NRC Research Press

REVIEW

Solar infrared radiation towards building energy efficiency: measurement, data, and modeling

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Abstract: With the recent discoveries and engineering solutions emerging in nanomaterials and nanostructures, independent band modulation of solar radiation on building envelopes, including glazing systems, has become increasingly viable as a potential means of improving building energy savings and indoor visual comfort. However, when it comes to the prediction of these new materials' potential energy performance in buildings, most studies utilize a simple solar irradiance (e.g., global horizontal solar irradiance, direct beam solar irradiance) or a rough estimation of solar infrared (e.g., 50% solar irradiance) as input, which may cause significant errors. Consequently, there is a pressing need for reliable performance estimations of the solar infrared control and response at the building's scale. To assess this, we need a solar spectral irradiance model, or at least a wideband (visible or infrared) solar irradiance model, as input. To develop this new type of model, one needs to understand the modeling-related key elements, including available solar spectral irradiance datasets, data collection methods, and modeling techniques. As such, this paper reviews the current major measurement methods and tools used in collecting solar spectral irradiance data with a focus on the solar infrared region, identifies the available related resources and datasets that particularly encompass the solar spectral irradiance data with a sufficient wavelength range, and studies existing solar irradiation modeling techniques for building simulations. These investigations will then form the background and backbone for a study scheme of solar infrared radiation modeling and indicate future research paths and opportunities.

Key words: solar radiation, solar infrared, building energy, solar systems, modeling techniques.

Résumé : Grâce aux découvertes récentes et les solutions d'ingénierie qui émergent des nanomatériaux et des nanostructures, la modulation du rayonnement solaire indépendante de la bande sur les enveloppes des bâtiments, y compris les systèmes de vitrage, est devenue de plus en plus viable comme moyen potentiel d'améliorer les économies d'énergie des bâtiments et le confort visuel à l'intérieur. Cependant, lorsque l'on doit prédire la performance énergétique potentielle de ces nouveaux matériaux dans les bâtiments, la plupart des études utilisent comme paramètre d'entrée une irradiance solaire simple (p. ex. l'irradiance solaire horizontale globale, l'irradiance solaire par faisceau direct) ou une estimation approximative de l'infrarouge solaire (p. ex. 50 % de l'irradiance solaire), ce qui peut donner lieu à des erreurs importantes. Conséquemment, il est urgent d'avoir des estimations fiables de la performance du contrôle de l'infrarouge solaire et de la réponse à l'échelle du bâtiment. Ainsi, nous avons besoin d'un modèle d'irradiance solaire spectrale ou au moins, d'un modèle d'irradiance solaire à large bande (visible ou infrarouge) comme paramètre d'entrée. Afin de développer ce nouveau type de modèle, il faut comprendre les éléments clés liés à la modélisation, dont les ensembles de données disponibles sur l'irradiance solaire spectrale, les méthodes de collecte de données et les techniques de modélisation. De ce fait, cet article présente la synthèse des principales méthodes de mesure et des outils actuellement utilisés dans la collecte de données d'irradiance solaire spectrale en mettant l'accent sur la région infrarouge solaire, il identifie les ressources et les ensembles de données connexes disponibles qui englobent particulièrement les données d'irradiance solaire spectrale avec un spectre de longueurs d'onde suffisant, et il étudie les techniques de modélisation de l'irradiation solaire existantes pour les simulations sur les bâtiments. Ces recherches constitueront ensuite le contexte et la base d'un schéma d'étude de la modélisation du rayonnement infrarouge solaire et indiqueront les voies et les possibilités de recherche futures. [Traduit par la Rédaction]

Mots-clés : rayonnement solaire, infrarouge solaire, énergie des bâtiments, systèmes solaires, techniques de modélisation.

1. Introduction

1.1. Solar energy and sustainable buildings

The total energy consumption of buildings is increasing at a daily rate and has far exceeded other major energy consumption areas such as industrial uses and transportation (Pérez-Lombard et al. 2008). Solar energy is clean, environmentally friendly, and freely available across the planet. Solar energy can produce both thermal and electrical power. The earth's fossil fuels are depleted and will eventually be exhausted. They are also responsible for increasing pollution, resulting in climate change, as well as other environmental issues. It is essential to use naturally available and renewable solar energy as a replacement for fossil fuel energy because solar energy is the most abundant, clean, and ultimately inexhaustible form of sustainable energy currently available (Peng et al. 2011). Meeting global building energy demands in a sustainable fashion will require not only increased energy efficiency and new methods of employing existing fossil fuels but

Received 6 November 2019. Accepted 4 June 2020.

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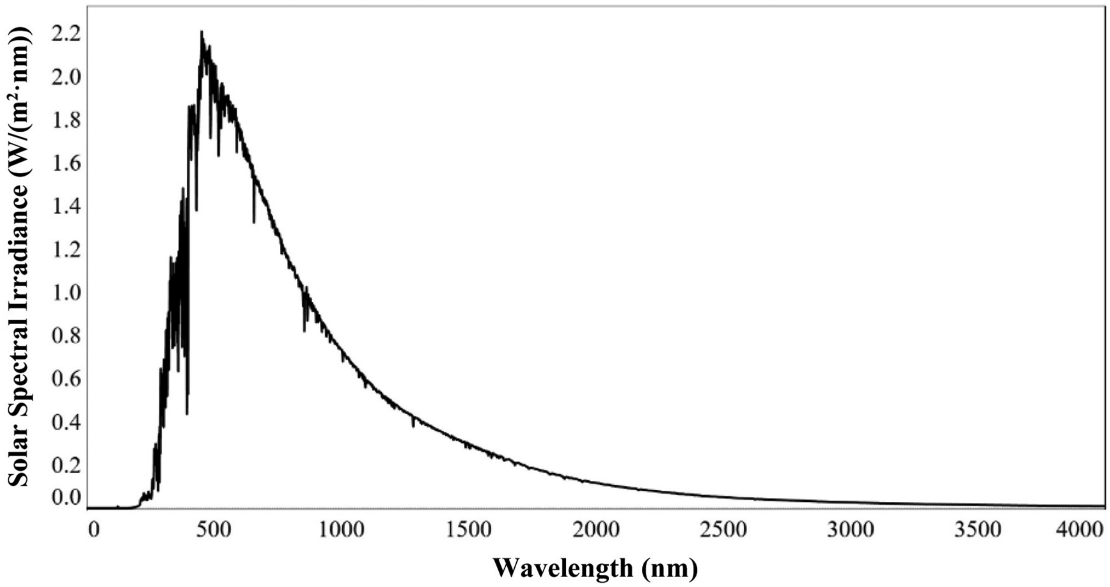
Fig. 1. Solar spectral irradiance.



