TRNSYS MODELING OF A HYBRID LIGHTING SYSTEM: BUILDING ENERGY LOADS AND CHROMATICITY ANALYSIS

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ABSTRACT

The TRNSYS [1] program provides algorithms to calculate the beam and diffuse radiation on any surface as a function of time based on horizontal radiation measurements. However, no methods are currently provided in TRNSYS to determine the spectral distribution of solar radiation. This paper describes the inclusion of a spectral model in TRNSYS. The model uses Gueymard's SMARTS2 (Simple Model of the Atmospheric Radiative Transfer of Sunshine) [2] algorithm to calculate the spectral power density of sunlight as a function of solar position, atmospheric turbidity, moisture content, and other atmospheric parameters. The inclusion of the spectral model was necessary to perform building illumination and energy load analyses on a 2500 m^2 office building equipped with a hybrid lighting system (HLS). The HLS uses two-axis tracking collectors to collect beam normal radiation that is later divided into visible and infrared components. The visible radiation is piped to luminaires inside the building using optical fibers, while the infrared radiation is focused on thermal photovoltaic arrays and used to generate electricity. The TRNSYS model was used to calculate annual building energy loads (lighting, cooling, and heating) and illumination chromaticity values (correlated color temperature and color rendering index) for office buildings in Tucson, AZ and Seattle, WA. These locations were selected to exemplify best and worst case results, respectively. Annual energy savings and chromaticity values for office buildings located in these cities are presented.

1. DESCRIPTION OF HYBRID LIGHTING SYSTEM

The major components of the HLS are the tracking collecting mirrors, the thermal photovoltaic array (TPV), the light distribution system that carries the light from the collecting mirrors to the luminaires, and the luminaires and their controls that deliver light to the building interior. These components are shown in Figure 1.

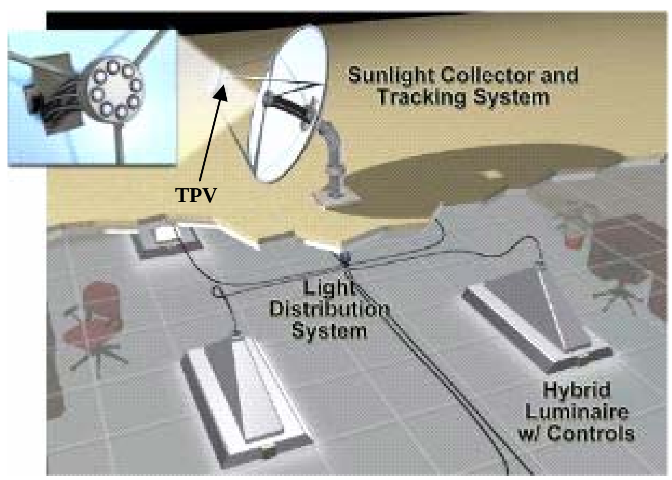

Fig. 1: Components of the HLS [3]

A spectrally selective "cold" mirror is located in front of the TPV. This mirror allows infrared radiation to pass through to the TPV. Visible radiation is reflected by this mirror into the fiber optic light distribution system.

Photosensors monitor the illumination level in the building interior. When beam radiation is available, the visible portion is piped in and the electric lighting is dimmed until the desired illumination level is reached. As the amount of beam radiation entering the building through the HLS decreases, the illumination provided by the electric lights increases to compensate. The luminaires are designed to use conventional bulbs and HLS side-emitting light rods.

2. LUMINOUS EFFICIENCY AND EFFICACY

The amount of illumination provided by a light source is a function of its spectral power density (SPD). Figure 2 shows SPDs of four light sources: beam normal solar radiation on a clear spring day around noon in Seattle (representative of air mass 1.5), a warm white energy efficient fluorescent bulb, a full spectrum fluorescent bulb, and an incandescent bulb (in this case, halogen) from 380-780 nm, the average visual sensitivity range of the human eye.

