The lumen revisited:
Implications for global lighting regulations

Peter Bennich
The Swedish Energy Agency
Box 380 69
S-100 64 Stockholm
Sweden
Email: peter.bennich@energimyndigheten.se

Mark Rea, Mariana Figueiro, Dan Frering
Lighting Research Center
Rensselaer Polytechnic Institute
Address: 21 Union Street, 3rd floor, Troy, NY, USA
Email: ream@rpi.edu

Summary

The lighting sector is presently seeing an unprecedented transformation due to new discoveries on the relationship between light and health that coincide with fast technological developments of lighting systems based on LEDs and smart control systems. The expectations for resource efficient lighting applications that meet the needs of users in different situations are righteously high, but manufacturers, practitioners and governments will need to understand how changes in energy regulations affect people. The regulatory framework in different regions aims at supporting this development by addressing everything from safety, productivity, and health to the use of natural resources, while constantly following technology developments. Thus, in line with the promises of the emerging new lighting technologies in recent years, minimum energy performance requirements (sometimes referred to Minimum energy performance standards, MEPS) combined with energy labels, are used as a way of phasing out old, inefficient lighting systems.

Real success, however, will as always depend on sound metrics and test standards that meet human needs. So far some focus has been directed to the development of revised or new test standards for various parameters such as colour rendering index (CRI) and system life. These have proven to be a challenge, but perhaps the largest barrier has been associated with the most fundamental metric of them all, the photopic luminous efficiency function underlying the candela and the lumen. In order to successfully support resource efficient lighting systems, it has become more and more evident that the photopic luminous efficiency function does not completely represent the human eye's sensitivity to light. Thus light source and application regulations based upon an inadequate representation of the "eye sensitivity" curve are less likely to meet the needs of humans and are more likely to waste lighting energy.

This paper discusses the possibility to achieve more accurate regulations for resource efficient lighting by formally defining a new luminous efficiency function that more completely represents the sensitivity of the human eye to light. This new function represents the entire useful spectral range of the physiological response of the human eye, rather than the partial sensitivity curve characterized by the photopic luminous efficiency function. A main advantage of this new function is that it eliminates the problems associated with multiple definitions of the candela and the lumen, thus providing a single definition of light, while simultaneously providing a foundation for different metrics and test standards specific to different applications. Thus, a single "universal lumen" can lay the foundation for regulations aimed at setting minimum energy performance requirements for light sources, and better supports national and/or international lighting application regulations.

As an example, the paper uses the EU regulations for lighting to demonstrate how requirements based on the universal lumen can be applied, but these examples could be done for corresponding regulations in other regions as well. The results demonstrate the necessity of proper metrics and test standards in the regulatory framework, and are one of the main reasons why governments must be involved in the standardisation process.

Introduction

Electrical lighting makes it possible to be active through the day, i.e. independent of access to daylight, and has since the past century been one of the hallmarks of a highly developed society. It is of no surprise, then, that the electricity use globally for lighting is relatively large: in 2005 ca 2700 TWh/yr, ca 16 % of the total electricity use of 16 900 TWh/yr [Waide 2007, Tsao 2010]. Consequently, the cost and environmental impact, not least due to CO_2 emissions adding to the climate change, is considerable; furthermore, projections of future use of electricity for lighting have indicated an almost 100 % increase by 2030, ca 5000 TWh/yr, in the absence of policy measures [Waide 2007]. A large part of the increase in lighting energy use of new and much needed lighting in areas where there is currently no electric lighting at all, but also more lighting is being installed in developed regions. As a result of this increasing demand, increased electricity production including new infrastructure for distribution of electricity will be required, which will add cost and environmental impact. However, as discussed in [Waide 2007], by *proper policy design programs* promoting more energy efficient lighting, the current use of electricity for lighting should be possible to keep at the same level as today while at the same time provide both new lighting for undeveloped regions and more lighting for developed regions.

As a result, lighting regulatory programs have been developed across the globe over the past decade; an overview of the present status can be found in [UNEP]. The main focus of the regulations is setting minimum energy performance (efficacy) requirements in terms of luminous flux divided by electric power; or lumens per watt [lm/W]. Additional requirements like colour rendering index (CRI) and lifetime often complement the efficacy requirements, in order to secure a basic lighting (CRI) and technical (e.g., lifetime) quality.

Parallel to the developments in the regulatory space, the technical development of new light sources based on light emitting diodes (LEDs) has been very fast: from being used mainly in special applications such as signal applications, LED are now entering all fields of lighting thanks to promises of unprecedented lighting properties, efficacy and versatility. In general, regulatory efforts sustain and accelerate the technical development of efficient products, but in order to get a proper steer, attention also needs to be paid to the underlying layers of standardisation (fig 1): without proper metrics and test methods, proper regulations cannot be designed, let alone be enforced.

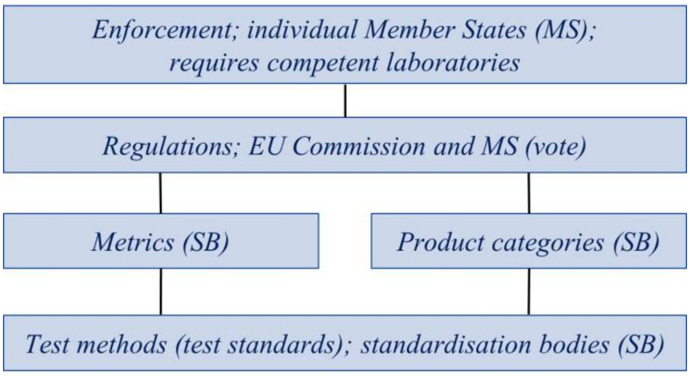

Figure 1. *The relationship between test methods, metrics, product categories and regulations. (Example from the regulatory structure within EU.) Test methods, metrics and product categories are normally developed by standardisation bodies (SB) although the boundary to the regulations regime is not strict. Regulations in Europe are developed by the European Commission after negotiations with individual member states (MS). Enforcement of the regulations are however the sole responsibility of each MS. Without proper test methods and metrics, it is almost impossible to design efficient and adequate regulations, let alone enforce them.*

Thus, the increased use of LED, being a relatively new technology, has spurred the development of new metrics and associated test methods for issues such as lifetime, colour rendering, and flicker. It is therefore expected that new metrics and test methods will be established in a couple of years.

