an uncoated glass. The material properties of the glass pane are listed in Table 1.

Table 1 Material properties of the uncoated glass pane for the solar spectrum

	d [mm]	T [-]	R_f [-]	R_b [-]
Glass	3	0.834	0.075	0.075

where d is the thickness of the glass, T is the transmittance at normal incidence, and R_f and R_b are front and back reflectance at normal incidence.
2. The second system (sys2) is a double pane glazing system composed of two identical uncoated glasses with a *12.7 mm* air layer in between. The glasses are the same as the ones used in sys1.
3. The third system (sys3) is a single pane glazing system with a coated glass. The material properties of the glass can be seen in Table 2.

Table 2 Material properties of the coated glass pane for the solar spectrum

	d [mm]	T [-]	R_f [-]	R_b [-]
Glass	3	0.646	0.062	0.063

4. The fourth system (sys4) is a double pane glazing system with two identical coated glasses and a *12.7 mm* air layer in between. The glasses are the same as the ones used in sys3.
5. The fifth system (sys5) is a double pane glazing system composed of a coated and an uncoated glass with a *12.7 mm* air layer in between. The coated glass is the first (outside) pane of the glazing system. The glasses are the same as the ones used in sys3 and sys1.

In the remainder of this section, the following nomenclature will be used in figures:

- WINDOW 6: **Win**
- Modelica window model: **Mod**
- Transmittance of a glazing system: **T**

- Absorptance in a pane of a glazing system: **A**
- First pane of double pane glazing system (outside): **P1**
- Second pane of double pane glazing system: **P2**

The properties **T** and **A** are for the solar spectrum.

Figure 1 and Figure 3 show the transmittance and absorptance of the first and second glazing system calculated at different incidence angles with WINDOW 6 and the Modelica window model. In these calculations, WINDOW 6 uses the full spectral data of each glass pane in the calculation of the angular properties of the glazing system. As shown in Figure 3, there is a maximum difference of about 10% in absorptance values between the WINDOW 6 and the Modelica window model. This difference is due to the current limitation of the Modelica window model which does not use spectral data for the calculations of angular properties of glazing systems. This discrepancy can be small for a single pane glazing system but may increase for multiple pane glazing system as shown in Figure 3.

Figure 2 and Figure 4 show the transmittance and absorptance of first and second glazing system when using spectrally averaged data in both models. The simulation results show good agreements between the two models. The maximum difference in absorptance values of less than 1% is mainly due to the number of significant digits in the WINDOW 6 output files.

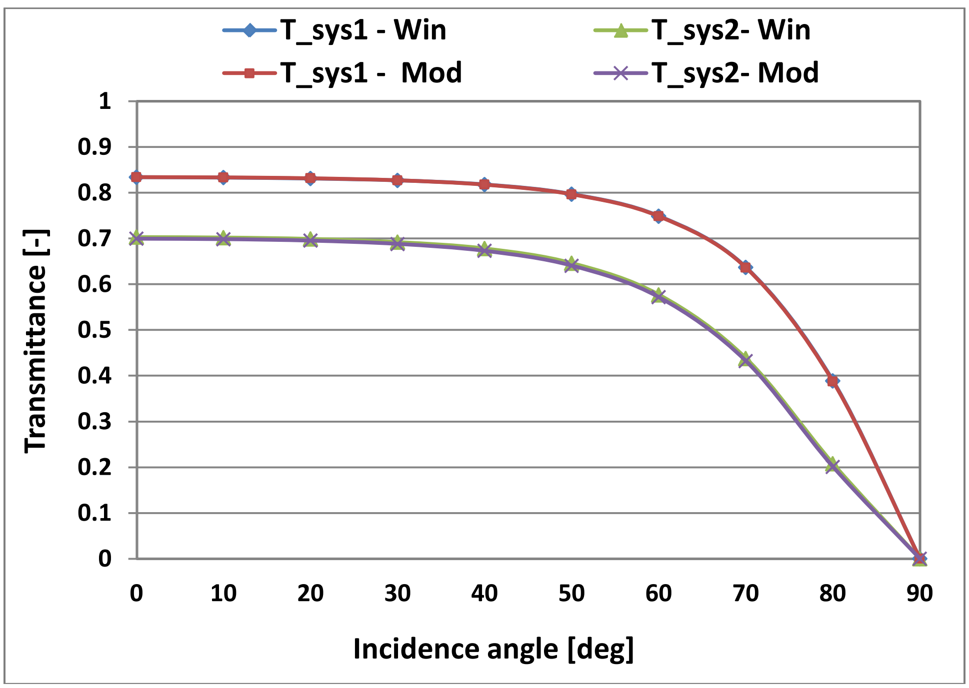

Figure 1 Transmittance values of single (sys1) and double pane (sys2) glazing systems calculated at different incidence angles using WINDOW 6 with spectral data and Modelica