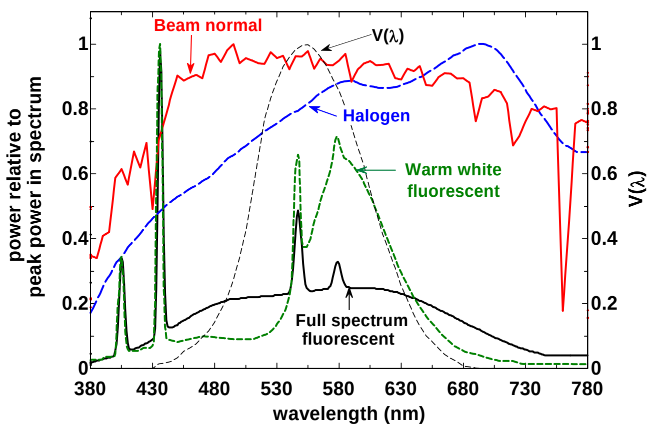

Fig. 2: Examples of light source spectrums in visible wavelengths: Beam normal radiation (AM 1.5), halogen, warm white energy efficient fluorescent, and full spectrum fluorescent.

Light is visually evaluated radiant power. To determine the amount of luminous power in lumens (lm) provided by a light source, the amount of radiative power at each wavelength is multiplied by the photopic luminous efficiency curve, V(λ), which is plotted in Figure 2 on the right vertical axis. The luminous efficiency curve converts radiant power watts (W) to luminous light watts (lW). The total number of light watts for a given SPD are then integrated and multiplied by 683 lumens/lW to yield the luminous power in lumens. Further details of this procedure are provided by [4].

The ratio of the luminous power (lm) in a given amount of radiant power (W) is called the luminous efficacy. Light sources with high efficacy deliver more light for a given amount of radiant power and tend to have SPDs with power concentrated in the visible spectrum. Most of the power of halogen bulbs and other incandescents is found in the infrared and typical efficacies for these bulbs are 15-25 lm/W. Fluorescent bulbs have more radiant power in the visible range. Typical luminous efficacy values for full spectrum fluorescent bulbs are 55 lm/W, and energy efficient fluorescent bulbs can approach 100 lm/W. About half of the power in natural sunlight is in the visible range with the other half in the infrared. Large luminous efficacies (approx. 100 lm/W) result because a significant fraction of the power peaks close to the maximum sensitivity of the eye at 555 nm (V(555 nm)=1).

In the HLS, the cold mirror filters the infrared from the visible radiation in the incident beam normal radiation. Visible light directed into the optical fibers has very little power in the infrared; the beam normal radiation delivered to the luminaires has an efficacy of about 200 lm/W.

When performing building energy analyses, the average lighting efficacy of light sources within a building is an important parameter. Higher efficacy lamps cause smaller cooling loads because less energy enters the building with the desired amount of illumination. The results section will further quantify this effect.

3. THE COLOR TEMPERATURE OF A LIGHT SOURCE

Though the luminous efficiency curve in Figure 2 indicates the relative sensitivity of the eye to power in different wavelengths, the color that will be perceived by a typical human observer from a given SPD cannot be calculated from this information. The color matching functions shown in Figure 3 are needed for this calculation.

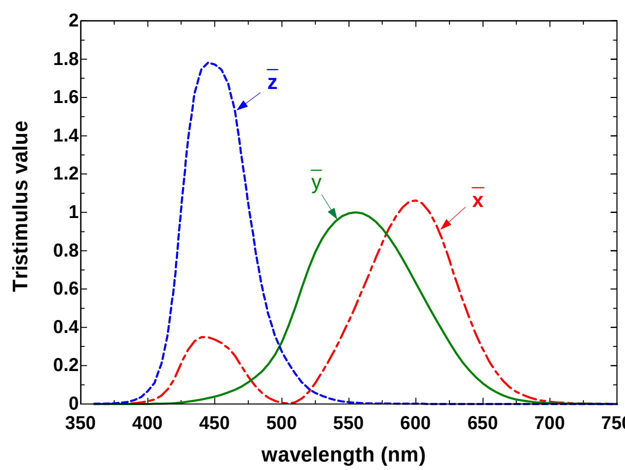

Fig. 3: The x, y, z color matching functions [5]

