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CONVERSIONS

(3)

Photometric, Radiometric, and Quantum Light Units of Measure:
A Review of Procedures for Interconversion

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Conversion constants and procedures necessary to interconvert photometric, radiometric, and quantum light units are described for sunlight and 9 electrical light sources.

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The American Society for Horticultural Science's Growth Chambers and Controlled Environments Working Group has recommended the use of quantum flux density as the primary method for reporting radiation (1, 3, 22), but occasions arise frequently where conversion of radiation units are convenient or necessary. These include comparison of reports using other units, engineering specifications, grower recommendations, and calibration of instruments.

Many different terms and units have been and are used in the literature to describe light or radiation. The selection of terms and use depends on discipline, location (indoors or outdoors), traditions, and bias of the reporter, audience, and publication.

Most professional societies have adopted in their editorial policies the use of Système International (SI) units completely or partially, yet the interpretation of SI units and derivations is not uniform from one group to another. As an example, units of $\mu E \cdot s^{-1} m^{-2}$, $\mu mol \cdot s^{-1} m^{-2}$, and $W \cdot m^{-2}$ all have been published in 1981 (12, 17, 23).

The problem of unit uniformity occurs in engineering as well as in plant science disciplines and causes problems in communication between groups. Conversion of units into similar units is necessary for comparison. Plant growers and manufacturers of equipment (greenhouse and growth-chamber lighting) as well as individual scientists need to convert from one system of measurement to another as simply as possible.

Wavelength interval and the generic source or its spectral content usually must be specified since conversion units are not equivalent for sources of different spectral content. Some conversion units have been published, but they are scattered throughout the literature,

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are not equally reliable, and are not complete in many cases (2, 4, 8, 9, 13, 14, 16, 18, 21, 24, 30, 33).

The purposes of this article are to provide definitions for many radiation units, show how the units relate to one another, and provide conversion constants and formulas so that one unit can be converted to another. The article is not intended to provide an exhaustive discussion of measurement errors.

Definitions of the units, while available in other references (e.g., 1, 3, 26, 27, 28, 29, 31, 32), are included in this article to provide the plant scientist with a single source of information and to help clarify some misunderstandings in the definitions. Savage (29, 30, 31) discusses some radiation units used in horticulture and their relation to SI metric units.

Conversion of units is a relatively simple mathematical process when tables are available and the time unit is considered. However, when using these conversion factors, it is important to realize that the converted number contains both conversion and measurement error. Based on our experience, the uncertainty associated with conversion of radiation units from generic type sources using the conversion factors presented in this paper is less than 10%. This error is due to lamp aging, operating procedures, and slight differences among similar lamps from different manufacturers (34). This uncertainty however, is less than the total overall error expected in measurements with any of the commonly used light sensors (4, 11, 19, 20, 21, 25). For example, Tibbitts et al. (33) found 3 photometric sensors to vary 22.5% from one another under a given light source. Absolute variation from the standard was a maximum of 12.7%. One should "not expect less than 10–25% error in radiation measurements made under non-ideal conditions" (4).

Conversions are on the basis of equivalent energy in specified wavelength intervals. Spectra are believed typical of lamps and ballasts in the United States. This paper extends the information from LI-COR (4) and McCree (21), and updates previous publications by Cathey, Campbell, and Thimijan (7, 8, 9).

The conversion data in Table 1 are revised from Campbell et al. (7) to agree with current manufacturers' ratings. Conversion constants through 1000 nm wavelength were calculated from spectral radiant power distributions measured with a specially constructed, narrow-band spectroradiometer (7). Relative spectral response is traceable to a National Bureau of Standard (NBS) calibrated incandescent lamp. Longer wavelength data derived from the literature are included also. Desired parameters were obtained by multiplying the spectral radiant power by an appropriate weighting function, wavelength for wavelength, and summing over the selected wavelength interval (4). For example, lumens were obtained employing the spectral luminous efficiency function for the International Lighting Commission (CIE) standard photometric observer (10). Ratios of the weighted sums then were calculated and reported.