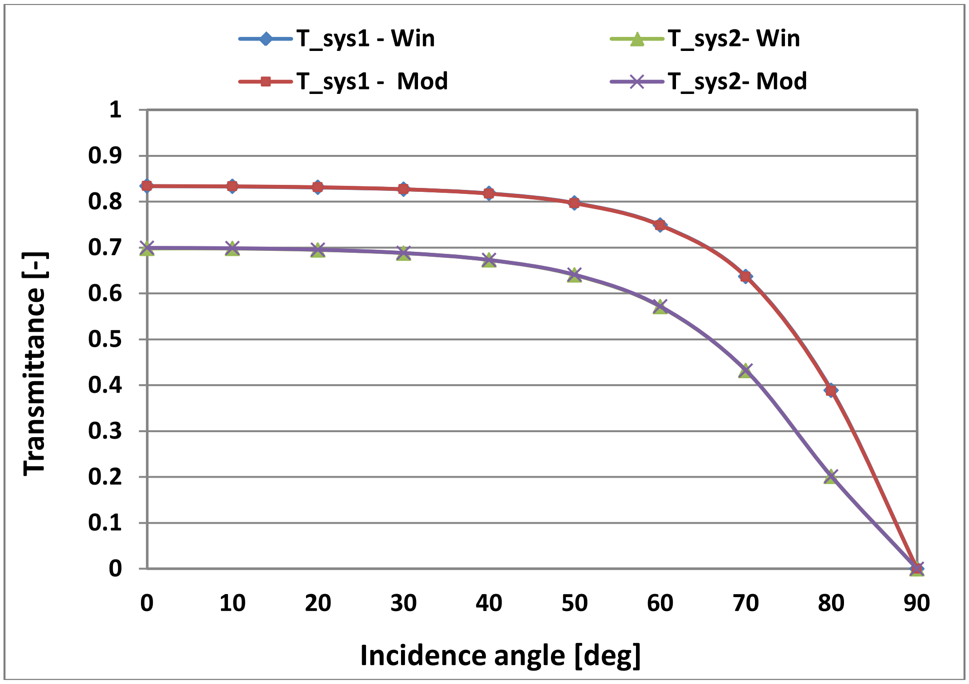

Figure 2 Transmittance values of single (sys1) and double pane (sys2) glazing systems calculated at different incidence angles using WINDOW 6 with spectrally averaged data and Modelica

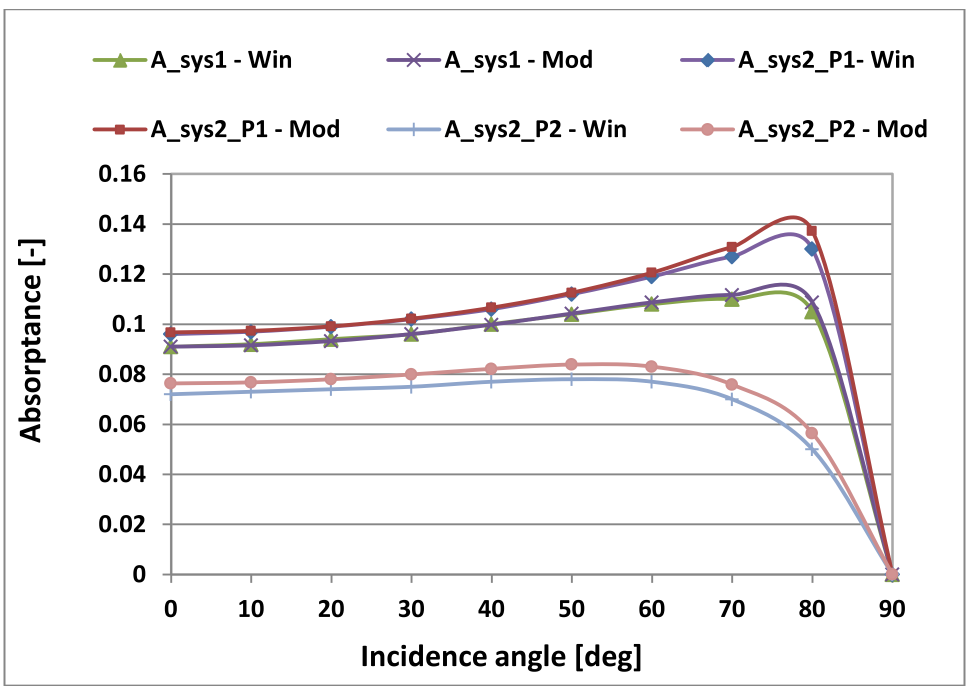

Figure 3 Absorptance values of single (sys1) and double pane (sys2) glazing systems calculated at different incidence angles using WINDOW 6 with spectral data and Modelica

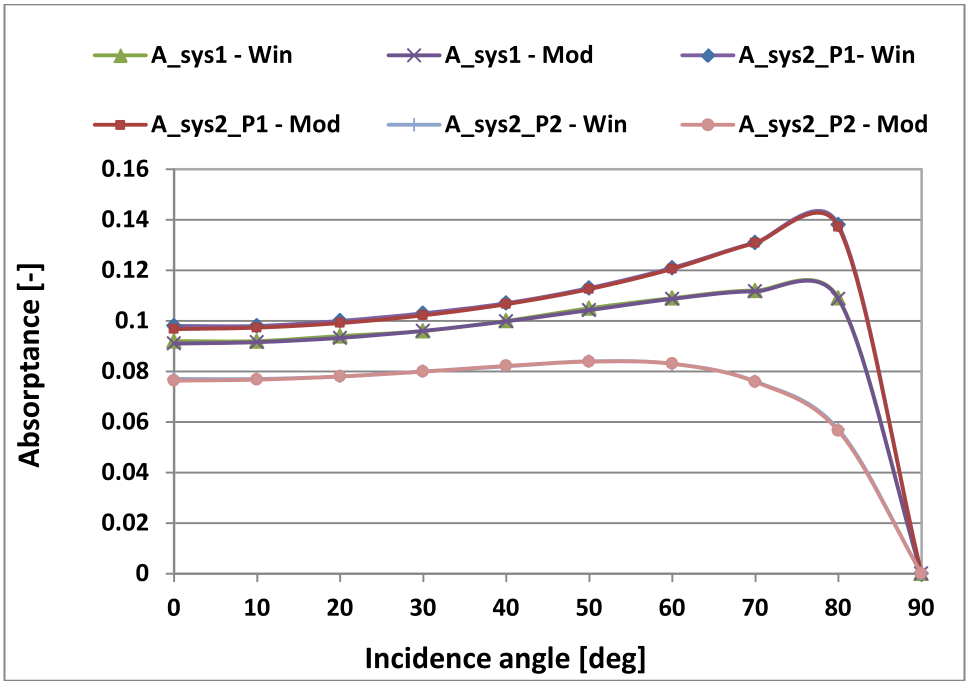

Figure 4 Absorptance values of single (sys1) and double pane (sys2) glazing systems calculated at different incidence angles using WINDOW 6 with spectrally averaged data and Modelica

Figure 5 to Figure 8 show transmittance and absorptance for the third (sys3), fourth (sys4) and fifth (sys5) system calculated in WINDOW 6 and Modelica using spectrally averaged data. In all these charts there are good agreements between both models with maximum differences of less than 1%.