The color matching functions are derived from experiments in which human observers used a colorimeter to match a given light source color by adjusting the power of light in only three wavelengths: red (700 nm), green (546.1 nm), and blue (435.8 nm). The X, Y, Z color system is derived from these measurements and uses the x, y, z color matching functions to calculate the tristimulus values, X, Y, and Z that completely describe a color stimulus. The tristimulus values are calculated according to [5] in the following manner:

$$X = \int_{\lambda} P(\lambda)\bar{x}(\lambda)d\lambda \qquad (1)$$

$$Y = \int_{\lambda} P(\lambda)\bar{y}(\lambda)d\lambda \qquad (2)$$

$$Z = \int_{\lambda} P(\lambda)\bar{z}(\lambda)d\lambda \qquad (3)$$

where P(λ) is the light source power at wavelength, λ.

From these tristimulus values, chromaticity coordinates x and y are calculated using

$$x = X/(X+Y+Z) \qquad (4)$$

$$y = Y/(X+Y+Z) \qquad (5)$$

The chromaticity coordinates x and y, derived from an incident SPD and the color matching functions, predict the perceived color of the light source using the x,y chromaticity diagram shown in Figure 4. To use this diagram, locate the position where the *x* chromaticity coordinate on the horizontal axis intersects with the *y* chromaticity coordinate on the vertical axis. The intersection point is the perceived color of the light source. The x, y chromaticity coordinates of the four light source spectrums of Figure 2 are indicated on this figure.

All four light sources appear white, though the warm white fluorescent gives a yellower, "warmer" light while the beam normal radiation gives a more blue, "cooler" light. The dark line on Figure 5 is created by calculating the chromaticity coordinates of blackbody SPDs at different temperatures. These spectrums are created using Planck's equation for blackbody radiation at a specified wavelength as a function wavelength and temperature (K).

The "warmth" or "coolness" of light sources is quantified by the temperature of a blackbody that yields the same color light. For instance, a blackbody at 3000 K produces the same color of light as the warm white fluorescent, though their chromaticity coordinates differ. The warm white fluorescent is said to have a correlated color temperature (CCT) of 3000 K. The CCT of the halogen bulb is 4100 K. Compared to the warm white fluorescent, more of the power of the full spectrum fluorescent occurs at shorter

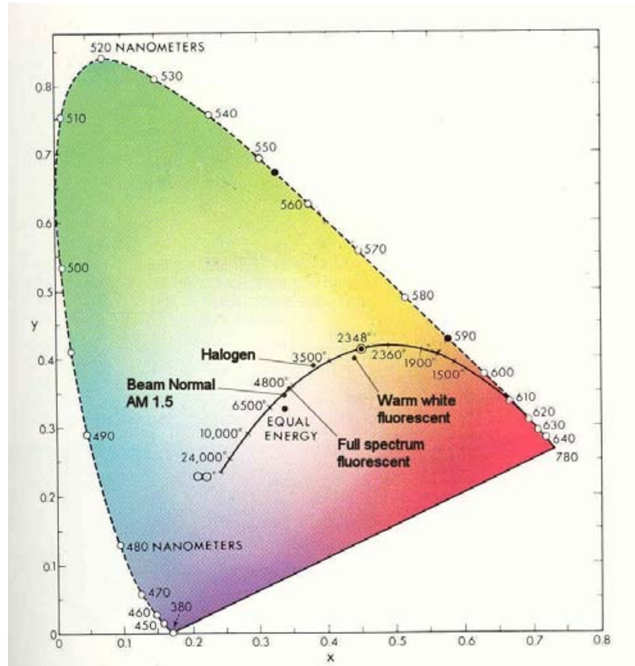

Fig. 4: 1931 CIE x,y chromaticity diagram

wavelengths, yielding a "cooler" CCT of 5000 K. Beam normal radiation in Seattle (AM 1.5) is 5200 K. The method by which x,y coordinates are transformed into a CCT is detailed by [5]. In general, it involves isotemperature lines that intersect the Planckian locus and interpolation of chromaticity coordinates between these lines to give a CCT value.