In that sense, the development of new lighting solutions follows the same pattern as seen in other product groups[1], where there is constant *interplay* between the technical, standardisation and regulatory efforts.

[1] As an example, the development of variable speed drives (VSD) for electrical motors, has led to efforts to develop new test methods for the system electrical motor + VSD.

However, there is one aspect that makes lighting very different to probably all other product groups or end-use applications: the *fundamental metric* underlying the candela and the lumen used in the standards[2] and regulations, namely the photopic luminous efficiency function, is defined in *terms of people* rather than on sole physical properties underlying other fundamental properties such as mass, length, electric current etc. More specifically, *light* is defined based on how optical radiation on the human retina is transduced to neural signals.

Developed in 1924, the original luminous efficiency function, V(λ), was based on the response of optical radiation at different wavelengths presented to the fovea in the retina and under experimental conditions where only the long-wavelength sensitive (L) and middle-wavelength sensitive (M) cones contributed to the observer's response; the third cone type, short-wavelength-sensitive (S) cones, did not participate in the response. Subsequent experiments have shown that S-cones participate in brightness perception as well as L and M cones [Rea 2010, Bullough 2011], that rods initiate visual sensation at very low light levels in non-foveal regions of the retina [CIE 1951], and, finally, that a class of ganglion cells in the retina are intrinsically photosensitive, contributing to both visual and non-visual (circadian) system responses to light [Berson 2002, Dacey 2003]. In 1951 a second, scotopic luminous efficiency function, V'(λ), was sanctioned by the CIE (Commission Internationale de l'éclairage). See fig 2 where both efficiency functions are depicted – the photopic luminous efficiency function, V(λ), and the scotopic luminous efficiency function, V'(λ).

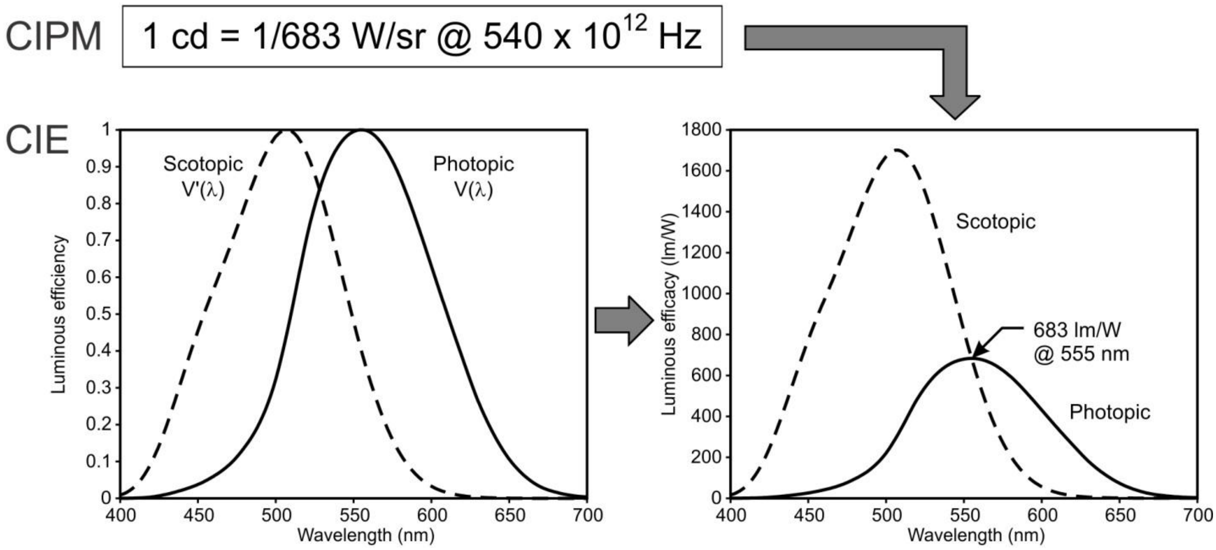

Figure 2: *The definition of light. Unlike other fundamental quantities light, or more formally luminous intensity, is defined in terms of human vision, and unlike other fundamental units in the SI system, its definition is administered by two agencies under a mutual recognition agreement (MRA). The International Committee for Weights and Measures (CIPM) defines the unit itself (the candela) as 1 cd = 1/683 W/sr @ 540 x* 10^{12} *Hz (often approximated as 683 lm/W at 555 nm as shown in the figure) while the Commission internationale de l'éclairage (CIE) defines the luminous efficiency functions (e.g., V(λ) and V'(λ) shown in the figure) used to weight the emission spectrum generated by different light sources. Both definitions must be used together to make practical photometry possible. From [REA 2014a].*

Instead of having one fundamental definition for light, there were suddenly two. As discussed in [REA 2014a, REA 2014b] and shown in fig 2, a link between the two functions was established by normalising the two curves at 555 nm (the peak of the photopic luminous efficiency function). But to make it worse, at light levels between the photopic and the scotopic levels, the mesopic regime, the neural response is best described as a non-linear combination of the two efficiency curves, in all leading to a range of efficiency curves.