also a daunting amount of solar energy. The two categories of solar energy use in buildings today are active and passive; they primarily contribute to meeting electricity, heating, cooling, and daylighting requirements. Using active solar energy in buildings usually requires an active electrical device that powers a solar energy system, such as photovoltaics, solar thermal collectors, and active solar components. Passive solar energy use in buildings strategically utilizes wall and window orientations and other architectural features to absorb or deflect the sun's energy, without employing any mechanical or electrical devices. Various applications of solar energy have successfully been used in a wide variety of areas, such as building-integrated photovoltaics, passive solar houses, utilization of solar heat, and daylighting.

1.2. Solar spectral characteristics and building energy needs

Solar radiation has both thermal and optical effects on building energy use, which is why it is necessary to understand its spectral characteristics. These spectral characteristics, both external to the earth's atmosphere and on the ground, are illustrated in Fig. 1, which shows spectral irradiance (W/(m^2·nm)) versus wavelength (nm) (Gueymard 2004). The solar energy that reaches the earth's surface lies between the wavelengths of 280 and 4000 nm; solar radiation wavelengths are not uniformly distributed. Knowledge of the spectral distribution of solar radiation provides important design input that can be used to improve the thermal environment of buildings and assist in selecting the materials most suitable for exposure to solar radiation. Three components of the solar spectrum — ultraviolet (UV) radiation, which spans the wavelength region from 280 to 380 nm; visible light (VIS), which spans wavelengths from 380 to 750 nm; and near-infrared (NIR), mainly spanning wavelengths from 750 to 2500 nm — interact with the earth's own electromagnetic and atmospheric envelope, resulting in significant variations in the magnitudes of solar radiation available for conversion into other forms of useful energy. Taking building windows as an example, of these three major components, VIS always provides benefits to indoor occupants and building energy savings (e.g., electrical lighting), whereas solar infrared is beneficial to building energy savings in winter but undesirable in summer (Eicker 2006). Thus, an ideal window should be capable of sufficient transmission of visible light, which is associated with the window's optical property of visual transmittance. This is accomplished by controlling transmitted solar infrared thermal radiation. During the winter season, an ideal building window shall be completely transparent to incoming visible and infrared radiation but reflects all other longwave radiation flux to the interior for energy savings. In summer, the ideal window should reflect 100% of solar infrared radiation from the sun and any longwave thermal radiation from the external environment while maintaining unidirectional transparency and thus allowing emissions of longwave thermal radiation from the building's interior to its exterior (Wang and Shi 2017). Such independent multi-spectral solar modulation, especially for the infrared region of solar irradiance, has been pursued for decades.

Fortunately, recent progress in spectrally selective nanomaterials and structures has facilitated an unprecedented number of approaches with great potential for allowing the independent control of solar infrared energy (750–2500 nm), such as plasmonic NIR absorptive thin film, multi-layer low emissivity coatings, and polymer foils (Correa and Almanza 2004; Park and Hong 2009; Schelm and Smith 2003; Smith et al. 2002). These new discoveries in nanomaterials and nanostructures make the aforementioned ideal building window viable to design. However, when it comes to the potential energy savings or thermal performance prediction in buildings, the majority of these existing studies utilized a rough estimation on solar infrared (e.g., 50% solar irradiance), which may cause significant errors. For instance, based on our own data collection and analysis, the fraction and the spectral distribution of incident solar infrared on the vertical building surface can be very different depending on the surrounding geographic features, orientations, and cloudiness levels. Consequently, there is a pressing need for reliable performance estimations of the solar infrared control and response at the building's scale. To assess this, we need solar spectral irradiance source data or at least wideband (VIS or Infrared) solar irradiance data as input. Ideally, the data would include a wide range of orientations described by various combinations of azimuth and elevation angles. The questions that immediately come to mind include how we can collect solar spectral data with sufficient solar infrared information for vertical surfaces (e.g., building walls and windows) and at what levels of depth related to wavelength resolution and orientations. Other questions are, with respect to currently available solar irradiance data sources, whether it is possible to build such a solar spectral radiation model with the infrared region and what modeling methods (statistically based or physically based coefficients or functions or relatively complex data mining) can be adopted to attain the model.

To explore the described questions, it is necessary to comprehensively review the current major measurement methods and tools used in collecting solar spectral irradiance data with a focus on the solar infrared region, the available related resources and datasets that particularly encompass the solar spectral irradiance data with a sufficient wavelength range, and existing solar irradiation modeling techniques. In brief, this review is composed of the aforementioned three parts (i.e., measurements, resources, and modeling techniques) that deal with issues critical to forming the background and backbone for a study scheme of solar infrared radiation and future research opportunities.