3. THE COLOR RENDERING OF A LIGHT SOURCE

The CCT defines the perceived color of a light source. It does not indicate how well the light source will render the color of objects it illuminates. For that, another colorimetric index is needed, the color rendering index (CRI).

The CRI of a light source is a measure of the color shift of objects illuminated by that light source in comparison to the same objects illuminated by a reference illuminant of comparable color temperature. A CRI of 100 means that the light source in question renders the color of eight color samples in the same manner as the reference illuminant. The CRI has been defined so that the color differences seen between a 3000 K fluorescent bulb and a 3000 K blackbody spectrum yield a CRI of 50.

The eight color samples used in the calculation of the CRI are defined by their spectral reflectances at given wavelengths. Samples are selected to yield a range of colors in the visible spectrum, e.g. sample one appears light greyish red under sunlight while sample six appears light blue. These reflectance curves can be found at [6].

The more closely the SPD of the light source matches the SPD of the reference illuminant, the better the CRI of the light source. Figure 5 shows the warm white fluorescent and halogen SPDs with their corresponding reference illuminants and their corresponding CRI values. The CRIs of the full spectrum fluorescent and the beam normal radiation are 90 and 100, respectively.

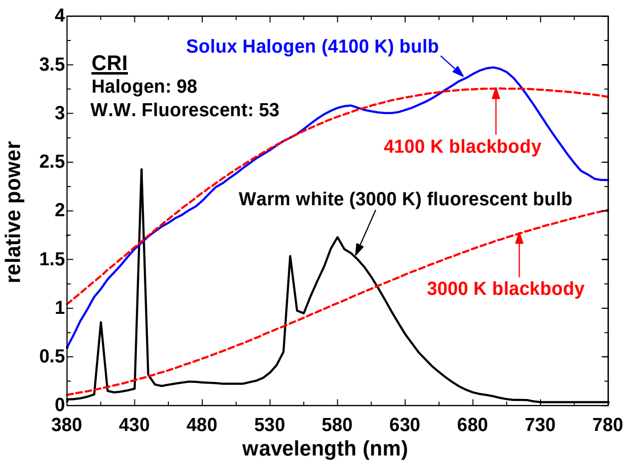

Figure 5: Calculation of the CRI for the halogen and warm white fluorescent spectrums.

The calculation of the CRI is somewhat involved and the reader is referred to [4], [5], and [6] for detailed explanations. In brief, the chromaticity coordinates of the light reflected by each sample (i = 1 through 8) are calculated using modified forms of equations 1 through 5 and a resulting color difference, ΔE_i, is calculated for each of the color samples lit by the light source and the reference illuminant. ΔE_i is used to calculate a color rendering index for each sample, R_i, defined by

$$R_i = 100 - 4.6\Delta E_i \tag{6}$$

and the CRI is the average of the eight color rendering indices:

$$CRI = \frac{1}{8}\sum_{i=1}^{8} R_i \tag{7}$$

4. THE ATMOSPHERIC MODEL, SMARTS2

The SPD of the light source is required to calculate luminous power, luminous efficacy, and the CCT and CRI of light sources. While TRNSYS uses TMY2 data that include the magnitude of beam normal radiation every hour of the year for many geographic locations, TMY2 data do not include the SPD of the beam normal radiation for that hour. Proper modeling of the hybrid lighting system requires an incident SPD on the collector each hour of the year. SMARTS2 was linked to TRNSYS to provide this SPD from 280-2500 nm at 5 nm intervals.