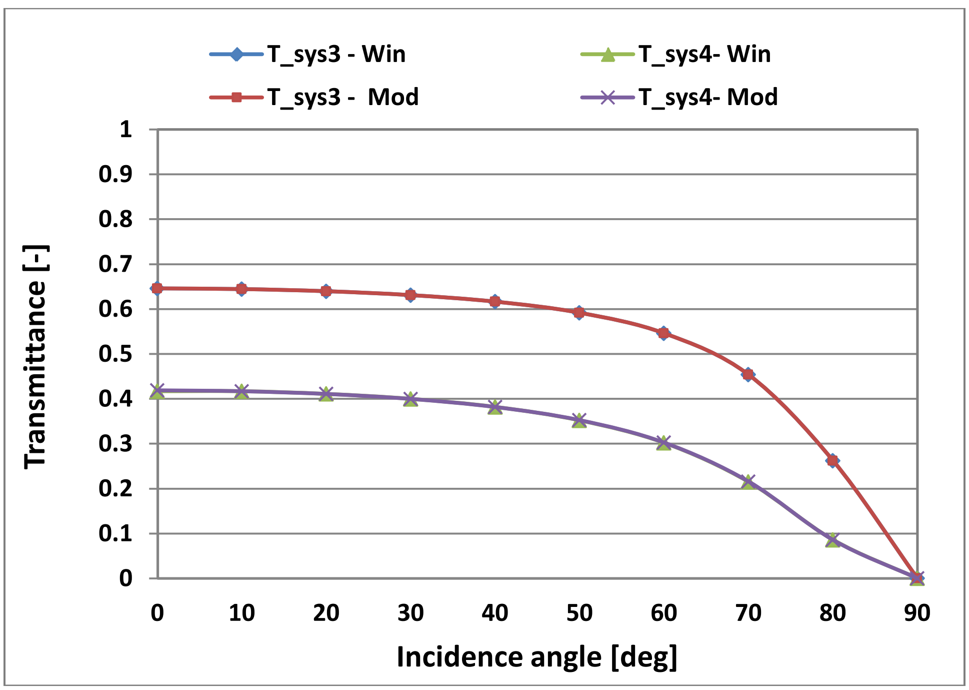

Figure 5 Transmittance values of single (sys3) and double pane (sys4) glazing systems calculated at different incidence angles using WINDOW 6 with spectrally averaged data and Modelica

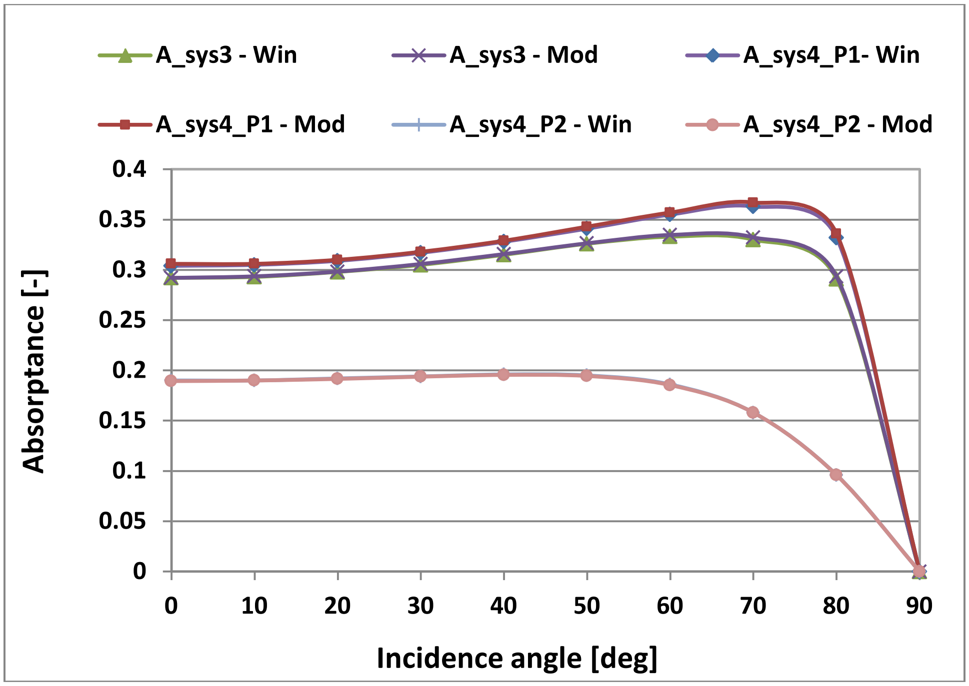

Figure 6 Absorptance values of single (sys3) and double pane (sys4) glazing systems calculated at different incidence angles using WINDOW 6 with spectrally averaged data and Modelica

