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Using architectural glazing systems to harness solar thermal potential for energy savings and indoor comfort

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A R T I C L E I N F O

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A B S T R A C T

The capacity of windows to transmit solar irradiance contributes significantly to indoor environments, which facilitates supplemental warmth courtesy of shortwave solar irradiance, impacting both human comfort and building energy dynamics. This study explores the impact of window glazing on indoor thermal comfort and building energy dynamics through shortwave solar irradiance. It presents a comprehensive analysis of 5,138 glazing systems and introduces a novel thermal effect index. This index was generated using a spectrally-resolved method to classify windows based on their capacity to transmit solar energy. The index divides the quantified thermal effects into 10 equally-sized ranges and assigns corresponding indices. In addition to recognizing the influence of specific solar spectral distributions on the thermal effects of glazings, this work also proposes a method for computing effective wavebands of spectral transmittance, allowing for the rapid evaluation of a window's thermal effects under diverse solar spectra. In essence, this study emphasizes the importance of the thermal effect in understanding solar energy utilization and determining implications for energy savings and enhanced indoor thermal comfort. By addressing the interplay between solar energy use and human comfort, this research offers valuable insights for future advanced envelope design and energy management strategies. With this knowledge, we will be better able to tailor advanced envelope products to meet both human needs and energy efficiency goals by harnessing solar energy.

1. Introduction

The sun's high temperature and abundant energy have a direct impact on human beings' daily lives, particularly through shortwave radiation. As shortwave solar irradiance passes through windows, it interacts with human skin and creates a thermal effect by affecting human thermal comfort, particularly in indoor near-window zones [1]. Shortwave solar irradiance has a spectral power distribution that distributes energy into different wavelengths from near-ultraviolet and visible to near-infrared wavebands [2]. The spectral power distribution of the solar irradiance reaching windows can vary depending on factors such as time of day, day of the year, window orientation, and weather conditions [3]. Windows serve as a medium for introducing sunlight into indoor spaces, and their transmittance properties have spectral power distributions that also exhibit variations, due to differences in manufacturing techniques [4]. For instance, our previous work has highlighted significant variations in thermal comfort resulting from the installation of different windows, despite their having similar properties [5]. Therefore, the selection of window glazing systems is crucial for determining the solar energy distribution that enters an indoor space and subsequently affects human thermal comfort [6].

Windows vary in their spectral characteristics and optical properties, due to differences in glazing systems, materials, and styles. To help customers, architects, and engineers understand window performance, the National Fenestration Rating Council (NFRC) requires labeling that displays a series of indicators, including U-factor, solar heat gain coefficient (SHGC), and additional information such as spectral-average visible transmittance (Tvis), air leakage, condensation resistance, and design pressure [7,8]. However, until now, the impact of windows on solar energy's thermal effects has not been evaluated and labeled. Thus, the necessity of introducing a new index that represents the ability of a window to allow sunlight indoors and influence human thermal comfort needs to be considered and evaluated.

The thermal comfort of a human being can be evaluated by a predicted mean vote (PMV) model, which assigns a continuous seven-scale vote based on factors such as air temperature, humidity, air speed, mean radiant temperature (MRT), metabolic rate, and clothing insulation [9].

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Nomenclature

Tvis	Spectral-averaged visible transmittance of window
MRT_delta	Additional mean radiant temperature
MRT_delta_s	Spectrally-resolved additional mean radiant temperature
TEI	Thermal effect index
Tsol	Spectral-averaged solar transmittance of window
Tsol_s	Solar-weighted solar transmittance of window
Tsol_eff	Effective waveband spectral-average solar transmittance of window

Among them, MRT represents the effect of longwave solar irradiance on human thermal comfort [10]. To incorporate the influence of shortwave solar radiation on human thermal comfort, the thermal effect of shortwave solar radiation on human skin can be converted into equivalent longwave radiation, referred to as additional mean radiant temperature (MRT_delta), for inclusion in the PMV model [11]. To further account for the spectral nature of solar irradiance, window transmittance, and skin absorptance, a spectrally-resolved method is proposed to improve the accuracy of thermal comfort prediction. The role of windows in influencing thermal comfort can be evaluated by calculating the MRT_delta values via this spectrally-resolved method, in order to obtain the spectrally-resolved additional mean radiant temperatures (MRT_delta_s) and incorporate them into conventional PMV models [12]. The evaluation can then be used to establish a thermal effect index (TEI) that provides a measure of the window's impact on the shortwave solar thermal effect.

The International Glazing Database (IGDB) collects optical data for certified glazing products, including spectral transmittance data measured using a spectrophotometer. This database serves as the primary data source for the LBNL WINDOW program that powers the NFRC window rating system [13]. Thus, generating TEIs for glazing systems in the IGDB will include an evaluation of the thermal effect of a significant number of glazing systems. For those glazing systems not present in the database and scenarios involving different solar zenith angles, windows facing different directions, and so on, an estimation of the thermal effect is necessary to avoid complex calculations. The spectral-average solar transmittance parameter (Tsol) of a glazing system is closely correlated with the MRT_delta_s but cannot fully capture the properties of the glazing that are related to its thermal effect. This is due to the failure to represent the spectral nature of window transmittance and involve the spectral interactions among window transmittance, solar irradiance, and skin absorption [14]. Thus, a simplified spectral-based method is also needed to effectively predict the thermal effect of glazing systems.

Furthermore, different levels of the solar thermal effect require different thermostat settings to maintain thermal comfort, leading to different energy consumption levels. EnergyPlus is a powerful tool that integrates building simulation, environmental factors, HVAC system data, and so on in energy simulations, enabling energy consumption predictions and comparisons for the different heating and cooling loads during the solar cycle [15]. Accordingly, the sustainability impact of TEI generation can also be evaluated.

This research underscores the necessity of developing a new index to evaluate the thermal effects of glazing products listed in the IGDB. If necessary, TEIs will be generated for the glazings listed in the database, with special consideration for their specific solar conditions and boundary settings. Next, energy consumption levels for the different TEI values will be analyzed and compared via EnergyPlus. Additionally, a fast estimation method will be proposed herein for individual conditions in which the solar spectral distributions reaching human skin are different from those of defined conditions, allowing for adaptation in response to specific needs.

2. Prior knowledge

Shortwave solar irradiance consists of direct, diffuse, and reflective solar irradiance; its effect on human indoor thermal comfort depends on the intensity and spectral power distribution of the sunlight reaching human skin. Under different conditions, the intensity and spectrum of solar irradiance can vary due to shifts in the three solar components reaching human skin. The dominant factors influencing availability are summarized in Fig. 1 [12]. The spectral transmittance of the window is one factor influencing the thermal effect of solar irradiance. A window's thermal effect depends on the intensity and spectrum of solar irradiance reaching that window, which is influenced by the factors highlighted in the gray boxes in Fig. 1. In essence, due to the spectral nature of the solar spectrum and window transmittance, the variations in the solar spectrum reaching the window influence the role that window plays.

To quantify the thermal effect, a value represented by MRT_delta_s, the superposition of direct, diffuse, and reflected solar irradiance reaching human skin must be calculated through the process outlined in Fig. 1 and converted into MRT_delta_s. Solar irradiance reaching the building can be obtained from certain local organizations' databases or simulated using software like SMART2. Window orientation determines whether direct solar irradiance can enter the indoors and reach human skin. The orientation degree of the window and solar azimuth angle can be used to consider the availability of direct solar irradiance indoors. Other factors can also be employed in the calculation, as well as defined values representing different conditions. With the variables defined and assumed, MRT_delta_s values can then be obtained.

The window visible transmittance described in the product specifications fails to consider spectral variations in solar irradiance and the weights of the transmittance across all wavelengths of the full waveband for the solar spectra obtained in differing conditions. Accordingly, the solar-weighted solar transmittance of a window (Tsol_s), which takes variations in the solar spectra into account, was developed to represent the transmittance properties of the window after consideration of the spectral nature and variations involved [12].