SMARTS2 calculates the clear sky beam normal SPD incident on a tracking surface given approximately ten parameters including elevation, precipitable water, aerosol optical depth, time of day, day of the year, location, and concentration of atmospheric pollutants. TMY2 data contain hourly precipitable water and aerosol thickness data. TRNSYS passes time of day, day of the year, location, and TMY2 data to SMARTS2 to find the clear sky SPD of the beam normal radiation for that hour. This SPD is integrated and scaled to match the beam radiation recorded in the TMY2 data file.

5. THE TRYNSYS HLS MODEL

The TRNSYS HLS model consists of interconnected component models that include a weather file, radiation processors, a hybrid lighting model, a building model, building schedules, utility rate schedules, and output components. Simulation results include annual energy and monetary savings gained from the hybrid lighting system as well as colorimetric indices, the CCT and the CRI.

The TMY2 weather file is used with SMARTS2 to generate the SPD of incident radiation on the collector for each hour of the year. This SPD is attenuated by the spectral and wideband transmittances of the collecting and cold mirrors, the fiber entrance region, the fiber itself, and the luminaires. The spectral transmittance of the mirrors and fiber are shown in Figure 6. The luminous and radiant power provided to the workspace is calculated from the SPD that remains after passing through these components.

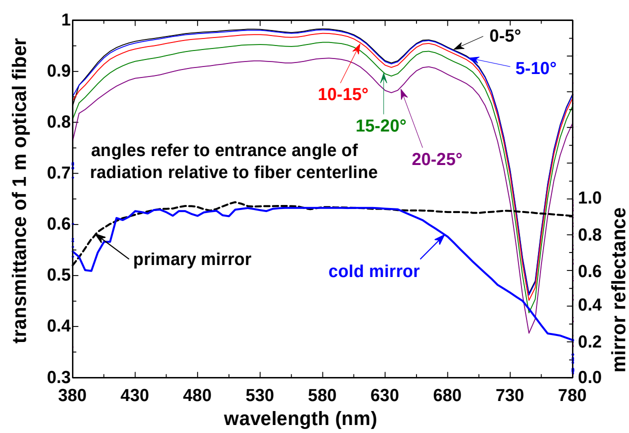

Figure 6: Spectral transmittance of one meter length of optical fiber and spectral reflectance of the mirrors [3]

Within TRNSYS, the light output from the hybrid lighting system model is sent to the building model. The building is modeled using the Type 56 multi-zone building model. Type 56 is a FORTRAN subroutine which is designed to provide detailed thermal models of buildings. The model consists of two windowless 2500 m^2 zones. One zone uses one of the three bulbs detailed in Figure 2 exclusively while the other zone pairs this bulb with light delivered by the HLS. Identical schedules in the two zones simulate the heating, cooling, and ventilation of a typical mixed-use environment. Additional gains in the model account for the people, computers, and lights in the building. Cooling in the building is supplied using a chiller with a constant COP of 3 and heating loads are met using an 80 % efficient natural gas furnace. Using local utility rate schedules, energy costs are calculated for the two zones of the building model with the difference representing the energy savings due to the hybrid lighting system.

The simulation uses a heating set point of 20°C with a night setback of 17 C. Cooling is active at 26°C and above. Relative humidity within the building is allowed to float between 30 and 60%. Illumination levels within the building are set to 500 Lux which is the IESNA recommended lighting level for general office work [7]. Occupancy schedules model a typical 8 am to 5 pm work week. Infiltration and ventilation rates are based on information provided in ASHRAE 62–2001. Rate schedules from utilities near the various locations are used to determine the time variant prices of natural gas and electricity.

Eight HLS 1.7 m^2 modules are used to collect the beam normal radiation. During clear sky conditions, this collecting area provides about half of the lumens needed to illuminate the workspace.