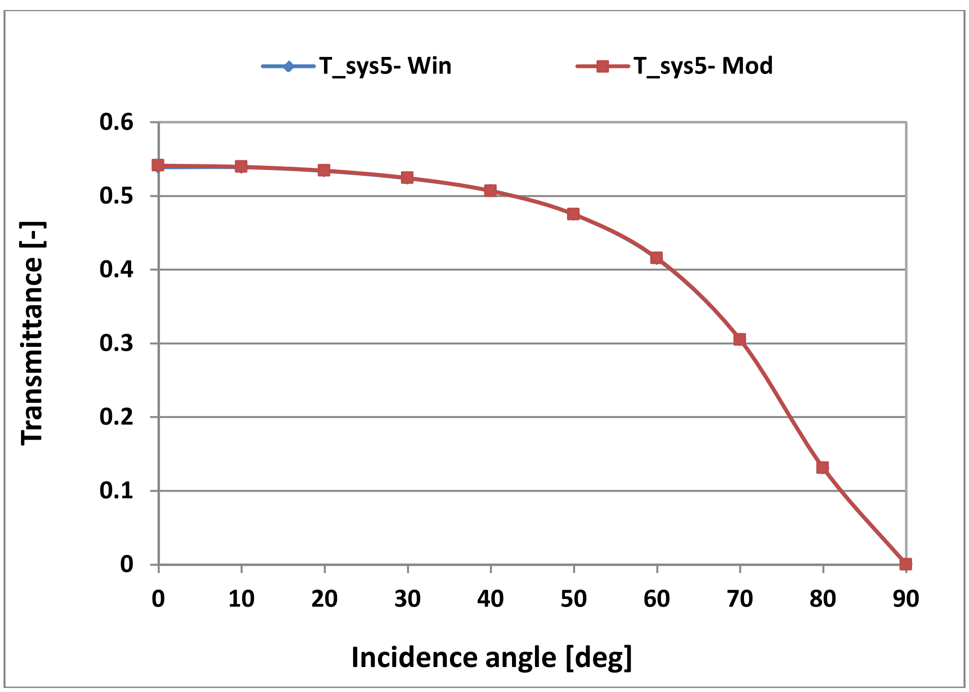

Figure 7 Transmittance values of double pane (sys5) glazing systems calculated at different incidence angles using WINDOW 6 with spectrally averaged data and Modelica

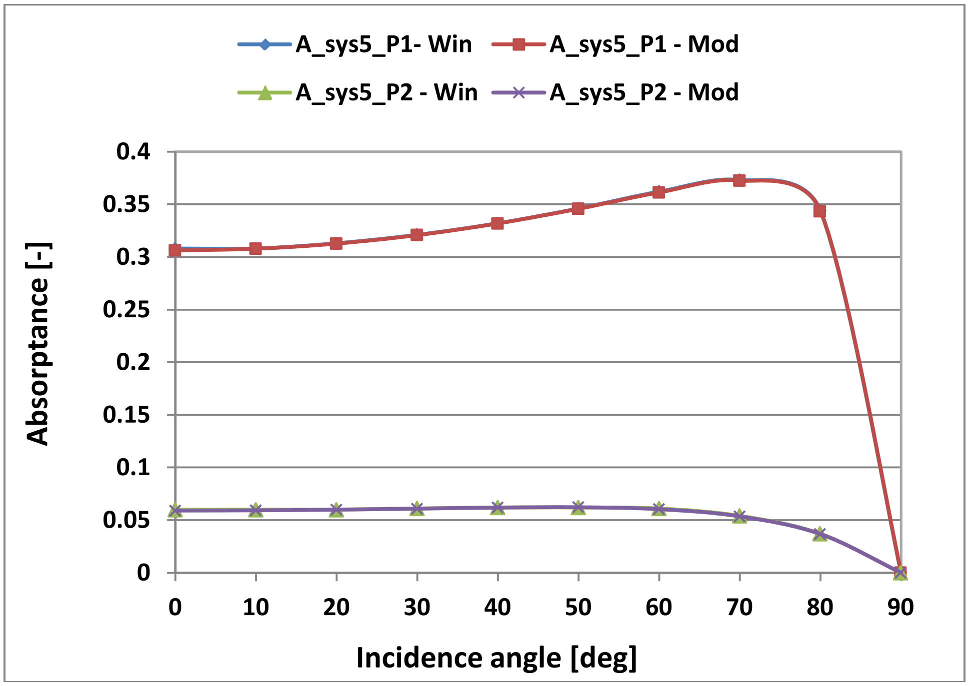

Figure 8 Absorptance values of double pane (sys5) glazing systems calculated at different incidence angles using WINDOW 6 with spectrally averaged data and Modelica

As a second validation step, we simulated the temperature distribution of the double pane glazing system (sys2) with the Modelica window model under steady state boundary conditions. We compared the results with WINDOW 6. WINDOW 6 uses in this case spectrally averaged data for the calculation of the angular properties of the glazing system. For the simulation, we set the interior air temperature T_{air_i} as well as the interior radiative temperature T_{rad_i} to *24 °C*. The interior convective heat transfer coefficient $h_{\_conv\_i}$ is set in both models to *4 W/m²K*, the exterior air temperature T_{air_o} as well as the exterior radiative temperature T_{rad_o} are both set to *32 °C*. The exterior convective heat transfer coefficient $h_{\_conv\_o}$ is set to *26 W/m²K*. There is a direct radiation heat source $Rad_{\_dir}$ in the solar spectrum which is equal to *500 W/m²* at normal incidence.
The outer and inner surface temperature of the first (P1) and second (P2) pane are computed and compared for both models. The simulation results show (see Figure 9) that the surface temperatures match within 0.05 °C.