Power per lumen was multiplied by the initial lumen output of a new lamp to obtain power output from a lamp. Lumen ratings were obtained from manufacturers' catalogs and from evaluated summaries of catalogs, particularly the *IES Lighting Handbook* (15). Additional power required to operate a lamp was derived from ballast manufacturers' catalogs and added to rated lamp watts. Lumen output and/or power consumption of a lamp may change as it ages. The mean lumen output of several commercial lamps are listed, on a consistent basis, in *USDA Farmer's Bulletin* 2243 (6).

Completed tables were in agreement with similar, reliable data from manufacturers and other published data (21), which also were derived from spectroradiometric measurements. Conversion constants derived from broad bandwidth radiometer measurements were not considered.

Estimates of longer wavelength radiant power and of conducted and convected power from lamps were based on measurements reported by Jack and Koedam (16) and on an energy balance of the individual lamp type. Broadband radiometers manufactured by Hewlett Packard and by Optronic Laboratories were used to check for large errors. However, conversion factors derived from broadband measurements—e.g., Tibbitts et al. (33)—are not recommended as these factors vary by up to 30% from our spectroradiometric data.

Photons per joule were calculated in the same manner as other conversion constants, and scaled by the Avogadro number. Where these numbers were substantially the same as those given by McCree (21), his values are given.

Conversion formulas

A. *Photometric*

10.8 lux = 1 footcandle

e.g., 10,000 lx = 929 fc

B. *Radiometric*

1 Langley per day
= 0.484 watt per square meter

e.g., 207 $\mathrm{Ly \cdot d^{-1}} = 100\ \mathrm{W \cdot m^{-2}}$

The *average power* ($\mathrm{energy \cdot time^{-1}}$) in a minute (min), in an hour (hr), or in a day (d) is often reported incorrectly as the energy sum in a time interval; e.g., 1273 $\mathrm{kJ \cdot d^{-1}}$ (5). The kilowatt-hour and joule are appropriate units for reporting energy sums, but the appropriate SI unit to report a rate (energy per unit time) is the watt. Energy sum units can be restored to rate units by dividing the energy sum by the time interval. Thus, the kilowatt-hour (an energy sum and a non-SI unit) can be converted to a rate unit (the watt) by dividing by the time interval in hours. A kilowatt-hour per hour is a kilowatt. To convert the number of joule per hour, usually quite large, into watts ($\mathrm{1W = 1J \cdot s^{-1}}$), divide by 3600 seconds in an hour; e.g.,

$$(1273\ \mathrm{kJ \cdot d^{-1}})/(24\ \mathrm{hr \cdot d^{-1}}\ 3600\ \mathrm{s \cdot hr^{-1}})$$

$$= 14.73\ \mathrm{J \cdot s^{-1}} = 14.73\ \mathrm{W}$$

The above conversion shows an example of situations where this conversion can be useful. The data reported for Columbia, Mo. during the week of December 6–12 indicate a 0.9 chance that the daily average solar radiation will be at least 1273 $\mathrm{kJ \cdot d^{-1} m^{-2}}$ (5). This converts to approximately 15 $\mathrm{W \cdot m^{-2}}$. To appreciate how low this value is, the approximate 24 hr average power received on a clear day in June at lat. 40°N is 281 $\mathrm{W \cdot m^{-2}}$ (Table 2) and at noon, 938 $\mathrm{W \cdot m^{-2}}$.

Non-SI metric units usually can be corrected to SI units by moving all prefixes to the numerator. Thus, a milliwatt per square centimeter is $10^{-3} \times 10^{4}$ watt per square meter = 10 $\mathrm{W \cdot m^{-2}}$. An erg is 10^{-7} joule. An erg per second and square centimeter is $10^{-7} \times 10^{4}\ \mathrm{joule \cdot second^{-1}\ meter^{-2}}$ = milliwatt per square meter ($\mathrm{mW \cdot m^{-2}}$). Note there is only one division (per) in an expression (30).

