Determination of the proportion of natural light in solar radiation using the method of conversion of lighting units into energy

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Abstract. In the article the method for the determination of the fraction of visible light in solar radiation was proposed. The solar spectrum was divided into three regions: ultraviolet, visible and infrared radiation. The spectral distribution of the intensity of solar radiation under various conditions was considered. With the help of the Mathcad software package, the spectral luminosity of a black body was calculated. Further, the proportion of natural light in solar radiation was estimated. The proposed method of converting lumens to watts consisted of 5 stages: normalization of the spectral luminosity curve of BB in the visible range by one; determination of the energy fraction of each wavelength introduced into the radiation intensity; obtaining the dependence of the illumination distribution on the radiation wavelength in lumens on the basis of the eye visibility curve; multiplying the values of the normalized spectral luminance curve with the values of the eye visibility curve in lumens; summation (integration) of the obtained values. This calculation showed that 1 W/m² of natural light is 213 lm/m², which was confirmed by 100,000 lux (lm/m²) with solar radiation of 1000 W/m².

1. Introduction
The only source of natural light is the Sun. It emits direct sunlight, part of which dissipates in the atmosphere and creates scattered radiation. Thus, they distinguish the light falling directly from the sun and the light of the “sky” - sunlight scattered by the atmosphere[1]. In the main agricultural regions of Russia in summer, the midday values of the direct energy radiation illumination are within 700–900 W/m² [1,2]. The attenuation of the solar flux in the atmosphere depends on the height of the sun above the horizon of the Earth and the transparency of the atmosphere. The smaller the height, the greater the number of optical masses of the atmosphere passes the sunbeam[3]. In general, illumination with direct sunlight varies widely: from 0 lx at sunrise and sunset to several tens of kiloluxes at midday in summer (usually not more than 120 klx) [4]. With the passage of a stream of direct solar radiation through the atmosphere, it is attenuated due to absorption (about 15%) and scattering (25%) of energy by gases, aerosols, clouds. The maximum of diffuse radiation is usually much less than the maximum of a straight radiation, but can reach 150-250 W/m² [2]. The range of variation of the illumination with diffused light is significantly less than the range of illumination with direct light. The illumination is 0.5 klx at the moments of sunrise or sunset and rises to 13-15 klx at midday hours for average atmospheric conditions[4]. The change in the transparency of the atmosphere has the opposite effect on diffuse
illumination compared to direct. With an increase in the turbidity of the atmosphere, the diffuse illumination increases[6].

2. Materials and methods
Direct solar radiation refers to the short-wave part of the spectrum (with wavelengths from 0.17 to 4 microns; in fact, the Earth surface is reached by rays with a wavelength of 0.29 microns). The solar spectrum can be divided into four main regions:
- ultraviolet radiation ($\lambda < 0.4 $ µm) - 8% of intensity. The short-wave ultraviolet region ($\lambda < 0.29 $ µm) is almost completely absent at sea level due to the absorption of O$_2$, O$_3$, O, N$_2$ and their ions;
- near ultraviolet range ($0.29 $ µm $< \lambda < 0.4 $ µm) reaches the Earth with a small fraction of radiation, but quite sufficient for tanning;
- visible radiation ($0.4 $ µm $< \lambda < 0.7 $ µm) - 46% of the intensity. Visible radiation is almost completely transmitted by the pure atmosphere, and it becomes a “window” open for this type of solar energy to pass to the Earth. The presence of aerosols and pollution in the atmosphere can be the reasons for significant absorption of radiation of this spectrum;
- infrared radiation ($\lambda > 0.7 $ microns) - 46% of intensity. Near infrared region ($0.7 $ µm $< \lambda < 2.5 $ µm). This spectral range accounts for almost half of the solar radiation intensity. More than 20% of solar energy is absorbed in the atmosphere, mainly by water vapor and CO$_2$ (carbon dioxide). The concentration of CO$_2$ in the atmosphere is relatively constant at 0.03%, and the concentration of water vapor changes greatly - almost to 4%.