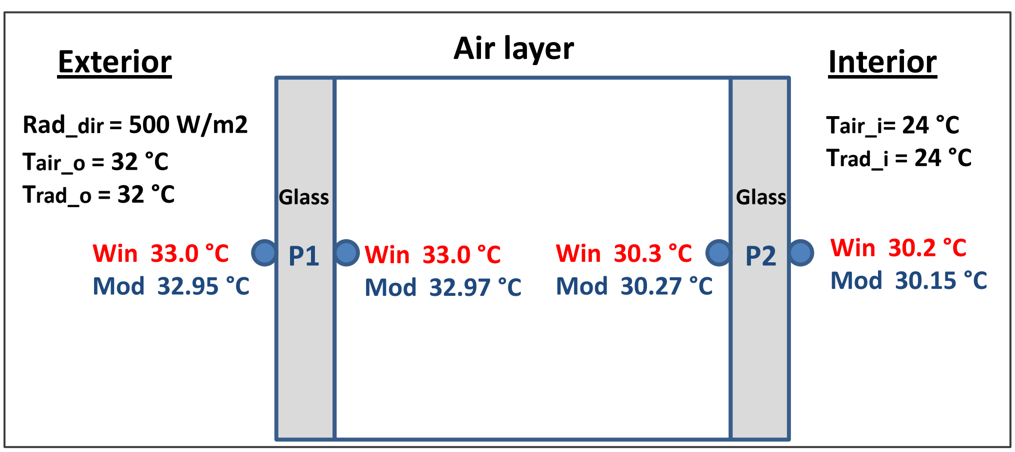

Figure 9 Temperatures and boundary conditions of the double pane glazing system calculated using Modelica and WINDOW 6

Validation with experimental data

For the validation of the Modelica window model, experiments were conducted in one test cell of the Advanced Windows Test Bed Facility (71T) at the Lawrence Berkeley National Laboratory. In these experiments, the exterior surface temperature of the window glass as well as the incident and transmitted solar irradiation were measured. These data were used to compare the simulation of the Modelica window model with experimental data. Figure 10 shows a photo of the Advanced Windows Test Bed Facility used for the validation. The oval indicates the test cell that was used.

Advanced Windows Test Bed Facility

The test bed facility 71T is located at the Lawrence Berkeley National Laboratory. This facility is an advanced window test facility with three identical test cells which serve for testing and evaluation of controls strategies and façade systems. Each of these test cells has a ground area of about $14\ m^2$, a room volume of about $47m^3$ and a south facing window. The room air temperature of the test cells is controlled to a fixed temperature. There are several sensors in the test cells which measure room air temperatures, exterior glass surface temperatures at the upper and lower window surface, plug loads, lighting loads, fan loads as well as transmitted solar irradiation at the upper and lower window surface. There are also several sensors located outdoors to measure external environmental conditions, such as solar irradiances, outdoor temperature, and wind speed (see Figure 11).

Figure 10 Advanced Windows Test Bed Facility at the Lawrence Berkeley National Laboratory

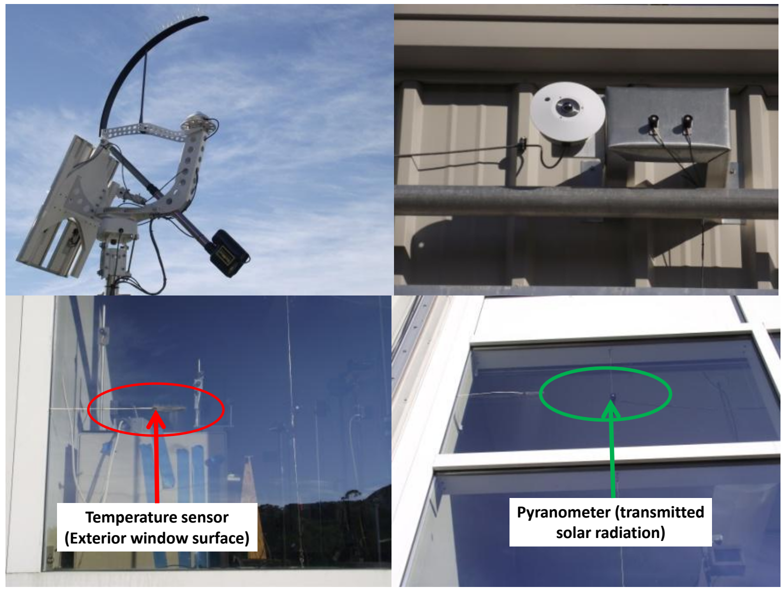

Figure 11 Pyranometer and pyrheliometer for diffuse and direct solar irradiation (top left), pyrgeometer for atmospheric infrared radiation (top right), thermistors for exterior surface temperatures (bottom left), and pyranometers for transmitted solar irradiation (bottom right) installed at 71T

The south window is modeled in Modelica. The window is a double pane glazing system composed of two *5.9 mm* pane glasses with a *12.7 mm* air gap in between. The first pane glass (outside) is coated while the second pane is uncoated. The material properties of the glass panes can be seen in Table 3. E_{f_lw} and E_{b_lw} are front and back long wave emissivity coefficients.

Table 3 Material properties of the double pane glazing system used at 71T for the validation of the Modelica window model

	d [mm]	T [-]	R_f [-]	R_b [-]	E_{f_lw} [-]	E_{b_lw} [-]
Pane1	5.9	0.436	0.424	0.456	0.74	0.05
Pane2	5.9	0.868	0.076	0.076	0.84	0.84

As a first validation step with experimental data, we measured incident and transmitted solar irradiation at two positions at the upper and lower window using LI-COR pyranometers (Li-200 2012) and compared the measurements with simulations. As boundary conditions for the Modelica window model, we recorded from January 12, 2012 until January 19, 2012 on a 15 minutes basis the diffuse solar irradiation on the horizontal surface as well as the direct normal irradiation using hukseflux pyranometers. The Modelica window model is simulated for the given period and the simulation results are compared with the measurements.