3. Method

3.1. Thermal effect simulation settings and glazing datasets

The MRT_delta_s values were calculated for the simulation of solar energy's thermal effect on humans in indoor near-window zones under different glazing conditions. Tsol_s values were then determined for comparison with the window transmittance data provided by various manufacturers. Since this research focused on investigating the role of windows, the fixed solar and skin absorptance spectra were used in the simulation. The calculations utilized the American Society for Testing and Materials G-173 spectrum, which is regarded as a reference air mass 1.5 spectrum [16,17]. The direct normal and diffuse horizontal irradiance spectra of the reference solar values were extracted from the simulation via SMART2 terminal-based software (version 2.9.5) [18,19]. According to the software output, the total broadband global irradiance of the reference solar values for the horizontal plane was 697 W/m^2. For skin absorptance, a white skin absorptance with a spectral-average absorptance of 0.570 was assumed, and the spectrum was extracted from the Reference Data Set of Human Skin Reflectance [20]. To align with the wavelength intervals of the solar spectrum, interpolation was employed for the skin's spectral absorptance.

The glazing spectral transmittance data for the simulation were derived from the IGDB, However, it was found that the wavelength intervals of the transmittance of the glazing systems in the IGDB were inconsistent. As a result, certain glazing systems (# 545) had to be excluded because their wavelength intervals of spectral transmittance differed significantly from the selected intervals of the solar spectrum and the skin's spectral absorptance. Some of the spectra that were retained were interpolated to include missing wavelengths and abridged

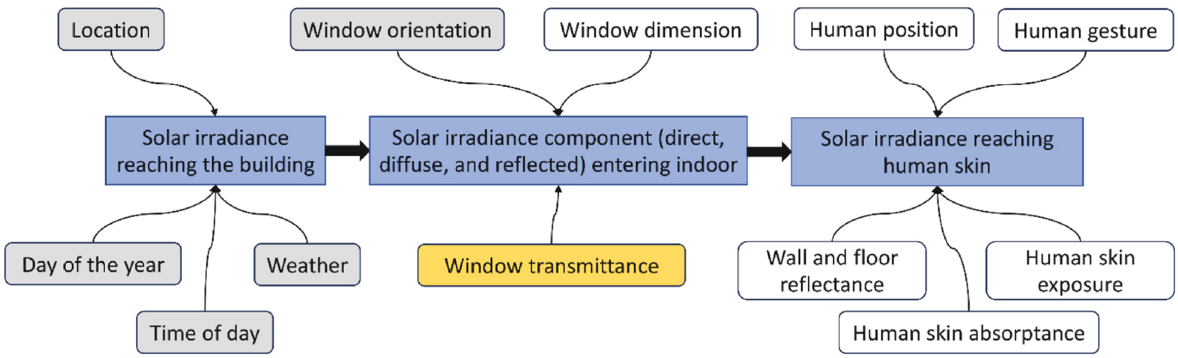

Fig. 1. Factors influencing the availability of shortwave irradiance on human skin. The solar radiation penetration process is depicted by rectangular boxes highlighted in blue and bold arrows. Factors influencing each node in the process are indicated by rounded rectangles and connected to their corresponding nodes with curved arrow connectors. Additionally, factors influencing the spectrum of the penetrated solar radiation are visually highlighted in shades of gray and yellow in which the window transmittance factor is the primary focus of this study.

to remove redundant wavelengths, aligning them with the selected wavelength intervals. In short, 5,138 out of 5,683 glazing systems were finally selected from the IGDB and tailored to match the required wavelength intervals for the upcoming simulation.

The settings of boundary conditions in the calculation of the MRT_delta_s and the calculation formula for Tsol_s remained consistent with our previous research [12]. It is important to note that we assumed that the window faced south and had dimensions of 2.8 m by 2.8 m, with a sill height of 0.5 m. Moreover, the occupant was assumed to be seated and facing the horizontal center of the window, at a distance of 0.5 m from the window.

3.2. *Thermal effects characterization*

This study provides a comprehensive characterization of the thermal effects resulting from different glazing systems. To accomplish this, this work focused on assessing the glazing's influences on three specific aspects: MRT_delta_s, indoor thermal comfort, and energy consumption.

3.2.1. *Glazing's influence on the analysis of spectrally-resolved additional mean radiant temperature*

A glazing is characterized and defined by multiple properties, including glazing type, appearance, thickness, thermal conductivity, and so on [21]. Representative quantifiable properties of selected glazing systems are summarized in Table 1. To further understand how differences in each glazing property influence the thermal effect, the MRT_delta_s values at different levels of the above-mentioned four properties were compared. The property data provided by the database were cleaned for this analytical purpose. Appearance and glazing type were categorical data. Missing appearance values in the database were deleted or filled in by searching out appearance information from manufacturer websites. Since a variety of appearance categories may mask relationships, only representative color information was analyzed. For example, royal blue, dark blue, and sky blue were all recorded as blue. In addition, only clustered appearances with members greater than 30 were involved in the comparison, in order to avoid bias. As for glazing type, the glazing systems in the database were categorized into four groups, according to the method by which the glazing was treated: monolithic, laminated, coated, and applied film. Thermal thickness and conductivity were continuous data points and divided into several categories for further comparison. Thermal conductivity was divided into the categories of (0.12, 0.9998), (0.9998, 1), and (1, 1.38) W/mK to ensure an equal number of glazing systems in each category, while thermal thickness was divided into 15 categories, each containing an equal number of glazing systems.

3.2.2. *Thermal comfort computation and thermal effect index derivation*

PMV values were calculated for all glazing systems in the same baseline indoor environment, which was assumed to be a typical interior condition. Particularly, the following assumptions were made: an indoor air temperature and MRT of 24 °C, air velocity set to 0.1 m/s, relative humidity of 50 %, metabolic rate of 1 met, and clothing level of 0.6 clo. Notably, without shortwave solar irradiance, these assumed indoor boundaries form a thermally comfortable condition (PMV = −0.5). The MRT_delta_s values obtained by computing solar, glazing, and skin spectral features were added to the baseline MRT values for calculation of the new PMV values. A total of 5,138 PMV values were calculated, corresponding to 5,138 glazing systems. Subsequently, these were compared to underscore the necessity of developing a new index to characterize the influence of glazing systems on the solar thermal effect. If deemed necessary, the MRT_delta_s values will then be divided into 10 levels to construct the index.

3.2.3. *Building energy impact analysis*

In this comparative study, 10 window models representing various thermal effect indicators defined in the preliminary stage were chosen and subsequently simulated in EnergyPlus to determine their respective energy performances. The associated properties of these window models are detailed in Table 2. From a theoretical perspective, window properties profoundly influence heating and cooling energy consumption, as building heating and cooling systems operate to ensure indoor thermal comfort. In such a context, MRT_delta is a major input parameter. Most energy simulation studies typically take zone-averaged MRT_delta, surface-weighted MRT_delta, or angle factor MRT_delta into their thermal comfort modeling and computation [22]. However, this becomes significantly more complex when considering solar radiation transmitted through windows and directly absorbed by occupants. This complexity arises due to two primary factors. First, MRT_delta_s values, which are driven by the absorbed solar radiation of occupants, could affect user thermal comfort, necessitating consideration in the simulation. Consequently, thermostat setpoints would require adjustment; for instance, the thermal sensation heightened by the absorption of solar radiation would require lower setpoint temperatures. Secondly, these MRT_delta_s values depend on solar irradiance; thus, this effect

Table 1
Properties of glazing systems selected from the IGDB.

Property	Minimum	Median	Mean	Maximum
Front emissivity	0.01300	0.8400	0.6999	0.9540
Back emissivity	0.01300	0.8400	0.5732	0.9560
Tsol	0.00003390	0.2955	0.3569	0.9104
Tvis	0	0.5319	0.5403	0.9786
Conductivity (W/mK)	0.1200	1.0000	0.9161	1.3800

Table 2
Properties of ten window models.