In summary, instead of having one unique definition of light (again defined based on how optical radiation on the human retina is transduced to neural signals) there are several. From a standardisation and regulatory stand point this leads to confusion: whereas light is about definitions, *lighting* is the *application* of light for different

[2] A word on terminology: in this paper "standards" only refers to metrics, product categories or test methods, i.e. anything that belongs to the standardisation layer in fig 1 unless specifically stated otherwise. Sometimes "standards" is mixed with "regulations" (like in Minimum energy performance standards, MEPS), which is avoided here.

situations: whereas a warm light (bias to the red part of the spectrum) may be preferred in relaxed situations ("cozy" lighting) and close to bedtime (to avoid disturbing the circadian rhythm), a cold light (biased towards the blue part of the spectrum) is better for work and reading (better contrast), or for waking up in the morning.

For each application it becomes necessary to consider which efficiency function and corresponding test method to use, and possibly, how to design efficacy and other requirements as part of a regulation. But since most regulations existing today are based on the *photopic* luminous efficiency function, there will be an inherent bias towards warmer light sources. As a result, not only do the regulations risk to be unfair to lighting solutions aimed for applications where the short-wavelength components of the spectrum is important, they will also risk to steer away the most energy efficient light sources or solutions. Because of these reasons, it is important that regulatory bodies engage in the current activities to solve this problem.

Whereas the CIE is currently working on a possible way out of the problem by adding more established luminous efficiency functions, which by all means could work well, this paper discusses another solution where the definition of light is redefined at the fundamental level. To give the regulatory perspective, examples based on the EU regulations on lighting applied on various light sources are used to illustrate how this could work in practice. In reality, however, more work and more in depth discussions are needed among all stakeholders to see how far such an approach can take us towards both better and yet energy efficient lighting solutions.

A new definition of light: the universal lumen

As presented in [REA 2014a, REA 2014b], another way out of the current situation is to define a *universal* luminous efficiency function, U(λ), fig 3, to be used as the *sole* spectral weighting function for measuring light as a fundamental quantity in the SI system. Importantly, it has been stressed that it should *not* be used in lighting applications and should be reserved for use only in the definition of light. Figure 3 compares V(λ) with U(λ) and illustrates the spectral sensitivity of *all* known photoreceptors in the human retina, the basic building blocks of any spectral weighting function. As can be seen in Figure 3, U(λ) spans the entire range of photoreceptor spectral sensitivities in the human retina whereas V(λ) only represents to spectral sensitivity of the L and M cones in the fovea. As such, U(λ) is a much better representation of the "human eye's sensitivity to optical radiation" than V(λ). If U(λ) was the only spectral weighting function used for measuring light, the SI system would not be compromised *and* the fundamental quantity (luminous intensity) would better characterize human sensitivity to optical radiation on the retina, as was originally intended.

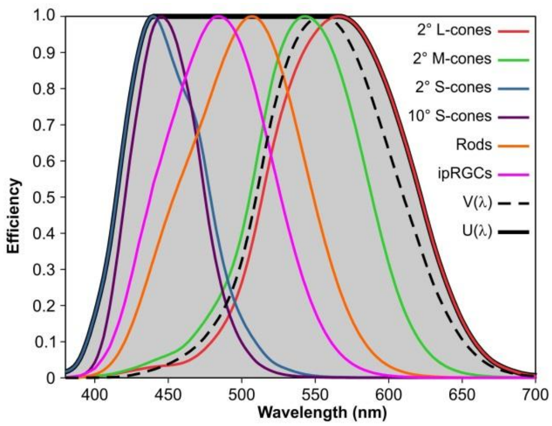

Figure 3: *The photopic luminous efficiency function (V(λ), the proposed universal luminous efficiency function (U(λ)) and the spectral sensitivity of the known photoreceptors in the human retina. The 2° functions represent the spectral sensitivities of the three photoreceptors in central vision (L-, M- and S-cones). The spectral sensitivity of rods is the same as the scotopic luminous efficiency function V'(λ). The spectral sensitivity of intrinsically photosensitive retinal ganglion cells (ipRGCs) which support phototransduction for the circadian system is also shown.*

Figure 4 shows the universal luminous efficacy function together with the photopic and scotopic luminous efficacy functions. All three functions obey the requirements of the CIPM and CIE MRA since all three functions are scaled to produce 683 lumens at 555 nm.

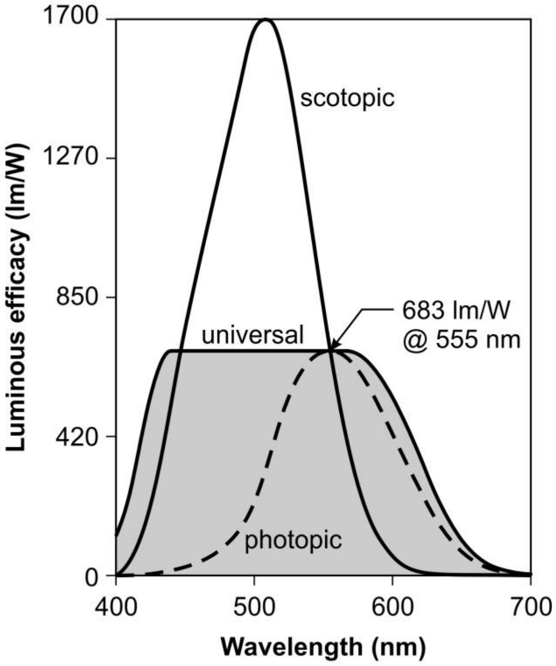

Figure 4: *The photopic, scotopic and universal luminous efficacy functions.*

To illustrate what this means in practice, table 1 compares several commercial light sources in terms of their correlated colour temperature (CCT), photopic and universal luminous efficacies (lumens/watt). For completeness, the colour rendering index (CRI) is also shown.