6. SIMULATION RESULTS AND DISCUSSION

The annual electrical load of the office building is the sum of the annual lighting and cooling loads. Figure 7 shows the percentage reduction in the total electrical load, the annual energy savings per 1.7 m^2 module, and the effect of the TPV as functions of location and lighting efficacy.

The HLS system performs much better in Tucson than Seattle. One reason is that eight modules in Tucson provide a larger percentage of the required illumination during the year than eight modules in Seattle. Figure 8 shows the number of hours in the year that the HLS is providing 0 to 100% of the required illumination in Tucson and Seattle.

As the number of modules increases, lighting fractions would increase until the HLS is providing 100% of the required illumination for some hours of the year. At this point adding additional collector area becomes counter-productive as more energy enters the building than required, increasing the cooling load and doing nothing to reduce the lighting load. For this reason annual energy savings per module begins to decrease at a certain number of 1.7 m^2 modules. Previous studies [8] have shown that for the 2500 m^2 building of this analysis, this saturation level corresponds to 15 modules in Tucson and 18 modules in Seattle.

Figure 9 presents chromaticity results for two days in Tucson. In this simulation, the building was equipped with warm white fluorescent bulbs that, if working without the HLS, provide a CCT of 3000 K and a CRI of 53.

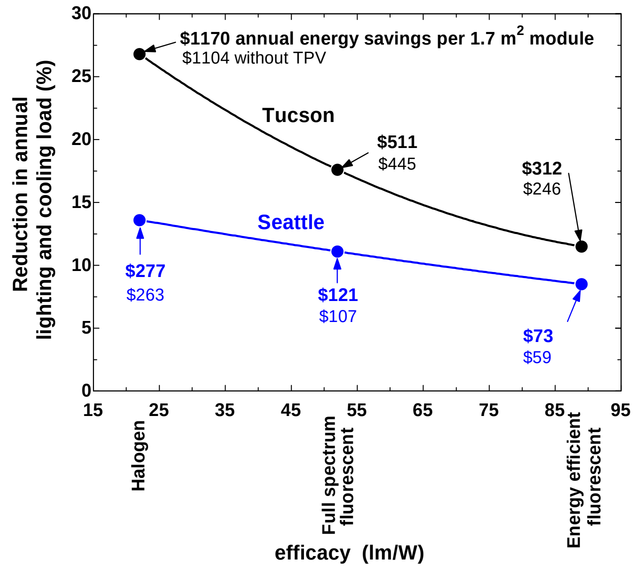

Fig. 7: HLS reduction in electrical load and annual energy savings per 1.7 m^2 module in Tucson and Seattle

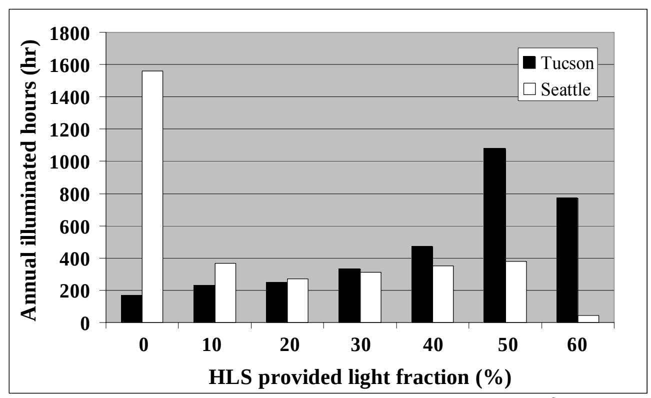

Fig. 8: Number of hours that HLS with eight 1.7 m^2 modules is providing specified percentage of required illumination to 2500 m^2 building in Tucson and Seattle.