Window model	U-factor (W/m^2K)	SHGC	Tvis
$Window_{TEI-1}$	2.71	0.10	0.07
$Window_{TEI-2}$	2.72	0.18	0.15
$Window_{TEI-3}$	2.72	0.26	0.23
$Window_{TEI-4}$	2.73	0.32	0.33
$Window_{TEI-5}$	2.73	0.38	0.37
$Window_{TEI-6}$	2.73	0.43	0.47
$Window_{TEI-7}$	2.73	0.50	0.59
$Window_{TEI-8}$	2.73	0.59	0.65
$Window_{TEI-9}$	2.74	0.70	0.78
$Window_{TEI-10}$	2.74	0.80	0.82

necessitates the establishment of a parametric relationship between solar irradiance and MRT_delta_s, which must then be incorporated into the simulation.

In this research, the thermostat setpoint temperatures were parametrically linked with the level of incident solar irradiance on external window surfaces facing south. To establish such a parametric relationship, a series of computations were conducted. Initially, the MRT_delta_s values were derived from the median point in each related thermal effect level for each window model. Subsequently, PMV models were employed to calculate the new room air temperature required to maintain thermal comfort at the target PMV value of 0. Finally, by comparing the newly calculated room air temperatures with the original temperature (prior to solar radiation) under varying levels of incident solar radiation, we could establish a straightforward linear regression model to depict temperature variation. Consequently, each window's TEI level had a distinct variation model that could calculate the necessary thermostat setpoint temperature, building upon the original setpoint temperature as a baseline. To incorporate this relationship into the energy simulation, the Energy Management System (EMS) module was configured in EnergyPlus. EMS has been utilized extensively in parametric energy simulation to devise customized control strategies and algorithms for simulating and optimizing the operation of diverse energy systems within a building. These methods have facilitated advanced energy performance simulations such as energy and daylighting performance that incorporate dynamic facades, smart HVAC systems in buildings, and energy performance through the integration of smart materials [23–26].

A prototypical small office building model provided in the ASHRAE 90.1–2019 of the Department of Energy (DOE) served as the foundational structure [27]. The building was divided into five zones based on their facade directions, as defined in the report [27]. Among the five predefined zones for the building, the zone with the facade facing south, named Zone 1, was simulated in this study. This zone had an area of 113.45 m^2 and six windows on its façade, totaling a window surface area of 20.64 m^2 and window-to-wall ratio of 24.44 %. Parametric simulations were performed for Zone 1 in a variety of climate zones.

Theoretically, the thermal effects of window systems on users contribute to both heating and cooling loads, as the setpoint temperatures of the heating and cooling thermostat require adjustment. To streamline the energy simulation process and comparatively observe the distinct impacts, only extreme climatic zones, specifically Climate Zones 1 (Honolulu, HI) and 7 (Grand Junction, CO), were considered in this case study. This approach was adopted because other zones with both heating and cooling energy use may not distinctly demonstrate the impacts of the thermal effects of various window systems with different thermal effect indicators. Consequently, the cooling loads for Zone 1 and heating loads for Zone 7 were extracted from the simulation results and compared across different window models.

To include the adjustment of thermostat setpoint temperatures in the simulation, a "Surface Outside Face Incident Solar Radiation Rate per Area" sensor was adopted. The thermostat setpoint temperatures for cooling and heating were used as actuators in the simulation. "Begin Timestep Before Predictor" was the program call manager, which occurred near the beginning of each timestep but before zone loads were calculated. Simulations were conducted at a resolution of 10 min. According to Fig. 2, the EMS program determined the HVAC setpoint, based on the average solar irradiation on six south-facing windows. For Climate Zone 1, a cooling demand region, the original setpoint was set to 21.11 °C; for Zone 7, a heating demand region, the original setpoint was 23.89 °C. As a result of the base model simulation report for Zone 1, the entire year was simulated as a cooling year. Therefore, the energy consumption was calculated for the entire year. For Zone 7, however, December to April was the cold season, which was also used for this simulation. We compared the parametric simulations with the baseline simulation (which utilized a selected window construction) and ran the model without considering the impacts of solar irradiance on the setpoint temperatures.

3.3. *Correlation calculations and dominant wavelengths extraction for predicting spectrally-resolved additional mean radiant temperature*

Tsol_s is a more comprehensive way of reflecting the features of the MRT_delta_s values because this variable is generated by considering the spectral nature of solar irradiance and window transmittance; however, this also means that the data measurement and associated computation effort are more complicated. For this research, Tsol was made easier to access and calculate by simply averaging the whole waveband of the window transmittance, but also less accurate due to its ignorance of the spectral nature. Therefore, a new variable was generated to offer an easier calculation that still considers the spectral nature. The effective wavebands of the window transmittance spectra incorporate the relationship between the solar spectrum and window transmittance spectra. Here, transmittance in these wavebands was averaged to obtain effective waveband spectral-average solar transmittance (Tsol_eff). In this research, simulations were used to identify the effective wavebands of window transmittance for the solar spectrum selected. One continuous waveband and two separate wavebands from the full spectrum were explored to obtain the best prediction of MRT_delta_s.

The brute-force method is a guaranteed way to enumerate and examine all possible solutions to a given problem [28]. This method provides the most trustworthy results for the correct solution but requires longer and heavier computation. We expected that the effective wavebands selected could serve as a benchmark for guiding further evaluation of the windows, and the problem we were trying to solve was small and simple, requiring reasonable computation space; thus, we selected the brute-force method to find effective wavebands for predicting MRT_delta_s. The brute-force method was employed to simulate all of the one-waveband combinations, and the correlations between the simulated waveband combinations and MRT_delta_s values were calculated to obtain the waveband with the highest correlation to MRT_delta_s. In the simulation, the length (denoted by i) and the start point of the waveband (denoted by j) were iterated, as shown in Fig. 3. Among the 87 wavelengths of the full waveband, the waveband from wavelengths j to (i + j-1) that had the greatest correlation was considered the most effective waveband for calculating the solar transmittance of the window, allowing for the spectral nature of the variables to be considered.

Two separate wavebands from the full wavebands were also simulated by the brute-force method. To reduce calculation burden and operation time, the effective waveband obtained from the one-waveband calculation was regarded as the first effective waveband, and the second waveband was iterated from the remaining wavebands that were longer or shorter than wavelengths in the first effective waveband (as described in Fig. 4). In the simulation, the start wavelength (denoted by f) and length (denoted by g) of the second waveband were iterated. The waveband from wavelength f to (f + g-1) that had the greatest correlation was the second waveband of the two effective wavebands. Tsol_eff could then be calculated by averaging the window transmittances in the wavebands selected.

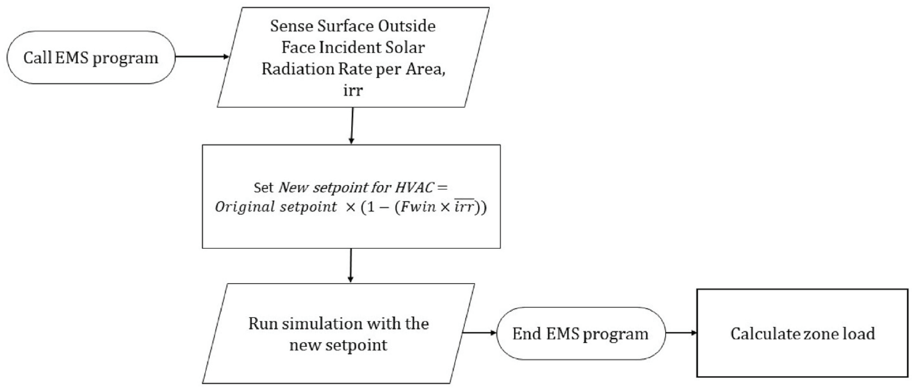

Fig. 2. Workflow for the EMS parametric simulation process. F_{win} refers to the variation %; *irr* refers to the incident solar irradiance W/m^2.