At wavelengths greater than 2.5 microns, weak extraterrestrial radiation is intensively absorbed by CO$_2$ and water, so that only a small part of this range of solar energy reaches the surface of the Earth. The far infrared range ($\lambda > 12 $ µm) of solar radiation is practically not transmitted to the Earth [7].

Most of the solar energy outside the atmosphere falls in the wavelength range of 0.2–4 µm, and on the Earth’s surface in the range of 0.29–2.5 µm [8]. In terms of application of solar energy on the Earth it is necessary to consider only radiation in the range of lengths of waves of 0.29-2.5 microns.

The indicator of atmospheric influence on the intensity of solar radiation reaching the Earth surface is called “air mass” (AM). AM is defined as the secant of the angle between the Sun and the zenith.

![Figure 1. Spectral distribution of the intensity of solar radiation in various conditions.](image)

The upper curve (AM0) corresponds to the solar spectrum outside the Earth atmosphere (for example, aboard a spacecraft), i.e. at zero air mass. It is approximated by the distribution of the radiation intensity of a black body at 5800 K. The AM1 and AM2 curves illustrate the spectral distribution of solar radiation on the Earth surface when the Sun is at its zenith and at an angle of 60 ° between the Sun and zenith, respectively [9].
Using the “Mathcad” software package, it is also possible to estimate the fraction of visible radiation in solar radiation. On the basis of Planck formula spectral distribution of luminosity of the black body (BB) for which the sun (Figure 2) is considered is defined.

Wavelengths of the solar spectrum: \( \lambda = 0.1 \cdot 10^{-6}, 0.2 \cdot 10^{-6} \ldots 100 \cdot 10^{-6} \) m.

Special calculation factors: \( C_1 = 3.74 \cdot 10^{-16}, C_2 = 1.44 \cdot 10^{-5} \).

Sun temperature: \( T = 5800 \) K.

The authors determine the total luminosity of BB using the integral and the total luminosity for the visible wavelength range of 360-760 nm. Next, taking their ratio, the authors determine the fraction of the visible region in solar radiation.

Plank radiation formula:
\[
E_p = \int_{0.1 \cdot 10^{-6}}^{100 \cdot 10^{-6}} \frac{C_1 \lambda^5}{e^{\frac{C_2}{\lambda^4 T}} - 1} \, d\lambda.
\]

Plank radiation formula for the visible spectrum:
\[
E_v = \int_{0.36 \cdot 10^{-6}}^{0.76 \cdot 10^{-6}} \frac{C_1 \lambda^5}{e^{\frac{C_2}{\lambda^4 T}} - 1} \, d\lambda.
\]

The proportion of natural light in solar radiation:
\[
\eta = \frac{E_v}{E_p} = 0.46874.
\]

With the help of the “Mathcad” software package, the proportion of natural light in solar radiation was estimated to be 46.8%, as mentioned above [7].

3. Conversion of lighting units to energy units
It is customary to measure illuminance in lux (lx) - the unit of measurement of illuminance in the International System of Units (SI). One lux is equal to the illumination of a surface of 1 m² with a luminous flux of radiation falling on it equal to 1 lm: 1 lx = 1 lm/m² = 1 cd·sr·m². However, it is not always convenient to carry out calculations in lux or lumen. In many sources, including [3,4,10,12], it is indicated that 1 W/m² = 683 lx (lm/m²) for a wavelength of 555 nm. However, in natural light, a set of wavelengths is 360 - 760 nm, and each contributes its share of energy to the intensity of radiation. One method of transmission is the following method, which includes the following steps:
- normalization of the spectral luminosity curve of BB in the visible range by one;
- determination of the energy fraction of each wavelength introduced into the radiation intensity;
- obtaining the dependence of the illumination distribution on the radiation wavelength in lumens on the basis of the eye visibility curve;
- multiplying the values of the normalized spectral luminance curve with the values of the eye visibility curve in lumens;
- summation (integration) of the obtained values.

The normalization of the spectral luminance curve of BB in the visible range by one is: \( \rho(\lambda_2) = \frac{E(\lambda_1)}{E_{\text{max}}} \).