2. Measurements for solar spectral irradiance including the infrared region

The solar irradiance at a specific site can accurately be obtained by ground-based measurements. These normally involve the measurement of global, direct, and diffused irradiance. Global horizontal irradiance (GHI) is defined as the sun's radiant energy arriving at the earth's surface and incident on a surface of unit area. It includes direct normal irradiance (DNI) projected onto the horizontal and diffuse horizontal irradiance (DHI), which refers to the irradiance scattered from all points in the sky, excluding circumsolar radiation (Stein et al. 2012). A variety of commercially available instruments can be employed when measuring specific ranges of solar irradiance. For instance, the most typical solar irradiance instruments are pyrheliometers and pyranometers, which are used for direct and global irradiance. Several well-established measuring methods have been developed and used that employ fixed or rotating shadow bands to measure diffuse radiation, and apertures to measure direct solar radiation. In addition, some manufacturers have also produced photometric and photosynthetically active radiation, called quantum sensors, to measure pre-defined isolated portions of the solar spectrum. However, due to the agricultural research purposes for using such solar irradiance sensors, the majority of this type of sensor focuses on the VIS portion of sunlight. Measuring the spectrum of sunlight is much more difficult and expensive than measuring broadband radiation using pyranometers, pyrheliometers, and quantum sensors.

Spectrometers have been widely adopted for evaluating the full spectrum of features of solar irradiance. Some manufacturers use the term spectroradiometer instead of the spectrometer in their measurements. However, regardless of the instrument name, in this research, we use spectrometer and spectroradiometer interchangeably to refer to measuring systems that output spectral measurements of absolute spectral radiation flux density (W/(m^2·nm)) (or photon flux density (μmol/(m^2·s·nm))).

The majority of these systems are built upon the same basic principles of operation, though construction may vary by model. They typically use diffraction grating or a prism to separate collimated light beams into wavelengths and offer a clear description of the spectrum distribution of a light source. Early instruments trace back to the solar spectrum (SOLSPEC) spectrometer, which was first introduced in 1983 for Atmospheric Laboratory for Applications and Science (ATLAS) missions measuring the sun's energy (Vignola et al. 2012). The SOSP spectrometer was first flown in the EURECA mission in 1992 to measure the absolute solar spectral irradiance from space (Thuillier et al. 2003). Both are composed of three separate spectrometers intended to measure the UV, VIS, and Infrared portions that cover the approximate wavelength range from 180 to 3000 nm. The solar data collected from these spectrometers is comparable with the results offered by Thuillier et al. (2003), whose spectrum was established as covering wavelengths from 200 to 2400 nm (Vignola and McDaniels 1993).

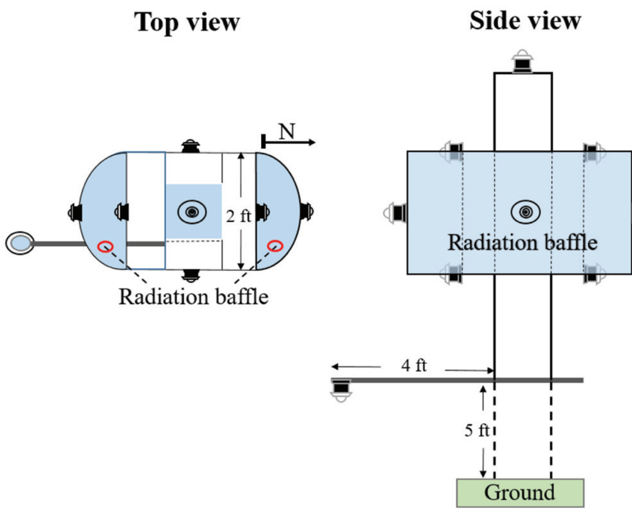
In general, solar spectral irradiance measurements are a clear requirement for instrument quality, variability, and uncertainty. Many portable spectrometers are designed to use short-term instantaneous measurement results and can receive light from a variety of angles. The ASD QualitySpec Trek portable spectrometer is a handheld device that precisely supports a full range measurement from 350 to 2500 nm. It can be combined with ASD software to improve, simplify, and streamline data collection (ASD 2019). Another series of spectrometers designed and produced by the Avantes Company includes the AvaSpec-ULS4096CL-EVO, which uses advanced complementary metal oxide semiconductor (CMOS) linear image sensors that are completely up to date and cover light wavelengths from 200 to 1100 nm. This instrument can measure light intensity in the UV, VIS, NIR, and Infrared areas with the installation of AvaSoft-Basic software (Avantes BV 2019). A less pricey broad spectral range spectrometer, the LR1 produced by ASEQ Instruments, can be custom designed with regards to spectral range and resolution. Its detector covers a wavelength range from 200 to 1100 nm and uses specific ASEQ spectra software to collect spectrum data. It is not easy to set up this spectrometer outdoors for long-term measurements because of its configuration. The LI-180 spectrometer by LI-COR Biosciences provides an accurate and portable spectral measurement device, but it only covers a spectrum range between 380 and 780 nm; it is mainly used for indoor light measurement. Currently, many spectrometers are manufactured, but only a small percentage can be used outdoors for long-term measurements, and most support short-term outdoor measurements or instantaneous measurement with portable equipment.