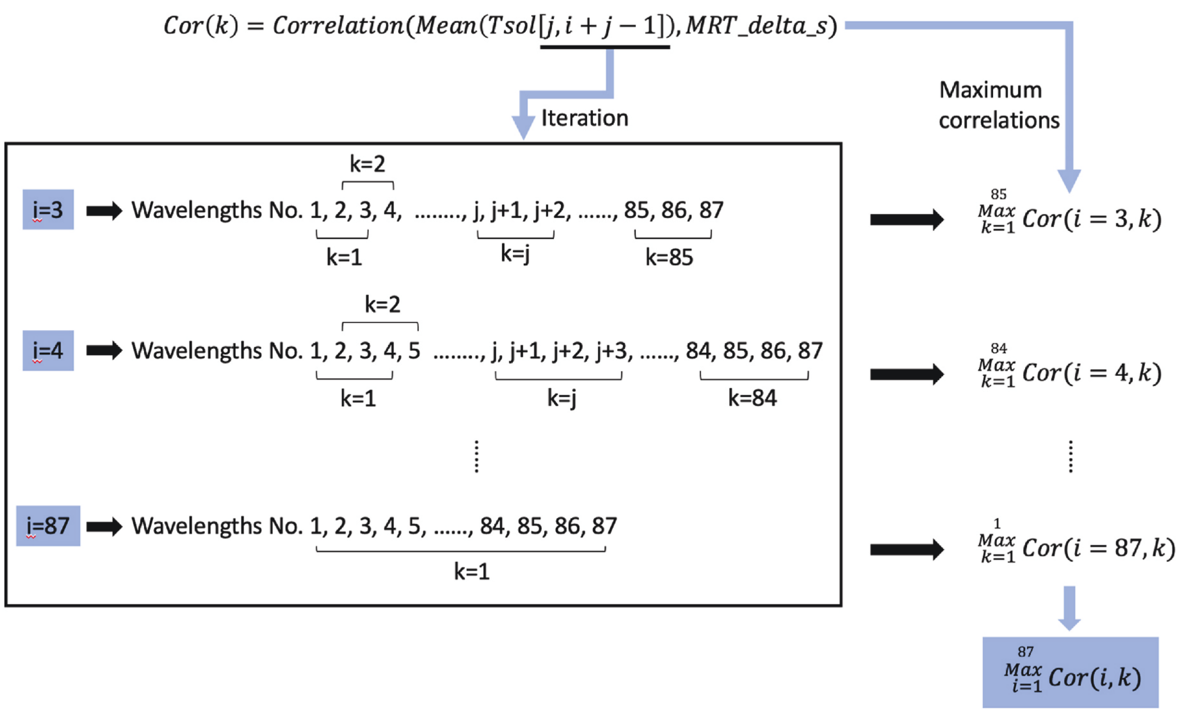

Fig. 3. Iteration process and correlation calculation for one effective waveband.

Spearman's rank correlation was used to evaluate the efficiency of an index to represent the TEI by comparing the index values and MRT_delta_s values. Spearman's rank correlation assesses monotonic relationships, meaning it compares the ranks of variables. In this research, we compared the consistency of variables and MRT_delta_s values for ranking glazing systems by their influence on solar energy's thermal effect. The correlations between MRT_delta_s and Tsol_s, MRT_delta_s and Tsol, and MRT_delta_s and Tsol_eff were compared to obtain relatively accurate and simple predictions of the window's role in the thermal effect.

4. Results

4.1. Differences in solar transmittances of glazing systems between those calculated by the spectrally-resolved method and those provided by the specification

The Tsol values of the IGDB glazing systems provided in the specification are depicted with black points in Fig. 4 and ordered from smallest to largest. The Tsol values were obtained by averaging the values at different wavelengths, without considering the weight of solar irradiance distribution at those wavelengths. The corresponding Tsol_s values of the glazing systems (which ranged from 0 to 0.91) were different from the Tsol values, as shown in Fig. 5. This indicates that the simplified and averaged spectral characteristics presented in Tsol could not substitute for the spectrally-resolved computation results. Accordingly, the spectrally-resolved method, which adopted the original spectral information of all components, was used in this work to generate the TEI values and obtain a better representation of the thermal effect.

4.2. PMV values

The PMV values of 5,138 glazing conditions were calculated in order to understand the extent to which glazing conditions might influence the human thermal comfort vote. As indicated above, the baseline PMV value without solar irradiance through the glazing systems was −0.5. Upon such a condition, the new computed PMV values influenced by the solar irradiance through the glazing systems ranged from −0.5 to 5.4 (rounded to one decimal place), exceeding the defined range of the PMV

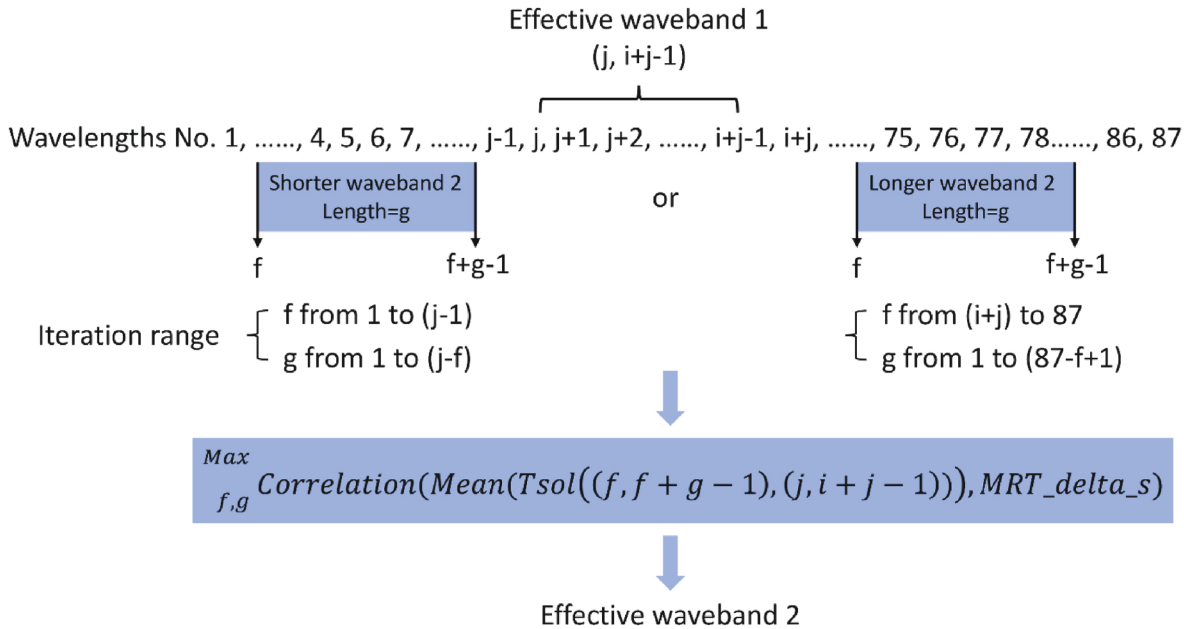

Fig. 4. Iteration process and correlation calculation for two effective wavebands.