Table 1: *Luminous efficacies of light sources (both lamps and drivers) defined in terms of the MRA between CIPM and CIE. Tabulated are the correlated colour temperature (CCT), the colour rendering index (CRI) and the photopic and universal luminous efficacies for a CFL (as reference) and a family of commercially available LED light sources. The last column shows the relative gain when using the universal luminous efficacy function rather than the photopic luminous efficacy function. It should be noted that the values are calculated based on the spectral distributions from actual light sources and that other values may occur for other sources of the same type.*

Manufacturer	Product Series	CCT (K)	CRI	Photopic efficacy (lm/W)	Universal efficacy (lm/W)	Relative gain (U/P)
CFL, 15 W	-	-	83	61	85	1.39
Philips Lumileds	LXM8PW27	2660	85	61.0	84.8	1.39
Philips Lumileds	LXM8PW30	2990	82	64.8	92.2	1.42
Philips Lumileds	LXM3PW61	3520	83	61.0	94.3	1.55
Philips Lumileds	LXM3PW51	4010	86	64.8	103.7	1.60

Philips Lumileds	LXMLPW51	3850	66	80.0	122.2	1.53
Philips Lumileds	LXMLPW21	5800	71	80.0	138.7	1.73
Cree	XP-G Warm white	3070	83	84.3	123.2	1.46
Cree	XP-G Neutral white	4640	77	89.9	150.2	1.67
Cree	XP-G Cool white	6530	72	102.5	150.2	1.47
Osram Opto	Duris E5	4010	84	88.9	143.8	1.62
Samsung	362A 2700 K	3030	87	84.6	127.6	1.51
Samsung	362A 3000 K	3040	87	87.2	131.8	1.51
Samsung	362A 3500 K	3530	85	91.3	140.5	1.54
Samsung	362A 4000 K	3960	83	94.0	147.8	1.57
Samsung	362A 5000 K	5120	85	95.3	166.3	1.75
Samsung	362A 6500 K	6910	85	94.0	178.7	1.90
Seoul Semiconductor	STW8C2SA 2600 - 3700 K	3520	76	83.9	120.5	1.44
Seoul Semiconductor	STW8C2SA 3700 - 4700 K	4420	79	92.2	147.5	1.60
Seoul Semiconductor	STW8C2SA 4700 - 7000 K	5270	83	92.2	161.9	1.76

Focussing on the difference between the efficacies based on the photopic and the universal lumen, respectively, two observations are important to make:

- The absolute efficacy increases for the universal lumens as compared to the photopic lumens but the *relative* gain (U/P) *varies* for the different light sources; in general light sources with high correlated colour temperature (CCT) (which emits more shorter wavelengths) will gain the most.
- With universal lumens as a basis, the possible *additional* savings will be significant (up to ca 35 % as demonstrated in the next section) for applications where short wave lengths are of particular benefit.

These observations have implications for possible changes of the regulations, as will be discussed in the next section.

The regulatory perspective: better and more efficient lighting

As partly mentioned in the Introduction, main drivers of the current regulatory efforts for energy efficiency of end-use equipment around the globe are possible savings of energy and cost, thereby increasing the security of supply as well as reducing the environmental impact, not least on the climate. The gap between potential energy savings and what is realised with current programs has been highlighted more and more in recent years (see e.g. [WEO-SR 2013]), which motivates increased efforts towards more efficient and stringent regulations.

Within the framework of ecodesign requirements on energy related products in EU [ECODESIGN], at present there are three ecodesign regulations setting requirements on efficacy as well as functionality [EC 244/2009, EC 245/2009, EC 1194/2012]. In addition, energy labelling [EC 874/2012] is used as a complement to inform the buyers (both private consumers and professional procurers) on the energy efficiency of the light sources (or lamps). The combination of minimum energy performance requirements and energy labelling creates a push-pull effect that stimulates innovation, development and deployment of efficient lighting. However, as part of the regulatory process, the regulations are about to be revised, and a probable way ahead is to merge the three regulations into one regulation only. Thus, it is a good opportunity to take a wider grip on everything from updated requirements (adjusted to the current status and projected technical development) to revised standards. And if carefully done, revised standards and regulations can also pave the way for better lighting as well.

To illustrate this, two examples will be given below, the first regarding the regulation on non-directional lighting [EC 244/2009] and the second regarding possible additional savings for a given application.

Example 1: Revised requirements for non-directional lighting (244/2009)

The efficacy requirements in 244/2009 [EC 244/2009] is expressed as a function between maximum power P_{max} and luminous flux Φ: for so called frosted lamps, table 1 in 244/2009 states that

$$P_{max} = 0.24\sqrt{\Phi} + 0.013\ \Phi \qquad [1]$$

Conversely, the minimum efficacy η_{min} can be calculated as

$$\eta_{min} = \Phi / P_{max} \qquad [2]$$

See figure 5, where the efficacy is plotted as a function of luminous flux, according to eq [2]. The blue curve represents the minimum efficacy based on the photopic lumen, whereas the red curve equals the minimum efficacy times 1.65, representing a *possible* adjustment of the requirements if universal lumen were to be used instead.