C. *Mixed conversion: photometric to radiometric*

a) lx to $\mathrm{W \cdot m^{-2}}$

$$\frac{(\mathrm{lm \cdot m^{-2}\ lx^{-1}})\ (\mathrm{lx})\ (\mathrm{mW \cdot lm^{-1}})\ (\mathrm{hr\ of\ light})}{(1000\ \mathrm{mW \cdot W^{-1}})\ (24\ \mathrm{hr})} = \mathrm{W \cdot m^{-2}}$$

Conversion of lx to $\mathrm{W \cdot m^{-2}}$ depends on the light source and the waveband of interest. Tables 1 and 2 provide the necessary data to interconvert photometric and radiometric units of sun and electrical light. Converting 10 kilolux (klx) cool-white fluorescent light for a 10-hr period per day to $\mathrm{W \cdot m^{-2}}$ (24 h average; 400–700 nm) would be:

$$\frac{(10{,}000\ \mathrm{lx})\ (2.93\ \mathrm{mW \cdot lm^{-1}})\ (10\ \mathrm{hr})}{(1000\ \mathrm{mW \cdot W^{-1}})\ (24\ \mathrm{hr})}$$

$$= 12.2\ \mathrm{W \cdot m^{-2}}$$

The 2.93 $\mathrm{mW \cdot lm^{-1}}$ comes from Table 1, subhead "Radiation per unit of luminous flux", row 400–700 nm, column FCW.

b) lx to $\mathrm{Ly \cdot d^{-1}}$

$$\frac{(\mathrm{lm \cdot m^{-2}\ lx^{-1}})\ (\mathrm{lx})\ (\mathrm{mW \cdot lm^{-1}})\ (\mathrm{hr\ of\ light})}{(484\ \mathrm{mW \cdot m^{-2}})\ (\mathrm{Ly \cdot d^{-1}})^{-1}\ (24\ \mathrm{hr})}$$

$$= \mathrm{Ly \cdot d^{-1}}$$

D. *Mixed conversion: quantum to radiometric*

$\mathrm{\mu mol \cdot s^{-1} m^{-2}}$ to $\mathrm{W \cdot m^{-2}}$

The term "$\mathrm{\mu mol \cdot s^{-1} m^{-2}}$" is based on photon numbers. Photons at different wavelengths have different energies. Thus, one must know both the number of photons per unit wavelength at each wavelength and the energy per photon at each wavelength to calculate total energy. This is a complex process which has been simplified to division by a constant for a known light source (Table 3) (7, 21):

$$\frac{\mu\text{mol}\cdot\text{s}^{-1}\text{m}^{-2}}{\text{Constant}} = \text{W}\cdot\text{m}^{-2}$$

Convert 1000 μmol·s^{-1}m^{-2} of high-pressure sodium to W·m^{-2} (400–700 nm) as follows:

$$\frac{1000\ \mu\text{mol}\cdot\text{s}^{-1}\text{m}^{-2}}{4.98\ \mu\text{mol}\cdot\text{s}^{-1}\ \text{W}^{-1}} = 201\ \text{W}\cdot\text{m}^{-2}$$

Assume our readings are instantaneous and the irradiance is constant. Then, to convert to the common basis of a 24-hr average, use the following formula:

$$\text{W}\cdot\text{m}^{-2}\ \text{(from above)}\ \frac{\text{h irradiation}}{24\ \text{hr}}$$

$$= \text{W}\cdot\text{m}^{-2}\ \text{(24-hr basis)}$$

It is not possible to make this 24-hr average calculation with one single reading in sunlight. In addition, it is impossible to convert 24-hr average sunlight power values into meaningful 8- or 16-hr average power values because the time distribution of power throughout the day is unknown since it has been discarded. Therefore, lamp light data must be degraded to 24-hr average values to be comparable with sunlight data.

E. *Mixed conversion: photometric to quantum*

lx to μmol·s^{-1}m^{-2}

Table 1: Electrical, photometric, and radiometric characteristics of selected new lamps compared to clear-sky summer sunlight.