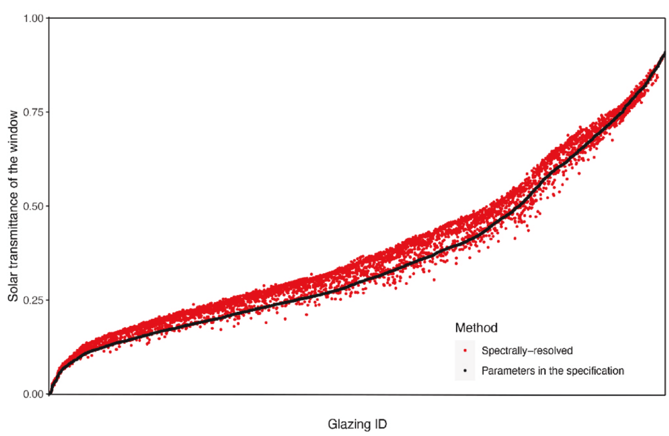

Fig. 5. Solar transmittance values of the glazing systems in the IGDB.

values (from −3 to 3). The reason for this exceeding of the threshold is that an additional MRT value was added to the calculation, in order to incorporate the effect of shortwave radiation. The scale of the PMV values is listed in Fig. 6. They ranged from −0.5 to 5.4, covering a rather wide range of thermal sensations from cold to exceedingly hot. This meant that we did need to classify these glazing systems by their influence on the thermal effect of sunlight on human beings, and thus a new index was needed for labeling.

4.3. Relationships among the glazing properties and spectrally-resolved additional mean radiant temperature

The relationships among the four glazing properties and MRT_delta_s are visualized in the boxplot in Fig. 7. The MRT_delta_s values of the monolithic glazings (soda-lime silica glass) were significantly higher than those of glazing systems that were coated, laminated, or applied film in form, as shown in Fig. 7(a). Additional fabrication processes for enhancing glazing performance included insulation capabilities, strength enhancement, solar blocking, and so on, which could have reduced the influence of solar irradiance on thermal comfort.

Glazing systems have different appearances, either by design or due to variations in manufacturing and fabrication techniques. It has long been believed that the colors blue and red have opposite influences on human thermal sensation [29], but significant differences in MRT delta_s values were not found for glazing systems with blue and bronze appearances (see Fig. 7(b)). This meant that the appearance of glazing did not play a determined role in its thermal effect, at least when we evaluated it from the energy intensity aspect. Moreover, the same appearance can have different solar transmittances. This being said clear glazing systems had significantly higher MRT_delta_s values than did glazing systems with a colored appearance.

Glazing thickness is also not a factor determining the thermal effect of glazing systems, as shown in Fig. 7(c). As for thermal conductivity, values in the range of 0.12–0.99998 W/mK tended to have lower MRT_delta_s values, as indicated in Fig. 7(d). Overall, some of the glazing properties did to some extent provide a preliminary

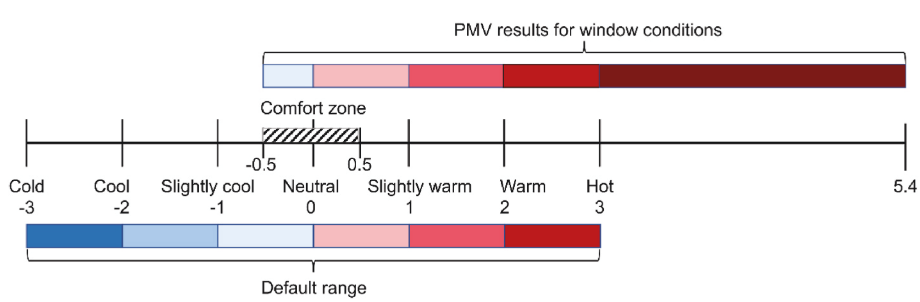

Fig. 6. PMV values for glazing conditions.

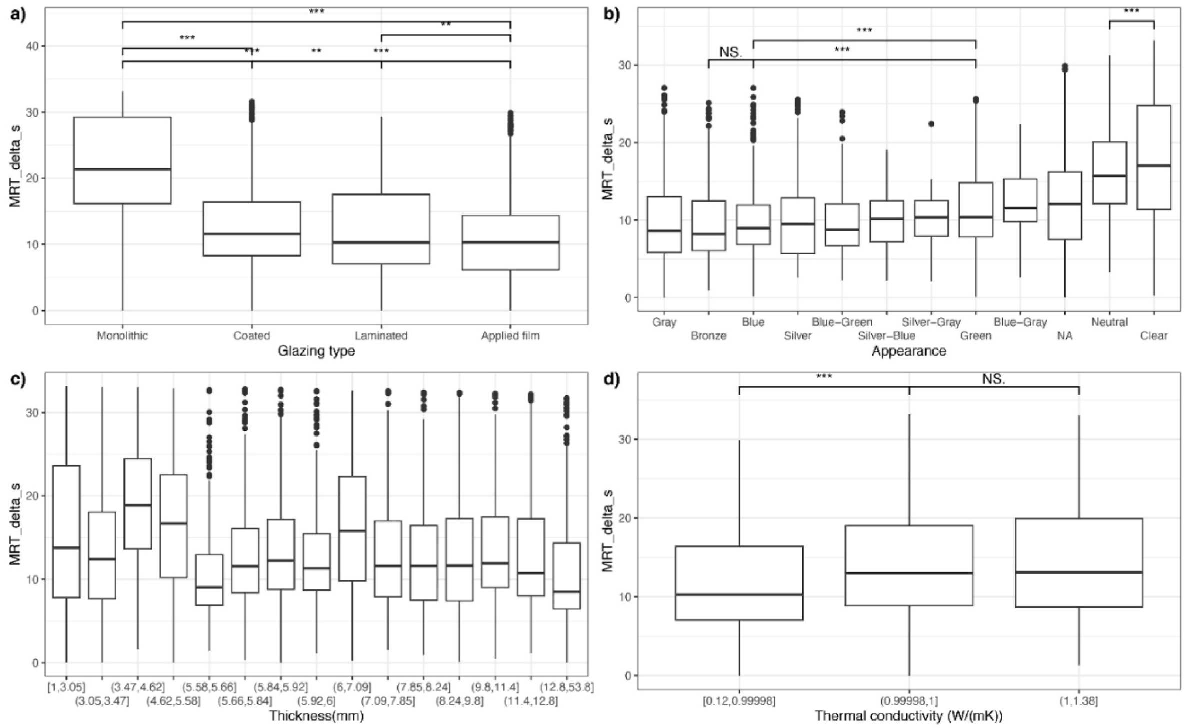

Fig. 7. The MRT_delts_s values distribution for different glazing properties by: a) glazing type, b) appearance, c) thickness, and d) thermal conductivity.

understanding of the thermal effect of the glazing, but generally, we did not use these properties as a guide when evaluating the thermal effect of a glazing system.

4.4. Index generation for selected glazings

The MRT_delta_s values under different glazing conditions were used to generate TEIs for the glazing systems, as indicated in Fig. 8. MRT_delta_s represents the thermal effect of shortwave solar irradiance without restrictions from other indoor thermal-related factors. Due to the control of all other variables except the glazing condition, the MRT_delta_s values could be used to represent the influence of the glazing condition and thus generate a TEI. The MRT_delta_s values ranged from 0.0014 to 36.15, which were then divided into 10 intervals to generate a 10-point TEI, with each interval covering an MRT_delta_s range of 3.61. By categorizing the MRT_delta_s values of the selected glazing systems in the database, each glazing was given an index to

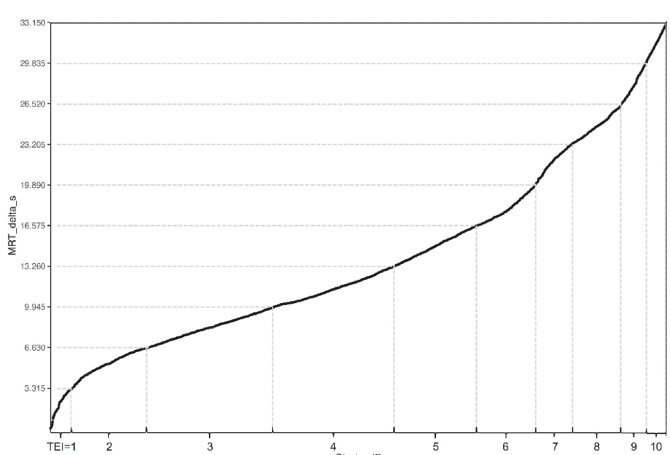

Fig. 8. The TEI values for glazing conditions.

represent the ability to transmit shortwave solar energy indoors and influence human thermal comfort.