With regards to long-term use in the field, characteristic outdoor spectrometer manufacturers include EKO Instruments and Apogee Instruments. EKO Instruments produces a series of spectroradiometers, such as the model WISER II, that can be used to accurately measure solar spectra. The WISER II measurement system covers the spectra range from 300 to 2550 nm and can be used outdoors under all weather conditions with the analysis software WSDAc. It has been calibrated according to the International Standards and National Institute of Standards and Technology (NIST) standards. Similarly, Apogee Instruments has developed two models of small and lightweight spectroradiometers for both field and laboratory use, along with Apogee Spectrovision software. Model SS-110 can measure the spectrum ranging from 340 to 820 nm, whereas Model SS-120 covers the spectrum ranging from 635 to 1100 nm. Both are calibrated with the LI-COR Model 1800-02 Optical Radiation Calibrator, which is traceable to the NIST standards. Furthermore, solar radiation energy is not equally distributed across all wavelengths in nature, or according to different solar positions, measurement plane orientations, seasons, and climatic conditions. The National Renewable Energy Laboratory (NREL) Solar Radiation Research Laboratory established a radiometer tower (see Fig. 2) in the 1980s to analyze vertical solar radiation with different orientations because surfaces (e.g., walls, windows) can generally be utilized to collect, transmit, or reject incident solar radiation for energy saving and (or) daylighting purposes. Five algorithms converting GHI and DNI to global irradiance on vertical surfaces were evaluated using the measurement data obtained from this dedicated station (Maxwell et al. 1986). At this time, there is no similar field dedicated station designs for spectral irradiance data measurement and collection, but building such solar spectral irradiance weather stations will be an essential step to develop and evaluate comprehensive solar spectral irradiance model.

3. Available solar spectral data resources including solar infrared

Long-term solar radiation datasets require many years to compile, and the time-consuming nature of their operation is currently im-

Fig. 2. Locations of pyranometers on a radiometer tower used to measure solar irradiance on vertical surfaces.



practical and inapplicable to the rising need for renewable energy (Gueymard and Wilcox 2011). Researchers (Gueymard and Wilcox 2011) have highlighted that currently there are only four stations in the US, and very few worldwide, that have been consistently measuring solar spectral radiation for more than 25 years. To the best of our knowledge, there is no consistent measurement of solar spectral irradiance. There are many studies currently underway regarding measurement accuracy, factors influencing this measurement, and calibration references for spectral measurement instruments. There are existing solar resource datasets maintained by organizations, universities, and companies, such as the National Solar Radiation Database (NSRDB) (Sengupta et al. 2018), the NASA/Global Energy and Water Exchanges (GEWEX) Surface Radiation Budget (SRB) (NASA 2019), and the Measurement and Instrumentation Data Center (MIDC) (NREL 2019). Data are normally stored in two kinds of formats: time series or spectral. The two most important features of the existing datasets are solar spectral radiation data at NIR, spanning from 700 to 2500 nm, and hourly recording.

The primary contribution to the sources of data available online is from the National Solar Radiation Database (NSRDB), which is composed of three parts: 30 years of solar radiation and supplementary meteorological data since 1961, updated solar radiation and supplementary meteorological data from 1454 locations in the US and its territories since 1991, and 30 min solar data from 1998 to 2014 (Sengupta et al. 2018). The datasets are provided in a time-series format. Other producers such as the Measurement and Instrumentation Data Center (MIDC) at NREL (NREL 2019), DLR Institute of Atmospheric Physic (DLR–ISIS) (Institute of Atmospheric Physics 2019), Meteonorm (Meteotest AG 2019), Solar Radiation Data (SoDa) (SoDa 2019), SUNY (Clean Power Research, L.L.C. 2019), and SolarGIS (SolarGIS 2019) also use this format. Organizations and laboratories including the NASA (Surface Radiation) (NASA 2019) and University of Colorado – Boulder (CU Boulder, Laboratory of Atmospheric and Space Physics (LASP) Interactive Solar Irradiance Datacenter) (SORCE 2019) use the spectrum format to store their datasets, allowing the solar irradiation data to be viewed under the selected spectral band. The example in Figs. 3*a* and 3*b* indicates the solar spectral irradiance in both time-series and spectrum formats, respectively. These were generated from the Solar Radiation and Climate Experiment (SORCE) website at CU Boulder.

This review found that most solar irradiation resources online provide data in a time-series format, and only three (NREL, NASA, and CU LASP centers) provide data in a spectrum format. The purpose of searching hourly solar infrared (700 ~ 2500 nm) data are not fully satisfied by such datasets. Data collected by NREL (Sengupta et al. 2018) and NASA (2019) include infrared solar spectral radiation information but unfortunately are not always recorded hourly; rather, some data are recorded daily and reported in 3 h averages, which hinders application in building energy simulations. The only available hourly solar spectra dataset is supplied by the MIDC, which has the measured GHI since the year of 2014. Furthermore, vertical or inclined incident solar spectral irradiance data for different orientations are quite limited because of the lack of an established measurement system. This makes it difficult to directly evaluate or validate the performance of spectrally selective designs on vertical building surfaces. However, these three data sources can be sufficient to support the horizontal solar infrared data modeling purpose. Meanwhile, the historical hourly meteorological datasets including temperature, humidity, cloud coverage, wind, etc., can also be linked to these data sources for potential modeling use.