	Light source[z]													
								HID discharge						
	Incandescent		Fluorescent						HG/				Sun[y]	
Parameter	60	100	FCW	FCW	FWW	PGA	PGB	HG	DX	MH	HPS	LPS	DL	SKY
						Electrical input power								
Total W	60	100	46	245	46	46	46	440	440	460	470	230	---	---
Lamp W	60	100	40	215	40	40	40	400	400	400	400	180	---	---
						Luminous output								
Total lm[x]	860	1740	3200	15,700	3250	925	1700	21,000	22,000	40,000	50,000	33,000	---	---
Total lm/W	14	17	70	64	71	20	37	48	50	87	106	143	107	124
Lamp lm/W	14	17	80	73	81	23	42	52	55	100	125	183	---	---
						Radiation per unit of luminous flux, mW/lm								
400–700 nm	3.99	3.97	2.93	2.93	2.81	6.34	3.96	2.60	2.62	3.05	2.45	1.92	4.02	4.56
580–700 nm	2.61	2.53	1.02	1.02	1.23	3.39	1.95	0.14	0.73	1.17	1.58	1.89	1.50	1.14
700–850 nm	5.01	4.66	0.06	0.06	0.05	0.08	0.41	0.17	0.19	0.37	0.93	0.26	1.43	0.77
800–850 nm	1.83	1.69	0.009	0.009	0.006	0.007	0.03	0.06	0.05	0.25	0.72	0.25	0.43	0.21
250–400 nm	0.07	0.08	0.13	0.13	0.09	0.24	0.28	1.10	0.41	0.33	0.026	0.004	0.60	1.74
400–850 nm	9.00	8.63	2.99	2.99	2.86	6.41	4.37	2.77	2.81	3.42	3.38	2.18	5.45	5.33
850–2700 nm	47.3	38.4	0.06	0.13	0.06	0.21	0.12	2.81	2.68	0.68	0.84	0.12	3.21	0.96
Thermal	5.8	4.8	4.4	5.0	4.4	17.0	8.8	8.9	8.8	3.9	2.6	1.6	0.12	0.01
						Radiation output, W *per lamp*								
400–700 nm	3.43	6.90	9.38	46	9.13	5.86	6.73	55	58	122	123	63	---	---
580–700 nm	2.24	4.41	3.27	16	4.00	3.13	3.32	3	16	47	79	62	---	---
700–850 nm	4.31	8.11	0.18	0.88	0.15	0.07	0.69	3.6	4.1	14.8	46.5	8.6	---	---
800–850 nm	1.58	2.94	0.03	0.14	0.02	0.01	0.05	1.2	1.1	10.0	36.0	8.3	---	---
250–400 nm	0.06	0.14	0.42	2.0	0.29	0.22	0.48	23	9	13	1.3	0.13	---	---
400–850 nm	7.74	15.00	9.56	47	9.28	5.93	7.42	58	62	137	169	72	---	---
850–2700 nm	40.7	66.8	0.2	2.0	0.2	0.2	0.2	59	59	27	42	4	---	---
Thermal	5.0	8.4	14	79	14	16	15	186	193	156	128	53	---	---
						Heat losses, W *per lamp*								
Conduction-convection	6.5	9.7	16	85	16	18	17	74	77	67	60	51	---	---
Ballast	0	0	6	30	6	6	6	40	40	60	70	50	---	---
						Distribution of output power as a fraction of electrical input power, mW/W								
400–700 nm	57	69	204	188	199	127	146	124	131	265	261	276	429	567
580–700 nm	37	44	71	65	87	68	72	6	36	102	168	271	160	142
700–850 nm	72	81	4	4	3	2	15	8	9	32	99	37	152	96
800–850 nm	26	29	0.6	0.6	0.4	0.1	1	3	3	22	77	36	46	26
250–400 nm	1.0	1.4	9	8	6	5	10	52	21	29	2.8	0.6	64	216
400–850 nm	129	150	208	192	202	129	161	132	140	297	360	313	581	663
850–2700 nm	678	668	4	8	4	4	4	134	134	59	89	17	342	119
Thermal	83	84	305	322	309	342	324	423	439	339	271	230	13	1
Conduction-convection	109	97	344	347	349	390	370	168	175	146	128	222	0	0
Ballast	0	0	130	122	130	130	130	91	91	130	149	217	0	0