4.5. Energy impact analysis results

4.5.1. Regression models for computing new thermostat setpoint temperatures

As illustrated in Section 3.2.3, with different levels of solar irradiance being absorbed by occupants in near-window zones, different air temperatures are needed to maintain human thermal comfort. By using the median MRT_delta_s for each TEI level and the boundary conditions defined in Section 3.2-3, the new thermostat setpoint temperatures needed under different solar irradiance values for each TEI window were achieved. In general, when occupants in the near-window zones are exposed to shortwave solar radiation, all windows, regardless of the TEI level, lead to certain thermal effects and trigger a reduction in the thermostat's setpoint temperature relative to a situation without incident solar radiation. As detailed in Section 3.2.3, we derived the variation percentages for each TEI level by comparing the newly-calculated thermostat setpoint under the incident solar radiation with the baseline setpoint temperature without such radiation. This comparison also revealed a linear relationship with the incident solar irradiance. Fig. 9 illustrates the declining variation percentage of the setpoint temperatures for the window at each TEI level, in conjunction with differing levels of solar irradiance. As depicted, at each TEI level, a higher solar irradiance induced a more substantial variation in the setpoint temperature. This change can be attributed to the increased MRT_delta_s values. Moreover, across the spectrum of window TEI levels, windows with higher levels exhibited a more profound impact on setpoint temperature adjustment, which can also be attributed to the significant influence of MRT_delta_s on thermal comfort.

4.5.2. EMS simulation results and comparative analysis

By establishing the parametric relationships in EnergyPlus via the EMS module, a series of heating and cooling load results were obtained for each climate. It should be noted that only the south-facing zones were integrated with this EMS module, which adjusted thermostat

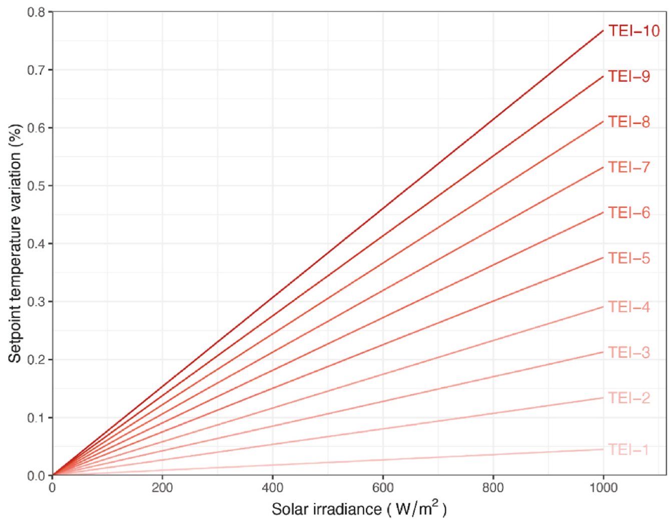

Fig. 9. Thermostat setpoint temperature variations of HVAC systems for windows with different TEI levels.

setpoint temperatures according to the level of incident solar irradiance. From the building's physical perspective, among the different TEI window models, the most pronounced influence was derived from the SHGC property (ranging from 0.1 to 0.8 from Window TEI-1 to Window TEI-10), influencing both heating and cooling loads independent of occupant thermal comfort characteristics. This influence of SHGC was also factored into the analysis. Hence, during the simulation procedure, the energy performance of each window model was examined. Notably, this simulation setup did not involve TEI-driven thermostat setpoint temperature changes but rather maintained constant heating and cooling setpoint temperatures (default settings from the DOE's prototypical models). The heating and cooling loads for each window model (devoid of adjustable thermostat setpoints) served as a reference to highlight the pure influence of thermal comfort effects stemming from shortwave solar radiation through window systems.

Fig. 10 depicts the cooling loads in the south-facing zones in Honolulu, HI (Climatic Zone 1), both considering and not considering the thermal effects of windows on occupants (using the solar irradiance-driven variable setpoint and constant setpoint temperature thermostats) for each window model. As evident from the figure, the building cooling loads of the south-facing thermal zones were significantly influenced by the windows at TEI levels ranging from 37.9 GJ in TEI-1 to 130 GJ in TEI-10. This variation resulted from both the increased solar heat gain due to the SHGC of the window system and the enhanced thermal effect on occupants. Fig. 10 also presents the percentage differences for each window model, indicating the variation between scenarios considering and not considering the thermal effects on occupants. Intriguingly, even after discounting the physical impact due to SHGC variation, it was still apparent that the thermal effects on occupants exerted a greater influence when the TEI values of the windows were at higher levels. To put it simply, based on this analysis, when windows with higher TEI levels are installed in a building, the cooling loads may increase dramatically. In this situation, the influence on occupant thermal comfort varied from 7.1 % to 104.4 % for TEI-1 to TEI-10. In summary, when incorporating the thermal effects of windows into energy usage considerations for cooling-dominated climates, lower TEI-level windows should be prioritized; failing to do so may significantly amplify cooling energy usage.

Conversely, Fig. 11 depicts the heating loads of south-facing thermal zones in International Falls, MN (Climatic Zone 7) for window models with different TEI levels. It can be observed that windows with higher TEI levels generally resulted in reduced heating energy consumption. For instance, the heating loads for the TEI-10 window model decreased by approximately 87.1 %, as compared to those of the TEI-1 window model. Analogous to the variations in cooling loads observed with different TEI windows, this change in heating load across different TEI windows can be attributed to both the physical effects (related to SHGC) and subjective impacts (related to thermal comfort) generated by the window systems. Excluding the physical effects caused by SHGC on heating energy use, the percentages in Fig. 11 still manifested the influences resulting from changes in thermostat setpoint temperature driven by the differential solar irradiance transmitted through the windows and the effect on occupants. These thermal effects generally contribute to annual heating load savings, with windows with higher TEI levels producing greater relative savings. This additional reduction in heating load ranged from 2.1 % to 18.1 % when transitioning from the TEI-1 to TEI-10 windows. In conclusion, windows at different TEI levels can significantly alter the heating energy use of a building located in a heating-dominated climate. Consequently, windows with higher TEI levels should be prioritized in these climates to achieve optimal heating energy savings.

It is important to highlight that the heating and cooling load analyses presented above were focused solely on the impacts on south-facing zones. From a comprehensive building energy perspective, the impacts

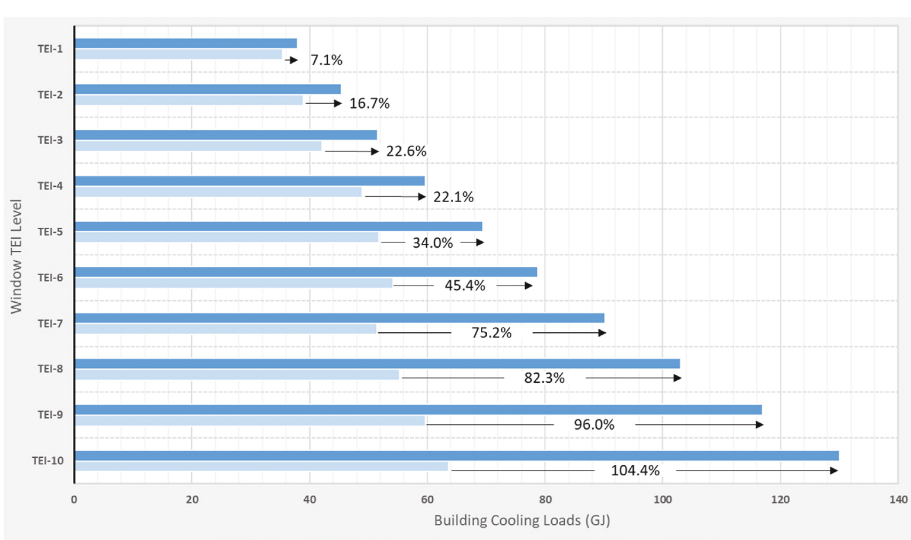

Fig. 10. Cooling loads according to windows with different TEI levels.