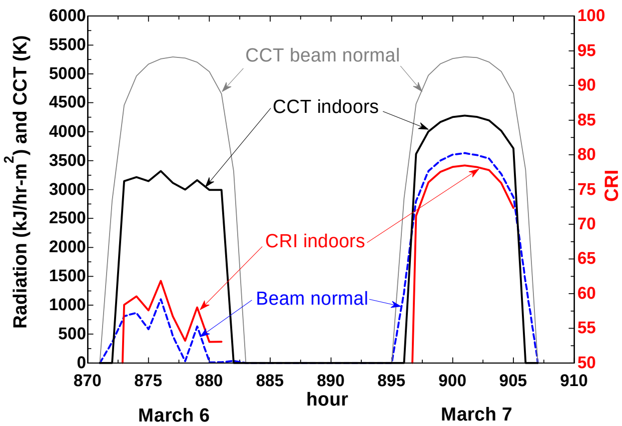

Fig. 8: CCT and CRI delivered by HLS in Tucson

March 6 was a cloudy day, with some hours yielding little beam radiation. For these hours the CCT and CRI match that of the fluorescent lighting. March 7 was a clear day. The spectrum of light delivered by the HLS combines with the spectrum of the fluorescent lighting to increase the CCT and CRI of the indoor light.

Figure 10 details the number of hours the indoor light is at the specified CCT for the given location and bulb source. Figure 11 presents CRI results similarly.

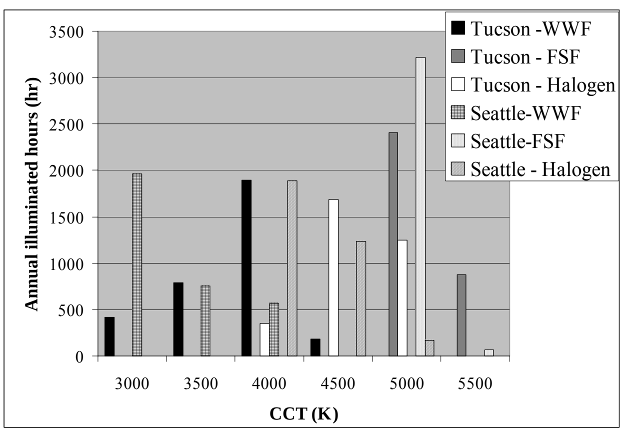

Fig. 10: The number of hours at the specified color temperature for all simulations. (WWF - warm white fluorescent, FSF - full spectrum fluorescent)

In general, the HLS maintains or increases the CCT and CRI of the indoor light provided by conventional bulbs. As the number of modules is increased and the bulbs are progressively dimmed, the CCT and CRI will approach that of the HLS delivered light.

7. CONCLUSION

TRNSYS and SMARTS2 were used to model the performance of an office building equipped with a hybrid lighting system in Tucson and Seattle. For each location, the annual energy savings and the chromaticity of the indoor light were found based on the efficacy and spectrum of the incident beam normal radiation and that of the conventional bulb paired with the system. These results and the flexibility of the TRNSYS code will assist commercial developers of this technology.

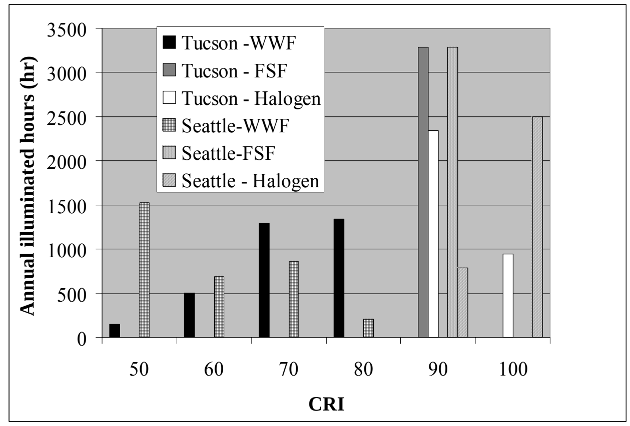

Fig. 11: The number of hours at the specified color temperature for all simulations.

8. REFERERENCES

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