[z] Data are believed typical of lamps and ballasts in the United States. For detailed spectral differences, see (7, 8, 9, or 15). Additional thermal radiation is expected because part of the radiation tabulated will be absorbed by and re-emitted from the environment. Fluorescent light sources: FCW = cool-white (2 sizes with similar spectral distribution); FWW = warm-white; PGA = plant growth A (e.g., Gro-Lux, Plant Light, Plant Gro); and PGB = plant growth B (e.g., Gro-Lux Wide Spectrum). HID discharge: HG = clear mercury; HG/DX = mercury deluxe; MH = metal halide B (sodium, scandium, thorium, mercury, lithium iodides); HPS = high-pressure sodium; and LPS = low-pressure sodium.

[y] Clear-sky summer sunlight: DL = daylight (includes both direct beam and skylight); and SKY = skylight (scattered sunlight; does not include emission from the atmosphere). Do not add DL and SKY spectral distribution of sunlight on Earth's surface.

[x] 1 lm·m^{-2} = 1 lux; mW/lm = W·m^{-2}·klx^{-1}.

Table 2. Photometric and radiometric characteristics of sunlight (average clear summer day).[z]

	Radiation in wavelength band (nm)					
Characteristics	Total	400–700	400–850	580–700	700–850	800–850
$mW \cdot lm^{-1}$	9.38	4.02	5.45	1.50	1.43	0.43
24-hr avg $W \cdot m^{-2}$ (daily, 30 klx)	281	121	164	45	43	13
$Ly \cdot d^{-1}$	581	($Ly \cdot d^{-1} = 0.484\ W \cdot m^{-2}$, total spectrum, ultraviolet through infrared)				
$\mu mol \cdot s^{-1} m^{-2}$ (24-hr avg)	$\longrightarrow$	552	$\longrightarrow$ ($\mu mol \cdot s^{-1} m^{-2}$, 400–700 nm = 0.51 $W \cdot m^{-2}$, total spectrum)			
$\mu mol \cdot s^{-1} m^{-2}$ (instantaneous) (near solar noon)		1837		(18.37 $nmol \cdot s^{-1} \cdot lm^{-1}$, 400–700 nm)		
klx (near solar noon)	100					
kfc (near solar noon)	9.3					

24.8

[z] 30 klx represents an average expected value, not necessarily an absolute maximum, at lat. 40°. The numbers listed here are provided as a relative indicator of the magnitude of the units under sunlight conditions. Measurements under different conditions will, of course, vary. All values are on a horizontal surface.

First, convert to $W \cdot m^{-2}$ using the procedure described above under C.a, but do not consider time interval of irradiation. Then, use the constants from the column headed "$\mu mol \cdot s^{-1} m^{-2}$ per $W \cdot m^{-2}$" (Table 3). Convert 10 klx cool-white fluorescent light to $\mu mol \cdot s^{-1} m^{-2}$ as follows:

$$\frac{(10{,}000\ lx)\ (2.93\ mW \cdot lm^{-1})}{1000\ mW \cdot W^{-1}}$$

$$= 29.3\ W \cdot m^{-2}\ (400\text{–}700\ nm)$$

and then:

$$(29.3\ W \cdot m^{-2})\ (4.59\ \mu mol \cdot s^{-1}\ W^{-1})$$

$$= 134.5\ \mu mol \cdot s^{-1} m^{-2}\ (400\text{–}700\ nm)$$

Alternatively, direct conversion can be made using lx per $\mu mol \cdot s^{-1} m^{-2}$ (Table 3):