Figure 12 shows a comparison between measured and simulated vertical incident outside global solar irradiation on the south window. This chart shows a good agreement between simulation and measurements. The maximum discrepancy of about 5% is mainly due to the tolerance in the instrumentation used to measure the vertical incident outside global solar irradiation. The manufacturer data specifies that the LI-COR pyranometer has a tolerance of about 5% and that it should only be used to measure unobstructed daylight. Figure 13 shows a comparison between measured and simulated transmitted solar irradiation through the window. Since the transmitted solar irradiation is measured at two positions, an average value is used in the comparison. The difference between simulation and measurements is similar to the difference in the incident global irradiation.

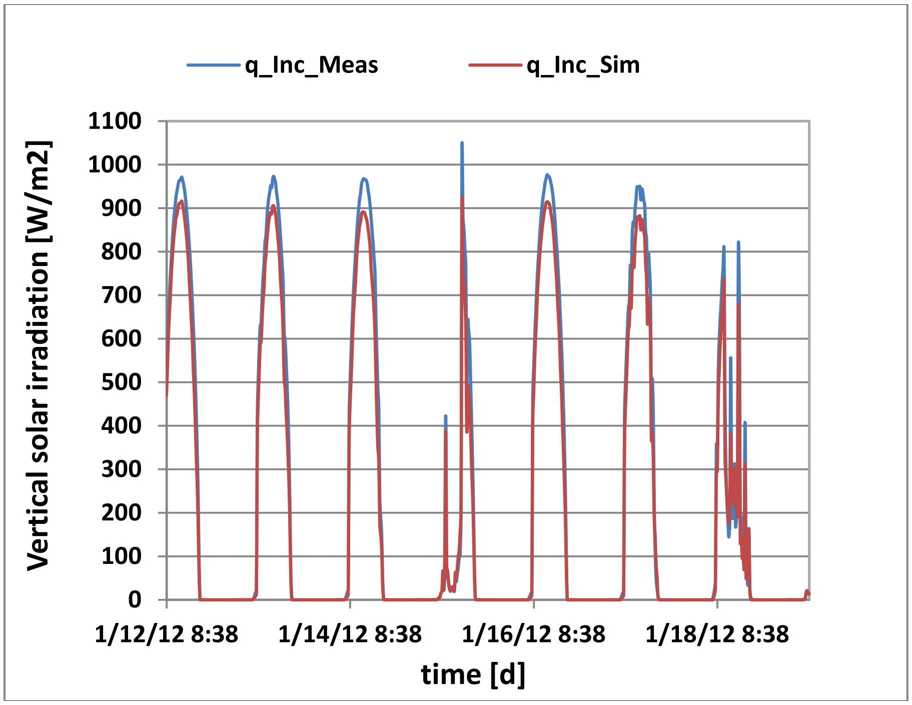

Figure 12 Comparisons between simulated (red) and measured vertical outside solar irradiation on south window

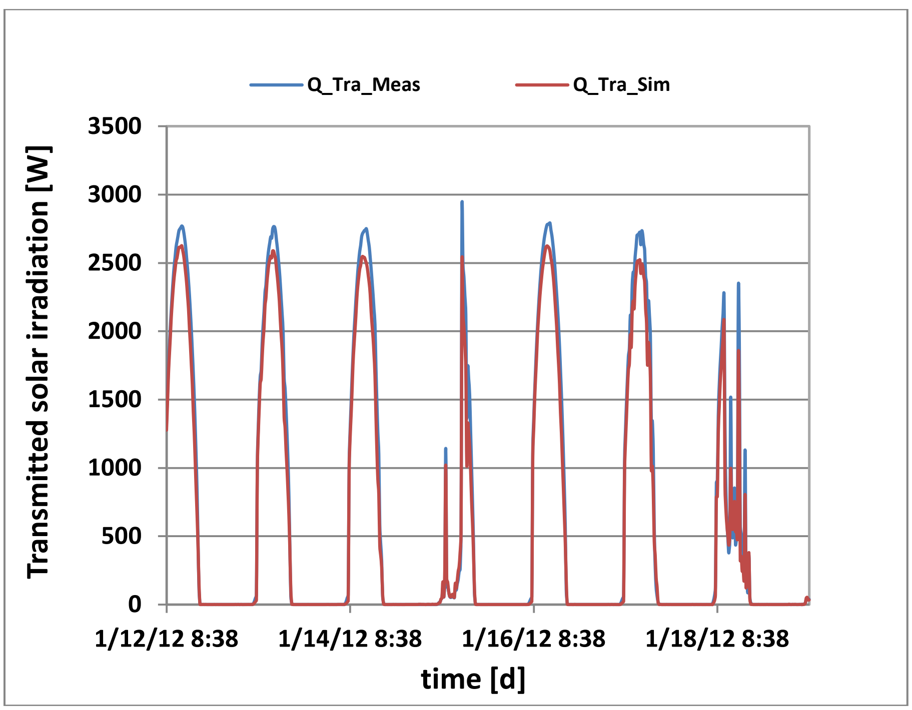

Figure 13 Comparisons between simulated (red) and measured transmitted solar irradiations

Figure 14 and Figure 15 show the simulation results obtained by comparing the Modelica window model with the measurements while considering a 5% tolerance in the measured data of the LI-COR pyranometers. The simulated solar irradiation is close to the lower bound of the uncertainty interval of the solar irradiation measurements.