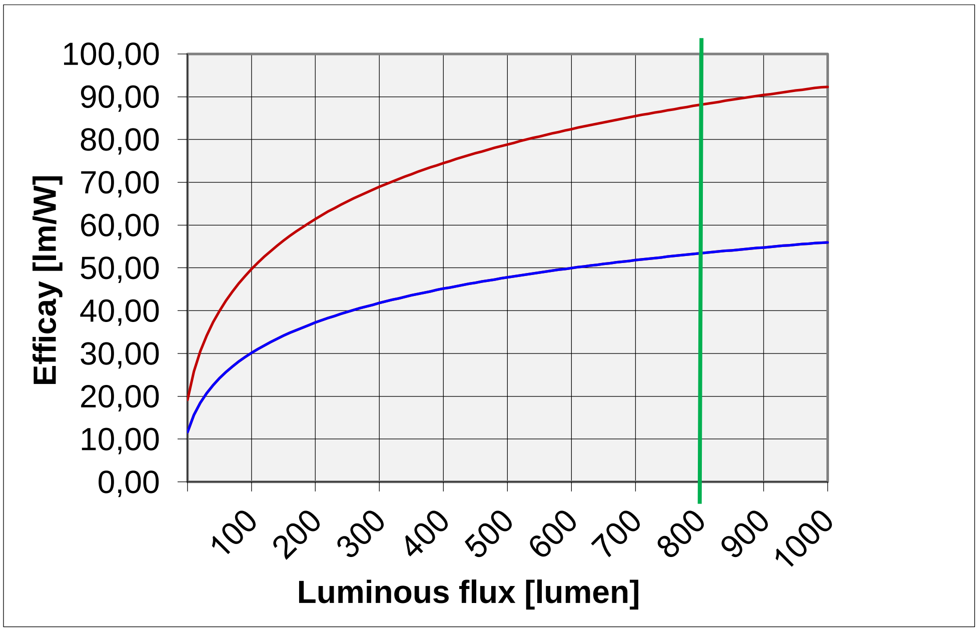

Figure 5. *Blue curve: Minimum efficacy calculated for the current requirements in table 1 in 244/2009 for frosted lamps (class A). Red curve: Minimum efficacy assuming a 65 % increase, adapted to requirements set*

using universal lumen instead. Green vertical line: A frosted lamp of 15 W must have a luminous flux of at least 800 lumens. See text for explanations.

Using the 15 W CFL light source in table 1 as a *reference*, equation [1] gives (indirectly) that the minimum photopic luminous flux must exceed 800 lumens. Equation [2] then gives that this corresponds to a minimum photopic efficacy of 53 lm/W, and since the calculated efficacy of the CFL in table 1 is 61 lm/W, the CFL will comply.

Next, assume the CFL should be replaced with a LED light source. The 15 W CFL has an efficacy of 61 lm/W which gives that the actual luminous flux is 915 lumens[3]. Eq [1] and [2] then gives that the minimum efficacy must be 55 lm/W. Comparing the CFL with a warm (2700 K) and cool (6500 K) LED light source from table 1 gives the result in table 2:

Table 2: *Examples of light sources suitable for non-directional lighting.*

Light source	CRI	Photopic lm/W	Universal lm/W	Relative gain
CFL, 15 W	83	61	85	1.39
Samsung 362A 2700 K	87	84.6	127.6	1.51
Samsung 362A 6500 K	85	94.0	178.7	1.90

With the current regulations, based on the photopic lumen, it is clear that all lamps are compliant[4] since they all have an efficacy larger than 55 lm/W. It is also clear that switching to LED leads to a reduction of the electric power down to 9.7 W (cool LED) – 10.8 W (warm LED) for the same luminous flux of 915 lumens.

Obviously there is room for a higher minimum efficacy since all three light sources are above 60 lm/W, thereby steering towards higher energy efficiency.

However, this effect could be *augmented further* by turning to requirements based on *universal* lumens: since the relative gain *differs* between the light sources, it becomes evident that the LED sources in table 2 would be preferred over the CFL. This is particular evident for the cool white LED where the relative gain is much higher (1.90) than for the other two light sources (CFL: 1.39; and warm white LED: 1.51).

In the example in figure 5, the red curve was based on a 65 % increase of the minimum requirements, leading to a minimum efficacy of 88 lm/W (the minimum efficacy @ 800 lumens; using this new requirement, the CFL would no longer comply whereas the LED sources would still comply. Depending on an analysis of the available light sources on the market or close to entry to the market, a regulator can set the requirements accordingly. In the EU it is common to use a multitier approach, where higher requirements are set according to a time table, giving time for producers, retailers and consumers to adopt.

The actual choice of new efficacy requirements, however, must be combined with other requirements such as CRI and type of application, but one important aspect should be clear: applications in which the short-wavelength portion of the spectrum is important, will benefit from using a spectral efficiency function that better represents how the visual system works, as demonstrated in Example 2 below.

Example 2: Possible additional savings for a given application

Figure 6 shows the photopic and universal efficacies (lumens/watt) plotted against CCT (K). As is evident both the photopic and the universal efficacies increase with an increase in CCT. Assuming a given application, *where the CCT is of importance*, there will be a difference in the energy needed to provide the desired luminous flux: the higher the CCT, like in an office lighting application, the less energy needed in general. However, since the

[3] Actually, since the lumen maintenance is different between different technologies (CFL, LED and halogens), table 6 in regulation 244/2009 set up rules for equivalency claims. Thus, there is a difference between equivalent luminous flux for CFL and LED, respectively, but since the corresponding difference in efficacy is rather low it is ignored here.

[4] In addition, they have a CRI > 80, another requirement in the regulation.

photopic lumen is biased towards longer wavelengths, light sources with a relative larger amount of short wavelengths will be penalised. On the other hand, since the universal lumen include the whole range of useful light, it will be more inclusive and not penalise any light source in particular.