4. Modeling techniques of solar spectral irradiance

4.1. The existing models

Since it is not possible to acquire solar spectral irradiance measurements for every location on earth, studies are being conducted to model this information. Since the 1940s, researchers have proposed different spectral irradiance models for engineering and building applications. These include five basic types: (1) empirical models, (2) rigorous and sophisticated codes, (3) simple transmittance parameterizations, (4) semiempirical models, and (5) reconstruction models. Empirical models refer to the classic modeling method based on an empirical understanding of solar spectral irradiance, in conjunction with historically measured weather and solar irradiance data, such as moon's spectral radiation curve (Gueymard et al 2002), Leckner's model (Leckner 1978), Brine and Iqbal's model (Brine and Iqbal 1983), and SOLAR2000 (Tobiska et al. 2000). Rigorous and sophisticated codes, such as BRITE and FLASH model (Bird 1982), LOWTRAN 7 (Bird and Riordan 1986), MODTRAN6 (Ball et al. 2014), SEA (Lean 2000), and SOLMOD (Shapiro et al. 2011), deeply consider the physical characteristics of the atmosphere and use references or measured vertical profiles of gaseous and aerosol constituents. The simple transmittance parameterization method is also generally built upon physical relations, but it simplifies the atmosphere's vertical profiles. For this type, NREL provides two working models, called the Bird Simple Spectral Model SPCTRAL2 (Bird 1982; Yeo et al. 2017) and SMARTS (Gueymard 2001; the latest version is 2.9.8 released in 2018), to help building architects and engineers accelerate their integration of solar technology into the grid. Semiempirical models combine types 1 and 2 (and sometimes type 3), involving both physical and statistical modeling processes. Reconstruction models are clearly different from types 1 through 4, modeling solar spectral irradiance variability by a linear combination of indicators of solar activity (Yeo et al. 2017).

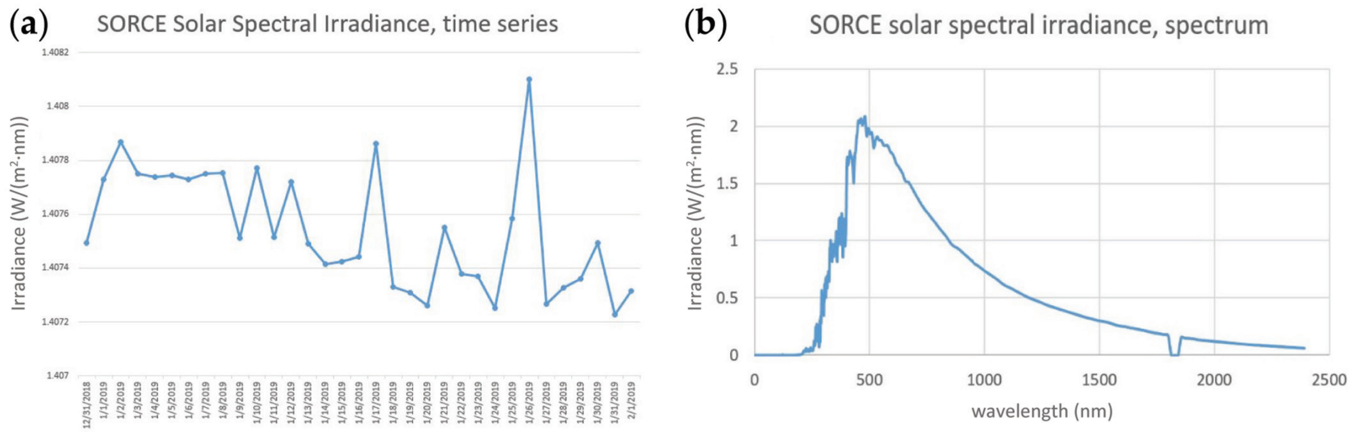
Table 1 presents the main features of these representative models used for characterizing solar spectral irradiance.

4.2. Features of the existing models

The modeling types for physical mechanisms cover the full spectrum, from 280 to 2500 nm (and even higher), including the solar infrared portion that is of interest in sustainable building design. However, for semiempirical and empirical models, the validated spectrum portion is mostly limited to 1100 nm, due to the limited range of measuring and testing apparatuses (e.g., LI-1800 spectrometer).

With regards to accuracy, all of the types described above except for type 2 adopt relatively simplified atmospheric parameters (e.g., type 2 uses the atmosphere as a one-layer medium attenuating extraterrestrial solar irradiance by means of five or more iden-

Fig. 3. (*a*) SORCE solar spectral irradiance data from the time series 2018-12-31 to 2019-02-01 (date format yyyy-mm-dd) on a 700 nm spectrum and (*b*) SORCE solar spectral irradiance data on a 0.1–2400 nm spectrum for 2019-01-01 (SORCE 2019). All dates were processed using Excel. Date format in *a* is m/d/yyyy.



tified scattering and absorption processes that lack accuracy if insufficient attention is paid to the details of the parameters used) (Bird and Riordan 1986). These models may lead to certain levels of error because the simplicity hypothesis is employed. Also, similar to the above spectral coverage discussion, the accuracy of semi-empirical and fully empirical models is dependent on the wavelength range measured using a spectrometer. For instance, the SEDES2 model (type 4) uses linear interpolation for the wavelength band beyond 1400–4000 nm (Myers 2012). Conversely, type 2 seems to present more accurate spectral irradiance results, but the use of this method requires highly restrictive input in terms of the ozone and water vapor profiles, air density profile, and size and altitude distribution of aerosols with single scattering albedo and an asymmetry factor or phase function, etc.

Regarding usability, the semiempirical and empirical models are more usable if only atmospheric reference models are employed. Local meteorological data (e.g., the TMYSPEC model) and geographic features can be used to identify or obtain the more representative solar spectral irradiance without complexity or costly measurements. Compared with this, models based on physical relations and computation need sophisticated codes to consider physical and solar variability, which are not always easy to implement. In addition, to achieve high accuracy for a selected location, physical models (types 2, 3, and 5) usually require more complex localized parameters like the air density and water vapor profiles, which are needed for the radiative transfer method. For example, regarding the modeling process for type 3, the best representation of the atmosphere is obtained using local geographic coordinates, several types of atmospheric measurements, and different aerosol models that use aerosol optical thickness (usually corresponding to 500 nm) and the Angstrom turbidity coefficient as inputs (Utrillas et al. 1998). These parameters are not readily available and require expensive and dedicated instrumentation and equipment.