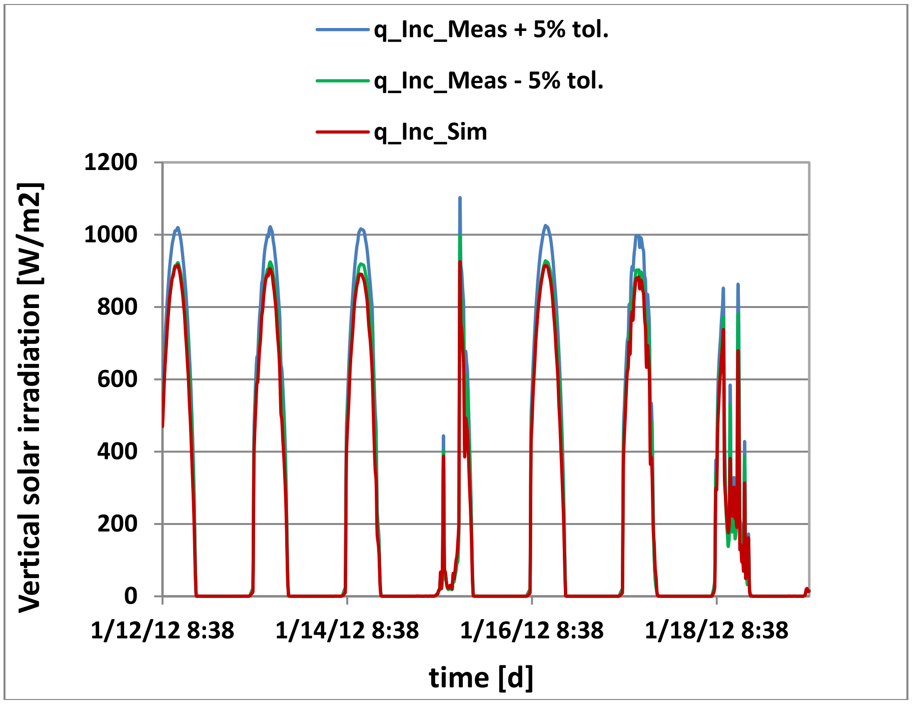

Figure 14 Comparisons between simulated (red) and measured incident vertical outside global irradiation, considering a 5% tolerance in the LI-COR pyranometers

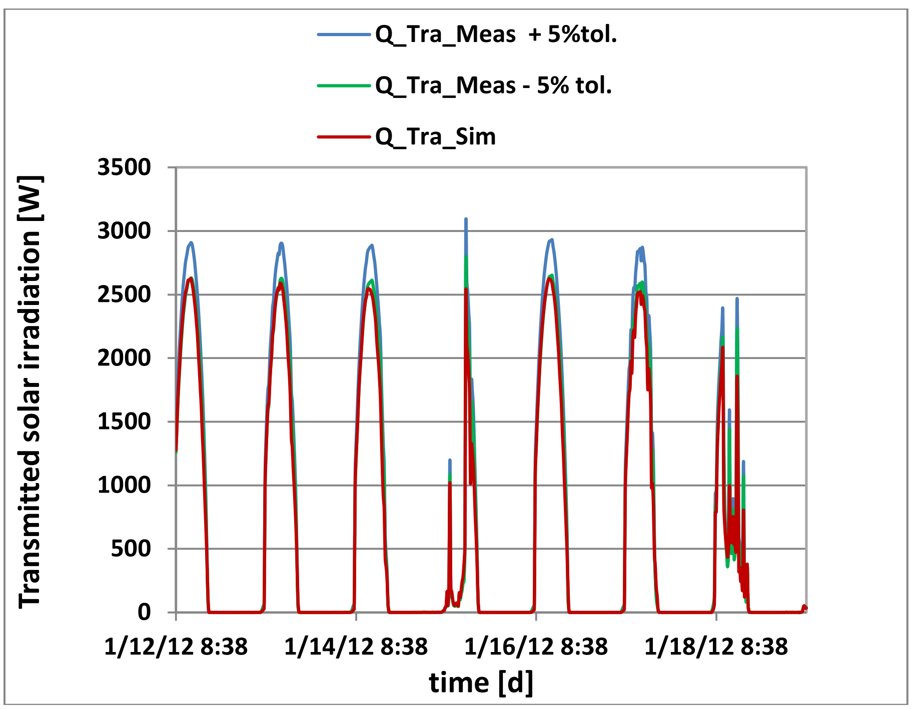

Figure 15 Comparisons between simulated and measured transmitted solar irradiation, considering a 5% tolerance in the LI-COR pyranometers

As a second validation step, we compared the measured exterior surface temperature with simulations. As boundary conditions for the Modelica window model for the computation of the exterior surface glass temperature, we recorded from January 12, 2012 until January 19, 2012 the solar irradiation data, the dry bulb temperature, the room air temperature, the horizontal infrared radiation, and the wind speed. The room air temperature is kept constant at *24°C* during the entire measurement period. Figure 16 shows the positions of the temperature sensors used to measure the exterior surface temperature of the window glass. The surface temperatures were recorded at two positions.

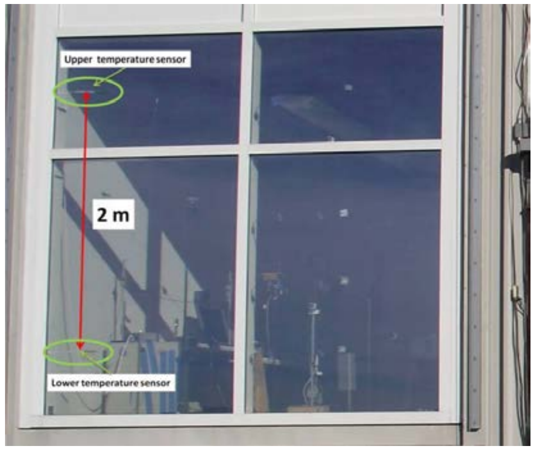

Figure 16 Position of temperature sensors used to measure the outside surface temperature

Figure 17 shows a comparison between simulated and measured exterior outside surface temperature at the window glass. The measured temperature used for the comparison is the average between the temperature recorded by the upper and lower sensor.