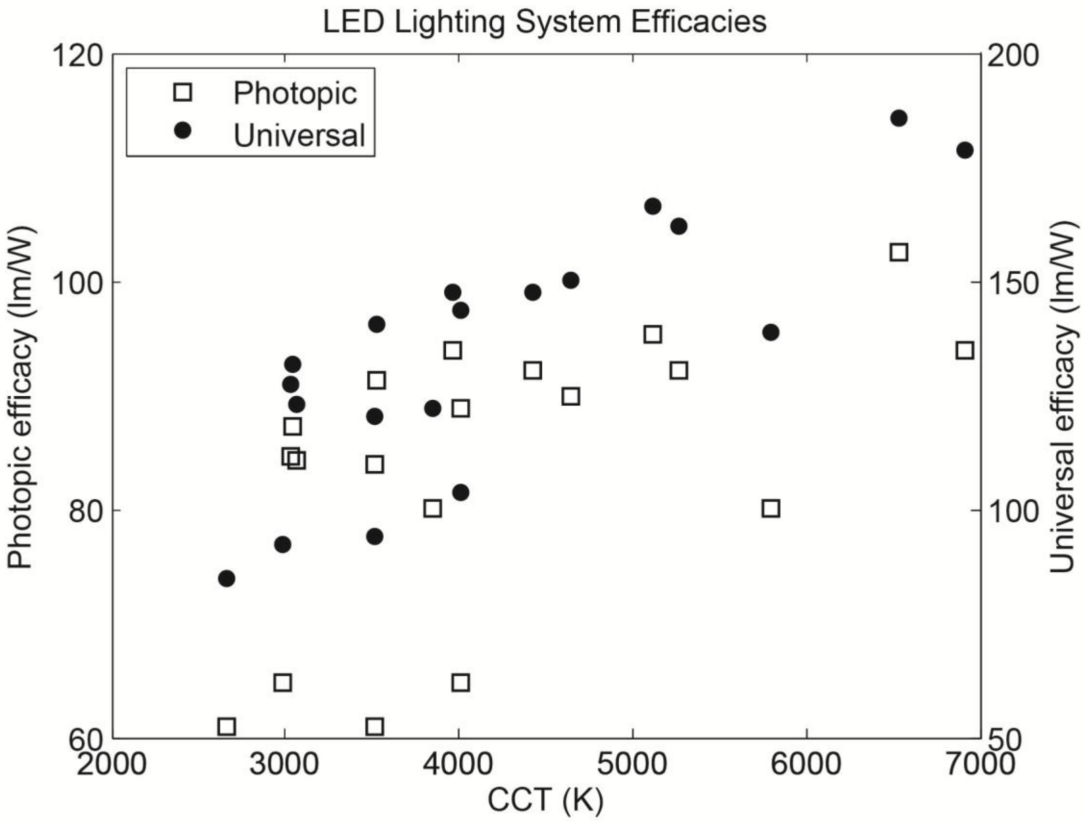

Figure 6: *The photopic (left y-axis) and universal (right y-axis) lumen as a function of the correlated colour temperature (CCT) for some of the light sources in table 1.*

Figures 7 and 8 aims reinforce the benefits of using the universal lumen. In figure 7, the relative photopic and universal efficacies are plotted against CCT. To calculate the relative values, the efficacies of the light sources plotted in figure 6 were normalized to those at a CCT of 2700 K, because most warm light sources have this CCT value. In Figure 8 the ratio of the relative efficacies ratios (universal/photopic) of the light sources plotted in figure 7 are plotted as a function of CCT, yielding the *relative efficacy ratio.*

As is clearly seen, the relative efficacy ratio increases with increasing CCT. In other words, at a given CCT, the additional savings relative to the 2700 K CCT light source if using the universal lumen ca *be as large as around 35 %.*

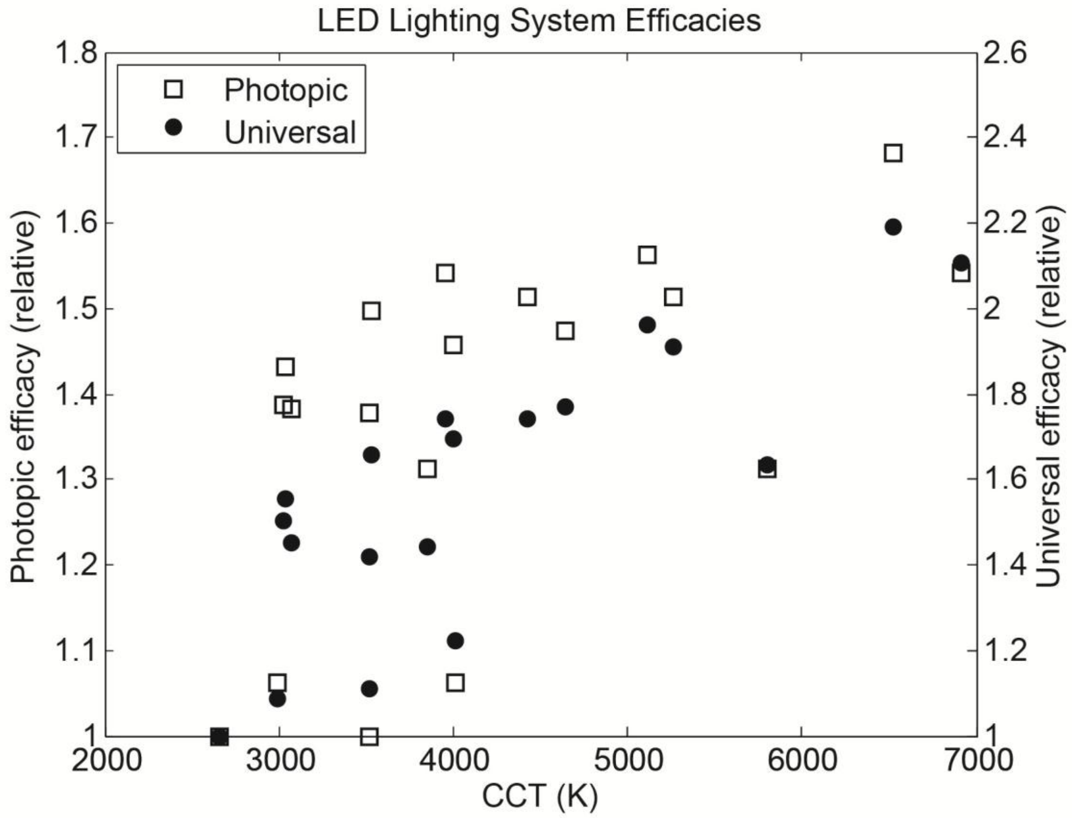

Figure 7: *The values for the photopic and universal lumen, respectively, in figure 6 are now normalised to the lumen value @ 2700 K. This gives the relative photopic efficacy (left y-axis) and relative universal efficacy (right y-axis).*