5. Solar infrared irradiance modeling for building energy analysis

5.1. Methods and governing functions in current building energy simulations

In all building energy simulation applications, solar radiation must be calculated on tilted surfaces (Fig. 4 shows the schematic diagram of the overall environmental radiative situations for building surfaces), which need solar irradiation inputs or appropriate correction factors and sky models. As shown in Fig. 4, the total incident solar irradiance on a titled surface can be calculated upon eq. 1 or complete version containing all diffuse components in eq. 2:

$$(1)\qquad I_t = I_{t,b} + I_{t,d}$$

$$(2)\qquad I_{t,d} = I_{t,d,\mathrm{iso}} + I_{t,d,\mathrm{cir}} + I_{t,d,\mathrm{hor}} + I_{t,d,g}$$

where I_t is the total incident solar irradiance on titled building surfaces, $I_{t,b}$ is the incident irradiance on titled surfaces from the direct beam component, $I_{t,d}$ is the incident irradiance on titled surfaces from the diffused component, $I_{t,d,\mathrm{iso}}$ is the incident irradiance on titled surfaces from the isotropic diffuse sky, $I_{t,d,\mathrm{cir}}$ is the incident irradiance on titled surfaces from the circumsolar brightening part, $I_{t,d,\mathrm{hor}}$ is the incident irradiance on titled surfaces from the horizon brightening part, and $I_{t,d,g}$ is the incident irradiance on titled surfaces from the ground.

Current major building energy simulation programs, such as EnergypPlus, TRNSYS, and ESP-r, use different solar radiation models on titled surfaces, including isotropic sky model, Hay-Davies model, Perez model, etc. The major differences of these models are the calculations of the diffuse irradiation part in eq. 2. For instance, the isotropic sky model ignores the $I_{t,d,\mathrm{cir}}$ and $I_{t,d,\mathrm{hor}}$ components; the Hay-Davies model bases on the isotropic model but employs an index representing $I_{t,d,\mathrm{cir}}$; the Perez model uses empirically derived coefficients to take all four components $I_{t,d,\mathrm{iso}}$, $I_{t,d,\mathrm{cir}}$, $I_{t,d,\mathrm{hor}}$, and $I_{t,d,g}$ into account. These solar radiation models need the measured solar irradiance data in weather files as inputs to compute the incident irradiance on the titled surface. Typical weather datasets include WYEC, TMY, CWEC, EPW, and others. Each of these datasets contains 1 year of hourly data (8760 h) synthesized to represent long-term statistical trends and weather patterns for a longer portion of the record. The solar irradiance data in a complete weather file includes three parts: GHI, DHI, and DNI. With two known solar data variables, the other variable can be calculated via the mathematical relations among them. When DHI and DNI data are absent from the source data, and only GHI is provided, some decomposing models may be used to split the GHI into these two components.

5.2. Features, needs, problems, and potential solutions

Present building energy simulation programs use readily available meteorological data, such as TMY data, which is normally maintained by several national meteorological organizations for various purposes, including building energy simulation. All of these weather files used by building energy simulation programs

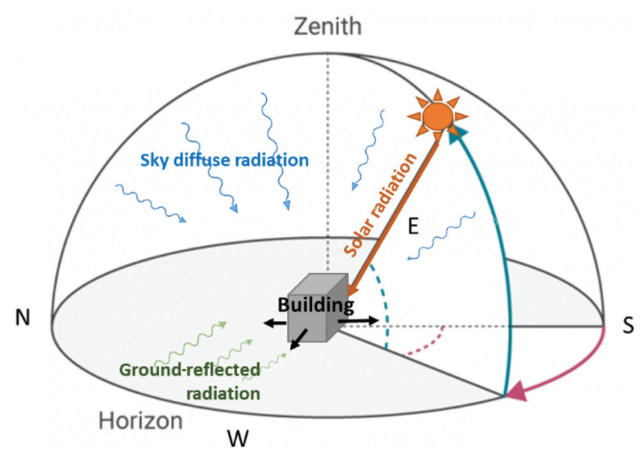
Table 1. Summary of existing solar spectral irradiance models.