The results show a good agreement between simulation and measurements at nighttime. The difference during the daytime is first correlated to the discrepancy that is shown in Figure 12 in the irradiation incident to the window which was lower in the simulation compared to the measurements. However, the difference will not significantly decrease if we consider the tolerance of the solar irradiation measurement as can be seen in Figure 18.

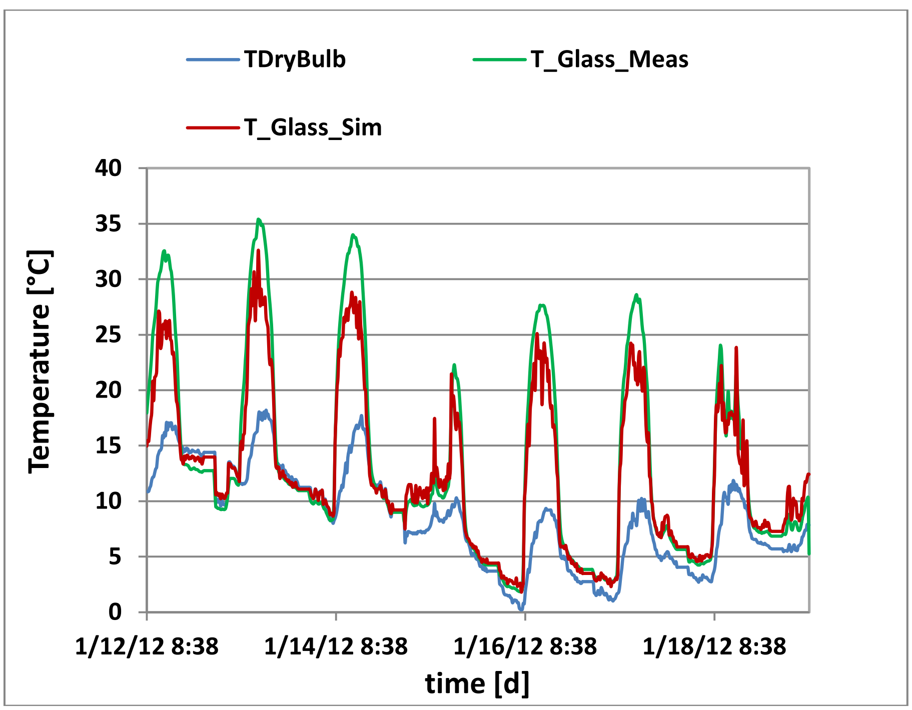

Figure 17 Comparisons between simulated and measured exterior pane outside surface temperature

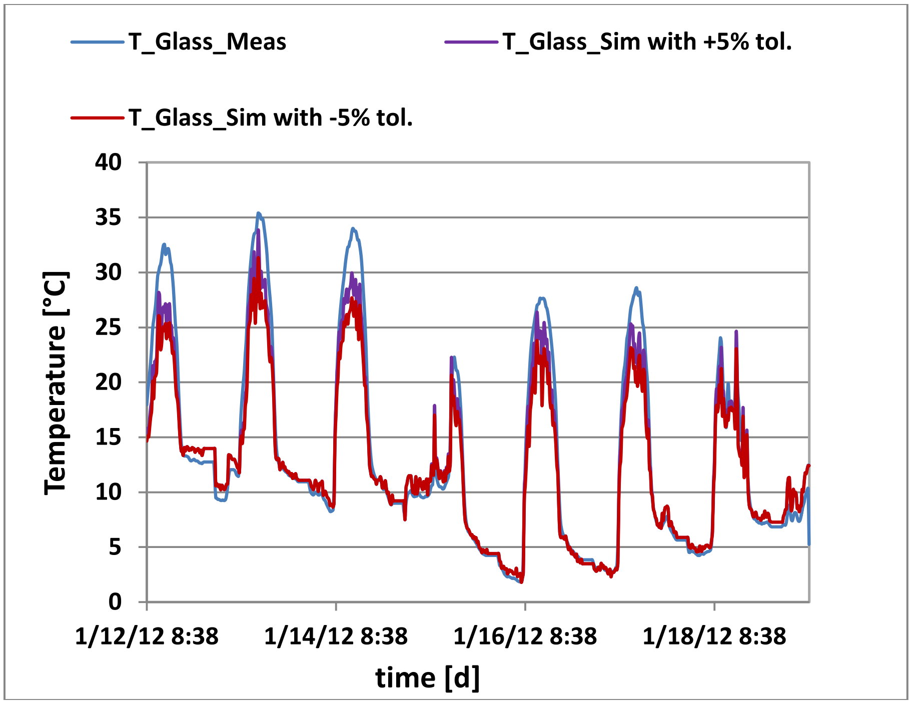

Figure 18 Comparisons between simulated and measured exterior pane outside surface temperature when considering a 5% tolerance in LI-COR pyranometers

We believe that the main reason for the difference between the measurements and the simulation during daytime is the error associated with the Room Temperature Vulcanizing sealant used for mounting temperature sensors which could not be shielded for the measurements. This can absorb solar radiation and thus leads to a temperature at the sensor that is higher than the glass temperature. To verify this assumption, we calculated the temperature difference (

transmitted solar radiation as well as surface temperature of window glass show good agreement with measurements when taking into account the uncertainties in measurements.

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