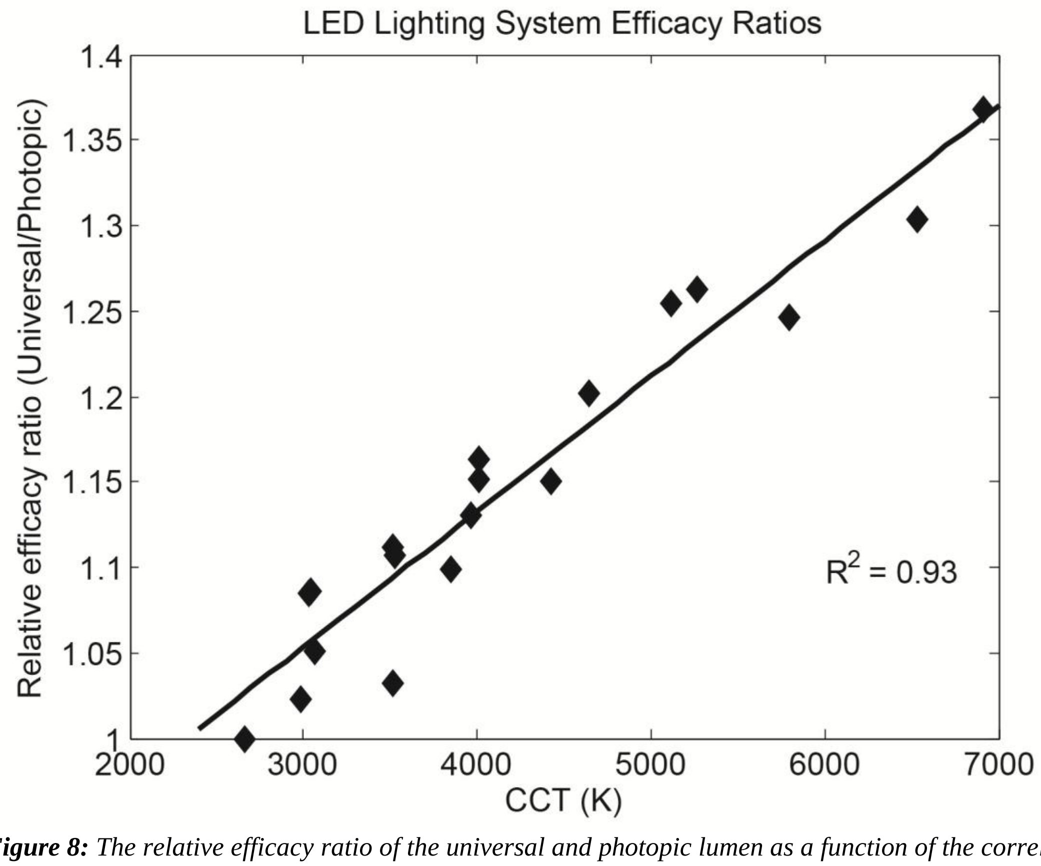

Figure 8: *The relative efficacy ratio of the universal and photopic lumen as a function of the correlated colour temperature (CCT) for some of the light sources in table 1.*

Conclusions

In times of increasing efforts to close the gap between the theoretical saving potentials of end-use appliances and equipment and the actual realised savings by current regulatory programs on energy efficiency, the relationship between the standardisation and the regulatory space has become increasingly important. Without sound metrics and test methods, it is impossible to design efficient and stringent regulations, let alone to enforce them.

Lighting, a pillar of modern society and at the same time being one of the major end-uses in terms of electricity use, has been a main part of many regulatory programs across the world for the past decade. Starting in EU in 2009, the time has come to revise the current regulations in order to adapt to the latest technological development as well as knowledge of the relation between light and health. However, with increased use of LEDs in various indoor and outdoor applications, many *standards* (e.g., colour, lifetime) need to be revised or developed in order to meet the need from the regulators.

The most important change needed relates to the fundamental *definition of light itself*: accumulative and new insights of the neural response to optical radiation on the retina has not been encompassed in the current definition of light (stemming back to 1924), leading to problems with everything from metrics, test methods and, ultimately, proper and adequate regulations. Although current efforts are being made by creating multiple definitions of light related to different applications, this paper instead explores the possibility to use a recent proposal presented in [REA 2014a], where a revised but still *one sole* definition of light is used; the universal lumen. The advantage is both a more stringent and scientifically satisfying definition of light itself, as well as providing a clearer path for regulators wanting to revise the current regulations to meet the need for both better and more efficient lighting.

It remains to be seen if this can be achieved or not, but hopefully this study will spur further efforts by both standardisation bodies and regulators in the near future.

Acknowledgements

PB would like to thank his colleagues at the lighting laboratory at the Swedish energy agency, Dr Christofer Silfvenius and Dr Jonas Pettersson, for fruitful discussions on the relation between metrics and regulations. Andrew Bierman at the Lighting Research Center is acknowledged for performing the calculations shown in the manuscript.

Glossary

Candela – The standard international unit of luminous intensity, equal to one lumen per steradian. The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

CCT (The correlated colour temperature) - CCT is a specification of the colour appearance of the light emitted by a lamp, relating its colour to the colour of light from a reference source when heated to a particular temperature, measured in degrees Kelvin (K). The CCT rating for a lamp is a general "warmth" or "coolness" measure of its appearance. However, opposite to the temperature scale, lamps with a CCT rating below 3200 K are usually considered "warm" sources, while those with a CCT above 4000 K are usually considered "cool" in appearance.

CFL (compact fluorescent lamp) - A family of single-ended fluorescent-discharge light sources with small-diameter [16-millimeter (5/8-inch) or less] tubes.