Representative model	Main input	Output	Type	Year
Moon's spectral irradiation curve (Gueymard et al. 2002)	Solar zenith angle; barometric pressure; scattering and absorption of water vapor, ozone, and dust particles; air mass	Spectral irradiation; total irradiation; illumination; the color of direct sunlight	1	1940
Leckner's model (Leckner 1978)	Solar zenith angle; Rayleigh scattering; ozone absorption; absorption by uniformly mixed gases; water vapor absorption and aerosol attenuation; air mass	Clear sky diffuse spectral irradiance on a horizontal surface	1	1978
BRITE and FLASH model (Bird 1982)	Molecular (Rayleigh) and aerosol (Mie) scattering; ground reflection for various albedos; absorption by aerosols, ozone, water vapor, carbon dioxide, oxygen, and other molecular species; the state of polarization	Average spectral radiance; spectral irradiance	2	1982
Brine and Iqbal's model (Brine and Iqbal 1983)	Absorption of radiation by molecules and uniformly mixed gases; attenuation by Rayleigh scattering and aerosol extinction	Solar spectral diffuse and global irradiance under cloudless skies	1	1983
Bird Simple Spectral Model (SPCTRAL2) (Bird 1982; Yeo et al. 2017)	Solar zenith angle; collector tilt angle; atmospheric turbidity; the amount of precipitable water vapor and ozone; surface pressure; Angstrom coefficient; aerosol models (forward scattering, aerosol single scattering albedo, Angstrom's exponent, aerosol asymmetry factor, single scattering albedo at 0.4 μm)	Global, direct, and diffuse spectral irradiance; spectral irradiance (280–4000 nm)	3	1986
LOWTRAN 7 (Bird and Riordan 1986)	Molecular absorption; molecular scattering; aerosol and hydrometeor absorption and scattering; refraction and earth curvature; representative atmospheric, aerosol, cloud, and rain model	Atmospheric transmittance; atmospheric background radiance; single scattered solar and lunar radiance; direct solar irradiance; multiple scattered solar and thermal radiance	2	1988
NRLSSI (Lean 2000)	Measured total solar irradiance; solar activity; sunspot darkening; facular brightening; solar cycle	Solar spectral irradiance (240–400 nm)	5	2000
SOLAR2000 (Tobiska et al. 2000)	Measured solar irradiance data; solar cycle; solar activity conditions	Solar spectral irradiance (1 – 1 000 000 nm)	1	2000
SMARTS (Gueymard 1995, 2001)	Extraterrestrial irradiance; sun position; ozone optical thickness; ozone optical mass; NO_2 optical mass; mixed gas (principally O_2 and CO_2) optical mass; water vapor optical mass; aerosol optical mass; aerosol optical thickness or Angstrom coefficient	Global, direct, and diffuse spectral irradiance (280–4000 nm)	3	1995, 2001
LBLRTM/CHARTS (Clough et al. 2005)	Water vapor, carbon dioxide, oxygen, nitrogen, ozone, pressure shift coefficient, the half-width temperature dependence and the coefficient for the self-broadening of water vapor, etc.	Solar spectral irradiance (350–5000 nm)	1	2005
SEA (Shapiro et al. 2011)	Solar activity (active state of the sun, quiet sun); neutron-monitor data	Solar spectral irradiance (130 – 10 000 nm)	5	2010
MGNM (Thuillier et al. 2012)	Mg II index; neutron-monitor data; reference spectrum; measured solar irradiance data	Solar spectral irradiance (121–400 nm)	5	2012

Table 1 (*concluded*).

Representative model	Main input	Output	Type	Year
SEDES2 (Myers 2012)	Global, direct, and diffuse horizontal irradiance; solar geometry; solar zenith angle; aerosol optical depth; precipitable water; angle of incidence; cloud cover	Direct and hemispherically tilted spectral irradiance under clear and cloudy skies (300–4000 nm)	4	2012
TMYSPEC (Myers 2012)	Hourly records of global, direct, and diffuse broadband irradiance; meteorological data (relative humidity, temperature, wind speed, etc.); aerosol optical depth; precipitable water vapor; station pressure	Hourly spectral distribution; monthly average hourly global (hemispherical) and direct spectral irradiance (300–1800 nm)	4	2012
SOLMOD (Haberreiter et al. 2014)	Intensity spectra; solar images; solar activity indices	Solar spectral irradiance (26–34 nm)	5	2011
MOCASSIM 2.0 (Bolduc et al. 2014)	Quiet-sun emissivity; total solar irradiance; sunspot fragmentation; erosion; faculae	Near- and mid-ultraviolet spectral irradiance (150–400 nm)	2	2014
SATIRE-S (Ball et al. 2014)	Total solar irradiance; full-disc magnetograms and continuum images of the sun to quantify the fractional disc area coverage by different surface components (quiet sun, sunspot umbrae, sunspot penumbrae, faculae, and network), as well as their spatial distribution	Solar spectral irradiance (115 – 160 000 nm)	4	2014
FARMS-NIT (Xie and Sengupta 2018; Xie et al. 2019)	Atmospheric profile, aerosol information, extraterrestrial solar radiance and irradiance, land surface conditions, surface orientation, solar geometry	Global, direct, and diffuse spectral irradiance (280–4000 nm)	3	2018, 2019

Fig. 4. Solar, sky, and ground radiation on building surfaces.

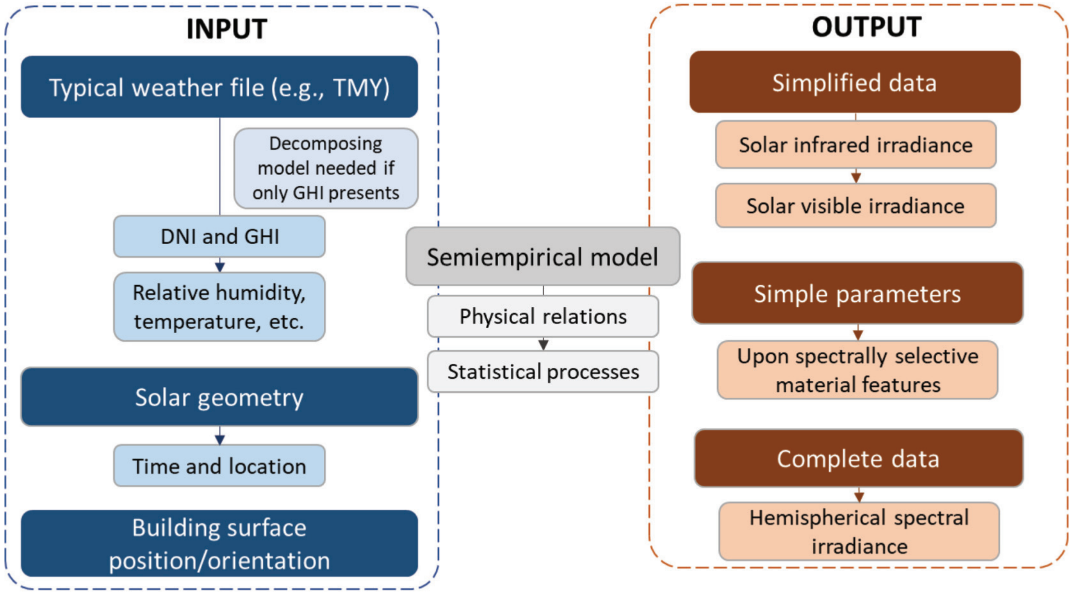


have broadband solar irradiance variables. So, with regards to the applicability of solar infrared irradiance modeling, the goal should be to integrate or accept these widely available weather files; that being said, a new spectral conversion model that is able to decompose hourly broadband global horizontal and direct normal solar radiation to visible and infrared components is needed. The development method of the TMYSPEC model by Myers (Myers 2012) for photovoltaic (PV) technology application purposes provides a possible solution. This method adapted the SEDES2 model to use the variables, including humidity, temperature, dewpoint temperature, diffuse irradiance, and global irradiance in the TMY file, combined with solar geometry based on time and location, to output hemispherical spectral irradiance. However, there are still three major issues to be completed.