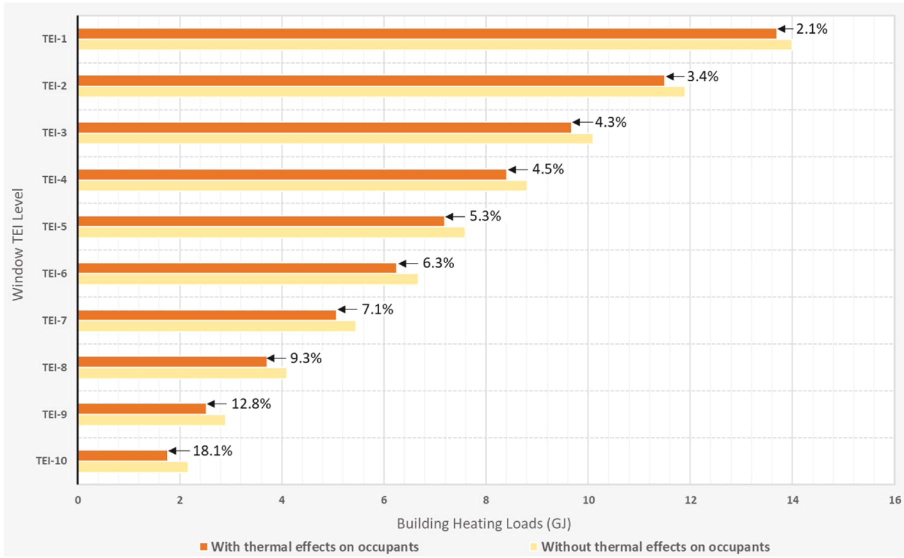

Fig. 11. Heating loads according to windows with different TEI levels.

associated with the TEI levels of the windows would likely be attenuated, given that thermal zones facing other directions are generally exposed to only a modest amount of diffuse solar radiation. Additionally, the above analysis was based on the assumption that the occupants were located within the near-window areas and exposed to solar radiation transmitted through the window systems. If the occupants were positioned outside these areas, the influence of such thermal effects on heating and cooling energy use would likely be reduced. Despite these caveats, the energy impacts of different TEI windows remain significant and warrant careful consideration during the window selection process in different climates. The variations in heating and cooling loads caused by different TEI windows can substantially influence overall building energy consumption, which in turn can affect both the operational cost and environmental footprint of the building. Further discussion related to these points is provided in Section 5.

4.6. Effective wavebands for calculating the solar transmittance of glazing systems and correlations

4.6.1. One effective waveband

The relationship between the length of the waveband and the highest correlation between MRT_delta_s and average window transmittance within the waveband with a corresponding length is shown in Fig. 12. With an increase in the length of the waveband, the highest correlation increased at first and then decreased, with a peak at a waveband length of 50. The highest correlation between MRT_delta_s and the average window transmittance was 0.994821, averaged by 50 wavelengths; this was higher than the correlation between MRT_delta_s and the average window transmittance calculated for the full waveband with 87 wavelengths. The effective waveband for calculating Tsol_eff was from the 13th to the 62nd wavelengths, which corresponded to the waveband (370 nm, 1,150 nm). Overall, Tsol_eff had a better performance than Tsol in terms of representing MRT_delta_s.

4.6.2. Two effective wavebands

The highest correlation for the simulated two-waveband combinations was 0.996, which was clearly larger than the 0.994821 value for the one-waveband correlation. The two wavebands were (13, 62) and (83, 85), which corresponded to wavebands (370 nm, 1,150 nm) and (2,250 nm, 2,400 nm). Accordingly, a second effective waveband extraction based on the results of the first effective waveband is recommended, with no heavy calculations required.

It should be mentioned that the two effective wavebands extracted

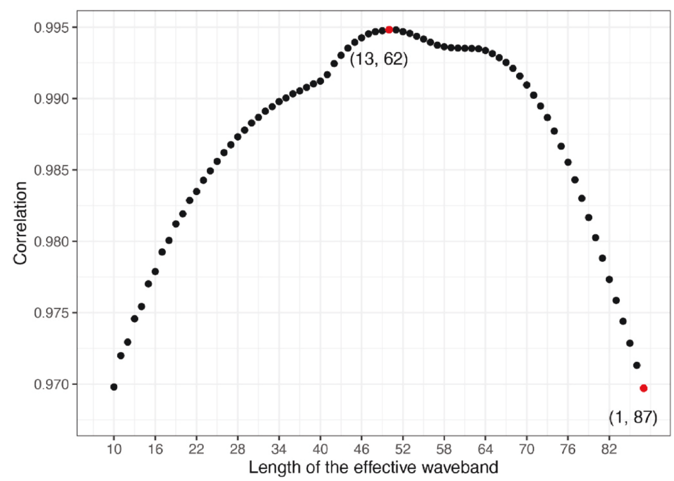

Fig. 12. Maximum correlations for the length of the effective waveband from 10 to 87. The points with a maximum correlation among all waveband combinations and corresponding to the full waveband are highlighted in red, and the starting and ending wavelengths for the two conditions are indicated in brackets.

only applied to calculating Tsol_eff for the selected solar spectrum. The generated wavebands rely on the solar spectrum selected, which means that different effective wavebands will be generated when the solar spectra reaching the window vary.

5. Discussion

5.1. Application potential of the thermal effect index and future steps

The development of the TEI for the fenestration industry is indispensable for two key reasons. First, it will equip designers and engineers with a quantifiable method for assessing the thermal effects of windows on user comfort. Despite the NFRC possessing an array of labels, the influence of fenestration on indoor occupants has been relatively overlooked. We generated TEI levels from 1 to 10 for 5,138 glazing systems, all selected from the IGDB. Given that the IGDB supports the NFRC window rating system, this new index could facilitate the direct evaluation of a significant number of realistic window conditions. The reason for excluding 545 of the glazing systems in the index's generation was the considerable discrepancies in the wavelength intervals of transmittance spectra provided in the database, as compared to those of the solar spectrum used for simulation. Secondly, the TEI can serve as a guide for households selecting window products. If this index was adopted market-wide, it would offer households a more comprehensive basis for their window selection and retrofit decisions, going beyond pure energy efficiency measures like SHGC and U-factor. The TEI could be utilized in commercial and residential glazing evaluations by both customers and designers. If incorporated into the NFRC label, the index could inform customers about the impact of solar penetration on human thermal comfort under certain window glazing systems. The higher the TEI of the glazing, the more the occupant is influenced by solar thermal effects, primarily in zones with south-facing windows. The specifics of this influence would vary depending on other factors related to thermal comfort evaluation and specific indoor conditions. However, a general understanding of the index would guide customers to a preliminary judgment about the glazing, promoting better performance in terms of thermal comfort and energy efficiency.

The TEI can also be applied in web-based window evaluations such as those conducted through the Efficient Windows Collaborative Platform, which offers window suggestions to customers based on location, house size, and age. However, this platform currently does not consider the direct impact of solar radiation on human skin. If the TEI were integrated into the platform's evaluation process, it could provide more informed suggestions that consider both comfort level and energy cost.