Figure 3. Normalized spectral luminosity curve.

The proportion of energy introduced by each wavelength in the radiation intensity is: \( \chi = \frac{\rho(\lambda_2)}{\sum \rho} \).

Figure 4. The curve of the proportion of the energy introduced by each wavelength in the radiation intensity.

The curve in Figure 4 was obtained for wavelengths in the range from 400 to 780 nm in 10 nm steps. Calculations are made in the program “Mathcad” (Table 1).

Table 1. Dependence of the share of energy made by each wavelength in the intensity of radiation

| No. | Wavelength, \( \lambda_2, \) nm | The proportion of energy introduced by each wavelength in the radiation intensity, \( \chi \) |
|-----|---------------------------------|---------------------------------|
| 1   | 400                             | 0.025                           |
| 2   | 410                             | 0.026                           |
| 3   | 420                             | 0.027                           |
| 4   | 430                             | 0.027                           |
| 5   | 440                             | 0.028                           |
| 6   | 450                             | 0.028                           |
| 7   | 460                             | 0.028                           |
| 8   | 470                             | 0.029                           |
| 9   | 480                             | 0.029                           |
The sum of the $\chi$ values is 1, i.e. the contribution of all wavelengths is given by intensity 1 in arbitrary units. Figure 5 shows the dependence of the visibility curve of the eye, presented in lumens. The maximum visibility of the eye falls on the length of 555 nm, as it is said in [10,11] at this wavelength of 683 lumens: $V = \text{interp}(p, \lambda, \chi)$.

![Figure 5. Dependence of lumen on wavelength.](image)

The dependence in figure 5 is obtained by multiplying each value of the eye visibility curve with a step of 10 nm by 683 lumens.

Multiplying the values of the dependence of the visibility curve and the dependence of the energy fraction of each wavelength gives: $Z_V(\lambda_2) = V_V(\lambda_2)/\chi$.

![Figure 6. Total lumens.](image)

### Table 2. Total lumens

| No. | Wavelength, $\lambda_2$, nm | $\chi$  | Curve visibility | $V_V(\lambda_2)$ | $Z_V$  |
|-----|-----------------------------|--------|-------------------|------------------|--------|
| 1   | 400                         | 0.023  | 0.0004            | 0.2732           | 0.00683|
| 2   | 410                         | 0.023  | 0.0012            | 0.8196           | 0.02131|
| 3   | 420                         | 0.024  | 0.004             | 2.732            | 0.07376|
| 4   | 430                         | 0.025  | 0.016             | 10.928           | 0.29506|
| 5   | 440                         | 0.026  | 0.023             | 15.709           | 0.43985|
| 6   | 450                         | 0.026  | 0.038             | 25.954           | 0.72671|
| 7   | 460                         | 0.027  | 0.06              | 40.98            | 1.14744|
| 8   | 470                         | 0.027  | 0.091             | 62.153           | 1.80244|
The sum (integral) of the multiplication values of two dependences is 213 lm. This suggests that 1 W/m$^2$ of natural light is 213 lm/m$^2$, which is confirmed by the generally accepted value of 100,000 lux (lm/ m$^2$) with solar radiation of 1000 W/m$^2$:

$$100000lx / (0.468 \cdot 1000W / m^2) = 213lm / W$$

4. Conclusion
The proposed method of converting lumens to watts consists of 5 stages: the normalization of the spectral luminosity curve of BB in the visible range by one; the determination of the energy fraction of each wavelength introduced into the radiation intensity; obtaining the dependence of the illumination distribution on the radiation wavelength in lumens on the basis of the eye visibility curve; multiplying the values of the normalized spectral luminance curve with the values of the eye visibility curve in lumens; summation (integration) of the obtained values. As a result, the proportion of natural light in solar radiation is 46.87%. With the help of the program "Mathcad" the method for converting lighting units into energy has been developed. The results showed that 1 W/m$^2$ can be equated to 213 lm/m$^2$.

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