First, the solar infrared model may not be useful for assessing the performance of innovative spectrally selective devices used for building energy efficiency if the spectral coverage is limited to 1100 nm. This is because the solar infrared region between 800 and 2500 nm occupies more than 50% of overall solar irradiance, which significantly impacts solar heat gains and losses in buildings, as well as their heating and cooling loads. Furthermore, recent findings regarding spectrally selective materials, coatings, and structures are often involved with the near and (or) mid-infrared region. However, the limit of 1100 nm is normally observed and experimentally validated in most existing spectral irradiance models. The solutions to extend the upper limit of 1100–2500 nm are to employ a set of spectrometers with a broader range covering both visible and solar infrared to form a new type of solar irradiation weather station. The NREL's radiometer tower (see Fig. 2) in the 1980s may be a basic structure for the station design.

Second, accurate predictions of solar infrared radiation on titled or vertical surfaces at different orientations are needed. Sufficient research on modeling and validation has been conducted to obtain titled or vertical surfaces' broadband solar radiation by inputting solar irradiance (e.g., GHI, DHI, and DNI), sky features, and coefficients representing local conditions. However, until now, no similar studies have been conducted to address spectral irradiance variations on titled or vertical surfaces at different orientations. Comparatively, this may involve more effects from sky features, air conditions, and even the surrounding terrain or infrastructure. Based on the review of existing solar radiation modeling methods, the approach coupling physical and statistical

Fig. 5. Schematic diagram of the solar infrared model development.



modeling techniques may lead to more accurate results. The parameters governing a physical property take values that fluctuate according to changes in the meteorological conditions. Thus, if we are interested in using a physical model to estimate data for a determined site, then statistics must be introduced for the model's input variables. In other words, a working model should be built on contemporary observations, theoretical formulations, and assumed references (e.g., vertical atmospheric profiles), combined with statistical techniques. This also means that long-term spectral irradiance data collection is necessary, and certain local coefficients and relationships can be obtained using more advanced statistical processes such as data mining techniques.

Third, the "raw" solar spectral irradiance data have two implementation issues when estimating the performance of a building's solar system via solar irradiance. One is the complexity of the dataset. If a spectral irradiance model constructed with broadband solar irradiance data in the weather file is achieved, then the simple broadband solar data are expanded into a more complex dataset, including a number of time-series pairs of the spectrum and solar irradiance elements. It is difficult to simply utilize this dataset in most existing building energy simulation programs. Another issue is related to the true spectral responses of a building's solar systems. Different spectrally selective systems and devices may have their own sensitivities when responding to different wavelengths. To facilitate the adoption of solar infrared or spectral models for building energy analysis, a simple index is needed. For instance, different PV modules have a variety of spectral responses, so a number of simple parameters and indices have been developed to represent solar spectral irradiance distribution in the PV field, such as the spectral correction parameter, spectral factor, APE, and AMCDF (Peng et al. 2019; Poissant et al. 2003; Rodziewicz and Rajfur 2019).

A schematic model design, shown in Fig. 5, is proposed upon the described needs, issues, and potential solutions.

6. Conclusions

After introducing emerging spectrally selective building systems and the ongoing needs of building energy studies, this work reviewed three aspects of solar spectral irradiance research: measurements, available data sources, and modeling methods. Regarding solar spectral irradiance measurements, long-term data collection of solar spectrum data are possible but often costly because such datasets require many years to complete and time-consuming collection processes, especially in terms of validating the procedures for titled and vertical surfaces with different orientations. This finding is also consistent with the current limitations of available solar spectral irradiance data sources. Very few data sources may cover a desirable spectral range (beyond 1100 nm), and the only usable hourly solar spectra dataset is built by the NREL MIDC. Also, the vertical and inclined incident solar spectral irradiance data for different orientations are quite limited because of the lack of measurement setups. The MIDC solar spectra datasets do not have simultaneous measurements for horizontal and inclined solar spectra. That being said, the MIDC dataset is still not sufficient for modeling the conversion procedure from the horizontal solar spectra to the titled surfaces' solar spectra. With respect to modeling methods, this review analyzed 18 prior models and categorized them into five types according to their modeling features. It was found that the best representative solar spectral irradiance model for a selected location will combine physical and statistical methods with some local data. For implementation in building energy simulations, particular attention should be given to modeling solar infrared irradiance on tilted surfaces and different orientations and utilizing the current weather files in the building energy simulation area. A schematic diagram of the expected solar infrared model is proposed. Related tasks to be done include data validation for vertical surfaces and different orientations, spectral coverage satisfying the analysis needs of emerging spectrally selective building devices or materials, and the applicable method connecting readily-available weather data sources and introducing simple parameters or indexes that represent solar spectral irradiance variations for analyzing such energy performance of devices.

Acknowledgements

This research was funded by the National Science Foundation (No. 1847024) — CAREER: Understanding the Thermal and Optical Behaviors of the Near Infrared (NIR) - Selective Dynamic Glazing Structures.

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