CIE (Commission Internationale de l'éclairage) - The International Commission on Illumination - is devoted to worldwide cooperation and the exchange of information on all matters relating to the science and art of light and lighting, colour and vision, photobiology and image technology.

Circadian rhythm - The natural pattern of physiological and behavioral processes that are timed to a near 24-hour period. These processes include sleep-wake cycles, body temperature, blood pressure, and the release of hormones. This activity is controlled by the biological clock, which is located in the suprachiasmatic nuclei of the hypothalamus in human brains.

Cones (cone photoreceptors) – retinal receptors that dominate the retinal response when the luminous level is high and provide the basis for the perception of color.

CRI (colour rendering index) - Measure of the degree of colour shift objects undergo when illuminated by the light source as compared with the colour of those same objects when illuminated by a reference source, of comparable colour temperature.

Ecodesign directive – The ecodesign method takes into account all the environmental impacts of a product right from the earliest stage of design.

Efficacy (of a light source) - The quotient of the total luminous flux emitted by the total lamp power input. It is expressed in lumens per watt (lm/W).

Fovea – A small region at the center of the retina, subtending about two degrees, that contains cones but no rods and that forms the site of most distinct vision.

LED (light emitting diode) – A p-n junction solid-state diode whose radiant output is a function of its physical construction, material used, and exciting current.

Light – radiant energy that is capable of exciting the retina and producing a visual sensation.

Lighting – The application of light to meet a specific design intent or objective.

Lumen – The standard International unit of luminous flux. Photometrically, it is the luminous flux emitted within a unit solid angle (one steradian) by a point source having a uniform luminous intensity of one candela.

Luminous efficiency function - Ratio of the radiant flux at wavelength λ_m to that at wavelength λ such that both radiations produce equally intense luminous sensations under specified photometric conditions and λ_m is chosen so that the maximum value of this ratio is equal to one.

Luminous flux – Radiant flux (radiant power); the time flow of radiant energy, evaluated in terms of a standardized visual response (spectral luminous efficiency function).

Mesopic vision – Vision with fully adapted eyes at luminance conditions between those of photopic and scotopic vision. (IESNA) In the mesopic region the spectral sensitivity of the human visual system is not constant, but changes with light level.

Photopic vision – Vision mediated essentially or exclusively by the cones. It is generally associated with adaptation to a luminance of at least 3.4 candelas per square meter.

Retina – A membrane lining the posterior part of the inside of the eye. It comprises photoreceptors that are sensitive to light and nerve cells that transmit to the optic nerve the responses of the receptor elements.

Intrinsically photosensitive Retinal Ganglion Cells - Also called photosensitive Retinal Ganglion Cells, or melanopsin-containing retinal ganglion cells, are a type of neuron in the retina of the mammalian eye.

Rods (rod photoreceptors) – Retinal receptors that respond at low levels of luminance even below the threshold for cones.

Scotopic vision – Vision mediated essentially or exclusively by rods. It is generally associated with adaptation to a luminance below about 0.034 candelas per square meter.

TWh (terawatt hour) - a unit of electrical energy equal to that done by one terawatt (10^{12} watts) acting for one hour.

References

Berson 2002: Phototransduction by retinal ganglion cells that set the circadian clock. Berson D, Dunn F and Takao M. Science 295, 1070–1073 (2002).

Bullough 2011: Testing a provisional model of scene brightness with and without objects of different colours Bullough J, Radetsky, L and Rea, M. Lighting Res. Technol. 2011; 43: 173–184

CIE 1951: See http://en.wikipedia.org/wiki/Luminosity_function

Dacey 2003: Functional architecture of the photoreceptive ganglion cell in primate retina: intrinsic photosensitivity, S-cone spectral opponency and irradiance coding. Dacey DM, Gamlin PD, Smith VC, Pokorny J, Packer OS, Liao H-W et al.Association for Research in Vision Meeting 2003; Abstract 3231.

ECODESIGN: See http://ec.europa.eu/enterprise/policies/sustainable-business/ecodesign/index_en.htm for more information

EC 244/2009: COMMISSION REGULATION (EC) No 244/2009 of 18 March 2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for non-directional household lamps: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:076:0003:0016:en:PDF

EC 245/2009: COMMISSION REGULATION (EC) No 245/2009 of 18 March 2009

implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for fluorescent lamps without integrated ballast, for high intensity discharge lamps, and for ballasts and luminaires able to operate such lamps, and repealing Directive 2000/55/EC of the European Parliament and of the Council. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:076:0017:0044:EN:PDF

EC 1194/2012: COMMISSION REGULATION (EU) No 1194/2012 of 12 December 2012 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for directional lamps, light emitting diode lamps and related equipment. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:342:0001:0022:EN:PDF

EC 874/2012: COMMISSION DELEGATED REGULATION (EU) No 874/2012 of 12 July 2012 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to energy labelling of electrical lamps and luminaires. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:258:0001:0020:EN:PDF

Rea 2010: Toward a model of outdoor lighting scene brightness. Rea, M, Radetsky, LC and Bullough, JD. Lighting Res. Technol. 2010; 1–24

Rea 2014a: Luminous Intensity: Trouble with the Curve. Rea, Mark. Proceedings LS14, Como, Italy, June 2014.

Rea 2014b: The lumen seen in a new light: Making distinctions between light, lighting and neuroscience. Rea, Mark. Lighting Res. Technol. 2014; 0: 1–22

Tsao 2010: The World's Appetite for Light: Empirical Data and Trends Spanning Three Centuries and Six Continents. Tsao, J and Waide, P. Leukos Vol 6 No 4, April 2010, p 259-281

UNEP: The UNEP en.lighten program; see http://www.enlighten-initiative.org/

Waide 2007: Lights labours lost, EIA report 2006. Waide, P and Tanishima, S

WEO-SR 2013: IEA World Energy Outlook Special Report, 10 June 2013