The comprehensive standardization of the TEI, however, requires further development. For a complete understanding of windows' impact on indoor thermal comfort, we need to consider not just the short-wave radiation effects of solar radiation, but also the long-wave thermal radiation and convective thermal consequences. The former is associated with the surface emissivity features and insulation capabilities of windows. For example, changes in surface condensation, emissivity, and the inner surface temperature of a window can significantly alter the radiative heat transfer for occupants [30]. These effects could be incorporated into the commonly used PMV model by adjusting the MRT value. Convective heat transfer can be considered from two perspectives: infiltration through window frames and drafts caused by temperature differences between the window surface and interior room temperature. Both factors are closely related to the insulating ability of the window. For instance, our previous work has demonstrated the impacts caused by temperature differences between the window's inner surface and indoor air temperature under varying supply air modes and placements [31]. To incorporate these effects, more airflow-related analyses will be needed. These analyses could then be included in the PMV model by adjusting local air speed and asymmetric temperature variation.

5.2. Effective waveband-based method for generalizing the thermal comfort effect evaluation for specific solar conditions

The TEI was generated by assuming a certain solar irradiance, skin color, and boundary settings. Due to the diversity of customer needs, it is indispensable to evaluate the performance of windows under specific conditions that are different from the reference settings. For instance, when the day of the year, time of day, weather, or window orientation varies, the solar spectrum reaching the window will vary accordingly, resulting in variations in window thermal performance that diminish the representativeness of the TEI.

The use of the spectrally-resolved method to calculate the thermal effect of a window under a certain solar spectrum requires multiplication of the solar and window transmittance spectra by wavelength, which can be both complicated and time-consuming. The intricate calculation is acceptable from a standardization perspective, but not necessary for rapid analysis and diagnosis. Thus, the spectrally-resolved method was applied to glazing systems in the IGDB to extract effective wavebands via the brute-force method, providing a range to average window transmittance spectra and generating Tsol_eff values. This effective waveband method, which was explained using the reference solar spectrum outlined above, could be extended to generate effective wavebands for representative solar conditions and enable the rapid generation of Tsol_eff. Tsol_eff could then directly be used in the straightforward traditional method to generate MRT_delta, which could subsequently be employed to obtain the human thermal comfort level via a web-based tool [32].

Relative to the longer spectral range data, a shorter waveband necessitates simpler measurement devices, due to the reduced demand for detection precision with regard to window transmittance, notwithstanding its effectiveness and lower operation demand. Conversely, longer wavebands require more advanced spectrometer measurements/devices. For example, the effective wavebands obtained for the reference solar spectrum in this research were (370 nm, 1,150 nm) and (2,250 nm, 2,400 nm), which eliminated the detection of the UV portion of window transmittance. The reduction in measurement demand could possibly allow for easier-access implements like mobile devices, facilitating more affordable computations and increasing the viability of household applications.

5.3. Energy impact and smart building integration for energy savings and indoor comfort

Our analysis illustrated that in heating-dominated climates, windows with higher TEI values are preferable, due to their potential to reduce heating loads. Conversely, in cooling-dominated climates, windows with lower TEI levels should be prioritized to mitigate the need for excessive cooling energy. As an alternative strategy, shading systems or overhangs could be deployed to limit direct solar irradiance, and thus minimize the consequent thermal effects on occupants and spaces. In mixed climates, where both heating and cooling needs are significant, the choice of window TEI level becomes more challenging. A careful evaluation and potentially a compromise in TEI level may be necessary to strike a balance between optimizing thermal comfort and minimizing energy use.

One compelling application of these findings is their integration with smart thermostats and occupancy sensors, specifically for near-window zones. Smart thermostats, which can be programmed to adjust temperature setpoints based on occupancy, time, and other factors, could be fine-tuned to consider the TEI levels of installed windows. For instance, in buildings with high TEI windows, smart thermostats could be programmed to reduce the heating setpoint temperature when solar irradiance is high, in order to leverage the thermal effects of these windows and save on heating energy. Conversely, in buildings with low TEI windows, smart thermostats could be programmed to increase the cooling setpoint temperature when solar irradiance is high to mitigate the additional cooling load induced by these windows.

Additionally, the integration of occupancy sensors in near-window zones could further enhance the potential energy savings. These sensors could provide real-time data regarding whether occupants are present in the near-window zones and thus are directly affected by the solar radiation transmitted through the windows. A smart thermostat could then dynamically adjust the temperature setpoints based on both the TEI level of the window and the occupancy status of the near-window zone. For instance, if the sensors detected that the near-window zone was unoccupied, the smart thermostat could maintain a constant setpoint temperature, thereby saving energy by avoiding unnecessary heating or cooling. By harnessing the interplay between window properties, occupancy patterns, and programmable temperature setpoints, building operators could leverage these integrations to optimize both thermal comfort and energy use.

Lastly, another future avenue of exploration could involve the development of smart window systems with tunable transmittance properties, both in terms of intensity and spectrum. In specific climates and under varying solar conditions, a series of computations using the established TEI and related spectral-based estimation methods could be performed to determine the optimal parameters for spectra- or intensity-tuned windows. Currently, several smart window systems, such as chromic-based glazings, structure-based dynamic windows, and suspended particle devices offer intensity tunability [33–35]. However, the development of spectra-tuning window systems remains elusive, due to inherent material constraints and the complexities involved in the materialization and manufacturing processes. This area may therefore warrant further dedicated research efforts.

6. Conclusion

This research presented a comprehensive analysis of the TEIs for 5,138 glazing products listed in the IGDB. We developed a spectrally-resolved method to evaluate the MRT_delta_s changes induced by different window glazings, which served as the basis for generating the TEI values. A notable finding is the range of the MRT_delta_s values, which spanned from 0.0014 to 36.15, representing a wide PMV change ranging from −0.5 to 5.4. Subsquently, a 10-level TEI was developed by categorizing the MRT_delta_s values of the selected glazing systems in the database, representing their ability to transmit shortwave solar energy indoors and influence human thermal comfort. Furthermore, our analysis demonstrated the significant impact of windows' TEI levels on both heating and cooling loads when under specific climatic conditions. For cooling-dominated climates such as Honolulu, HI, lower TEI-level windows are advisable, as they minimize cooling loads and thereby reduce energy consumption. Quantitatively, the cooling loads differed drastically between windows with different TEI levels, ranging from 37.9 GJ for TEI-1 to 130 GJ for TEI-10. In contrast, heating-dominated climates such as in International Falls, MN, would benefit from windows with higher TEI levels, as they contribute to substantial heating load reductions of up to 87.1 %. Nevertheless, these results are constrained to specific settings. In real-world scenarios, the energy impacts of different TEI windows may be attenuated, due to building orientation or occupant position. Despite these variables, the TEI holds significant value in optimizing thermal comfort and energy efficiency in various climates. With the help of a TEI, customers can make more informed decisions, potentially enhancing overall building performance and reducing environmental footprints.

Our research indicates the necessity of this new index, the TEI, which evaluates the thermal effect of glazing products and incorporates it into the existing NFRC window rating system. The TEI will complement existing parameters, enriching our understanding of a window's impact on thermal comfort. In scenarios where the specific conditions differ from the default settings in the IGDB, we propose a fast estimation method that allows for a more comprehensive and adaptable approach to evaluating window transmittance. Future research should focus on enhancing the adaptability of the TEI and fast estimation method to more diverse real-world conditions, considering factors such as different solar zenith angles and varying building orientations. Furthermore, the potential influence of window glazing on thermal comfort beyond the near-window areas should also be studied. As we continue to refine these methods, we will ensure that the TEI becomes an effective tool for optimizing building energy consumption and improving occupant thermal comfort.

CRediT authorship contribution statement

Nan Wang: Writing – original draft, Methodology, Discussion, Formal analysis, Investigation, Data Visualization. **Neda Ghaeili:** Energy simulation, Investigation, Formal analysis. **Julian Wang:** Conceptualization, Methodology, Project administration, Data Interpretation, Research Discussion. **Yanxiao Feng:** Investigation, Data curation. **Enhe Zhang:** Formal analysis, Discussion. **Chenshun Chen:** Formal analysis, Discussion.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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