$$(lx)/constant = \mu mol \cdot s^{-1} m^{-2}$$

$$\text{e.g.,}\ \frac{10{,}000\ lx}{74\ lx\ (\mu mol \cdot s^{-1} m^{-2})^{-1}}$$

$$= 135.1\ \mu mol \cdot s^{-1} m^{-2}$$

Definitions

A. *Photometric units, illuminance*

1. Footcandle = one lumen per square foot. The 16th General Conference on Weights and Measures (CGPM), Oct. 1979, decided that the candela is the luminous intensity of a source emitting monochromatic radiation of frequency 540 × 10^{12} Hz and radiant intensity 1/683 watt per steradian. This corresponds to 683 lumens per watt of radiation at approximately 555 nm wavelength, which is near the maximum of the standard photopic spectral luminous efficiency curve (15).

2. Lux = one lumen per square meter.

B. *Radiometric units, irradiance*

1. The watt per square meter ($W \cdot m^{-2}$) is energy per unit time and unit area. One $W \cdot m^{-2}$ is a joule per second and square meter ($J \cdot s^{-1} m^{-2}$). The International Steam Table calorie [cal (IT)] is 4.1868 joule (25). Thus, one $W \cdot m^{-2}$ equals 14.3 $cal \cdot min^{-1} m^{-2}$ or 0.2383 $cal \cdot s^{-1} m^{-2}$. When using the term "$W \cdot m^{-2}$", the wavelength region must be specified as well as the time interval averaged.

2. The Langley (Ly) is one $cal \cdot cm^{-2}$ and is expressed generally in the form of $Ly \cdot d^{-1}$. One $Ly \cdot d^{-1}$ equals 0.484 $W \cdot m^{-2}$, derived from the number of joule per calorie and second per day. Several slightly different values have been assigned to the calorie and to the Langley.

C. *Quantum units, photon flux density*

1. Microeinstein per second and square meter ($\mu E \cdot s^{-1} m^{-2}$). The einstein has been used to represent the quantity of radiant energy in Avogadro's number of photons (29, 31) and also Avogadro's number of photons (22, 32). The second definition has the einstein equal a mole of photons. While commonly used as a unit for photosynthetically active radiation (PAR) (22), the einstein is not an SI unit.

2. Micromole per second and square meter ($\mu mol \cdot s^{-1} m^{-2}$). This term is based on the number of photons in a certain waveband incident per unit time (s) on a unit area (m^2) divided by the Avogadro constant (6.022 × 10^{23} mol^{-1}). It is used commonly to describe PAR in the 400–700 nm waveband.

Table 3. Multiply $W \cdot m^{-2}$ by constant to obtain $\mu mol \cdot s^{-1} m^{-2}$ or divide lx by constant.

	$\mu mol \cdot s^{-1} m^{-2}$ per $W \cdot m^{-2}$ [z]	lx per $\mu mol \cdot s^{-1} m^{-2}$ [y]	
Lightsource	400–700 nm	400–700 nm	400–850 nm
Sun and sky, daylight	4.57	54	36
Blue sky only	4.24	52	41
High-pressure sodium	4.98	82	54
Metal halide	4.59	71	61
Mercury deluxe	4.52	84	77
Warm-white fluorescent	4.67	76	74
Cool-white fluorescent	4.59	74	72
Plant growth fluorescent A[x]	4.80	33	31
Plant growth fluorescent B[x]	4.69	54	47
Incandescent	5.00	50	20
Low-pressure sodium	4.92	106	89

[z] After McCree (21). The value for mercury has been changed from 4.74 given for color-improved. McCree measured plant growth B. Note that both quantities are for the 400 to 700 nm wavelength band so the $W \cdot m^{-2}$ must be in the 400-700 nm band to be correct. Conversion to power in other bands, including total power, can be made using data in Table 1. The conversion depends on the wavelength band, which must be specified.

[y] Values calculated from Table 1 and McCree (21).

[x] For examples, see Table 1, footnote z.

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