Article

The Energy and Exergy of Light

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Abstract: **** Add abstract. ****

Keywords: keyword 1; keyword 2; keyword 3

Suggested 6750 words.

Install the wordcount package from https://github.com/benmarwick/wordcountaddin to count words.

Terminology for this paper:

1. Light is the visible portion of the electromagnetic spectrum.
2. "spectrum" means a range of wavelengths.
3. "spectra" are several ranges of wavelengths.
4. Lamps are devices that convert electricity into light.
5. To avoid ambiguity, we should not use "lights" to mean "lamps."
6. Always be specific about energy and exergy. Any time you use the words energy or exergy, be sure you mean it. If you mean either, say "energy or exergy."
7. Never use the word "useful" unless you mean the useful stage of the energy conversion chain.
8. Let's be very clear about power and energy. Use overdots ($\dot{X}$) to indicate powers (rates).
9. Review the nomenclature tables at the end of the paper. If you use a new variable name, be sure you can't use a letter that already exists in the nomenclature tables. If you must use a new variable letter, add it to the table the first time you use it.
10. Only single letters for main variable names. Use subscripts to provide additional meaning. Use decorations to indicate rates.
11. The exergy-to-energy ratio (ϕ) is *not* second law efficiency (η_X) The energy-to-exergy ratio (ϕ) applies at every statepoint. η_E and η_X apply across energy conversion devices.

Style for this paper:

1. Do not use "this," "that", or "it" as the subject of a sentence. (MKH pet peeve!) Sentences that have those words as subjects are almost never clear to the reader yet almost always clear to the writer. Why? The antecedent is almost always ambiguous.
2. Spell out "Figure X," "Equation Y," and "Figure Z." Capitalize all.
3. Use SI units for everything.
4. Every number that deserves a unit must have a unit. Do not write "683" without units, for example.
5. Use the Oxford comma: "This, that, and the other;" not "This, that and the other."
6. Write comments to other authors in the text with "**** comment — MKH ****".

LaTeX hints:

1. Use short lines with return characters after every clause.
2. Comment lines after the equation environment to continue a sentence or paragraph.
3. Check comments in `LightingPaper2020.bib` file for hints about bibliography generation.
4. Use "~" character for non-breaking space. "~" is especially useful between numbers and their units. E.g., 683~lm/W.
5. Quotation marks: Opening quotes with two back-tics: ". Closing quotes with two apostrophes: ". Do not use the quotation mark key on the keyboard.

1. Introduction (PB, 500 words)

1.1. Broad context and the problem

Artificial light provides an invaluable energy service, allowing activities to be undertaken when it is too dark for natural light. Around 20 % of global grid-connected electricity consumption is taken by lighting [1]. With the modern breakthrough technology of light emitting diode (LED) lamps, which now make up 40% of residential lamp sales [2], applications have spread beyond illumination to many other fields including human physiology and photosynthesis for horticulture [3]. The use and analysis of lighting energy efficiency is applied to a range of fields, including energy economics (***REF***), societal exergy analysis [4], energy history [5], and forecasting energy efficiency improvements [2]. However, a key problem for the energy analyst arises: there are differing concepts and definitions of what lighting efficiency is, which matters on two counts. First, is that with the rise of LED lamps, the proximity to the efficiency limits of lighting appears within reach – but what is the limit? Second, following on, given the expanding role that global artificial lighting plays now, understanding precisely its envisaged contribution—via increasing efficiency—to reducing energy use to meet carbon targets is very important. The aim of this paper is therefore to bring clarity to the analyst *** or practitioner?*** of the definitions of the energy and exergy conversion efficiency of artificial light for illumination. We exclude non-illumination purposes, such as horticulture and heating.

1.2. Lighting fundamentals

We require at this point two key aspects of lighting fundamentals (noting we will get into more detail later in ***Sections X and Y ***). First, is to understand what we mean by 'light'. Electromagnetic radiation is quantified in terms of energy, wavelength and frequency, related by Planck's equation:

$$E = h\nu = \frac{hc}{\lambda}\,, \tag{1}$$

where E is energy, h is Planks constant, ν is frequency, c is the speed of light, and λ is wavelength. Only radiation within the range of wavelengths 380 nm < λ < 750 nm is considered to be "light," i.e. part of the visible light spectrum [6]. Only within this spectrum are wavelengths to which the human retina respond - as shown in Figure 1 and as such are used by humans for illumination.

**** MKH make our own graph with the ggspectra package. ****

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## `summarise()` ungrouping output (override with `.groups` argument)
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Second, modern lighting is provided by energy conversion through three stages: primary energy (e.g., coal) which is then converted to final energy (i.e., electricity, measured in watts), and last to useful energy output (i.e., the provision of visible light energy, measured in lumens). The efficiency conversion from final-to-useful stage energy is the focus of this paper, though we note that human perception and satisfaction of human needs is accomplished as an energy service, which occurs at the post-useful stage.

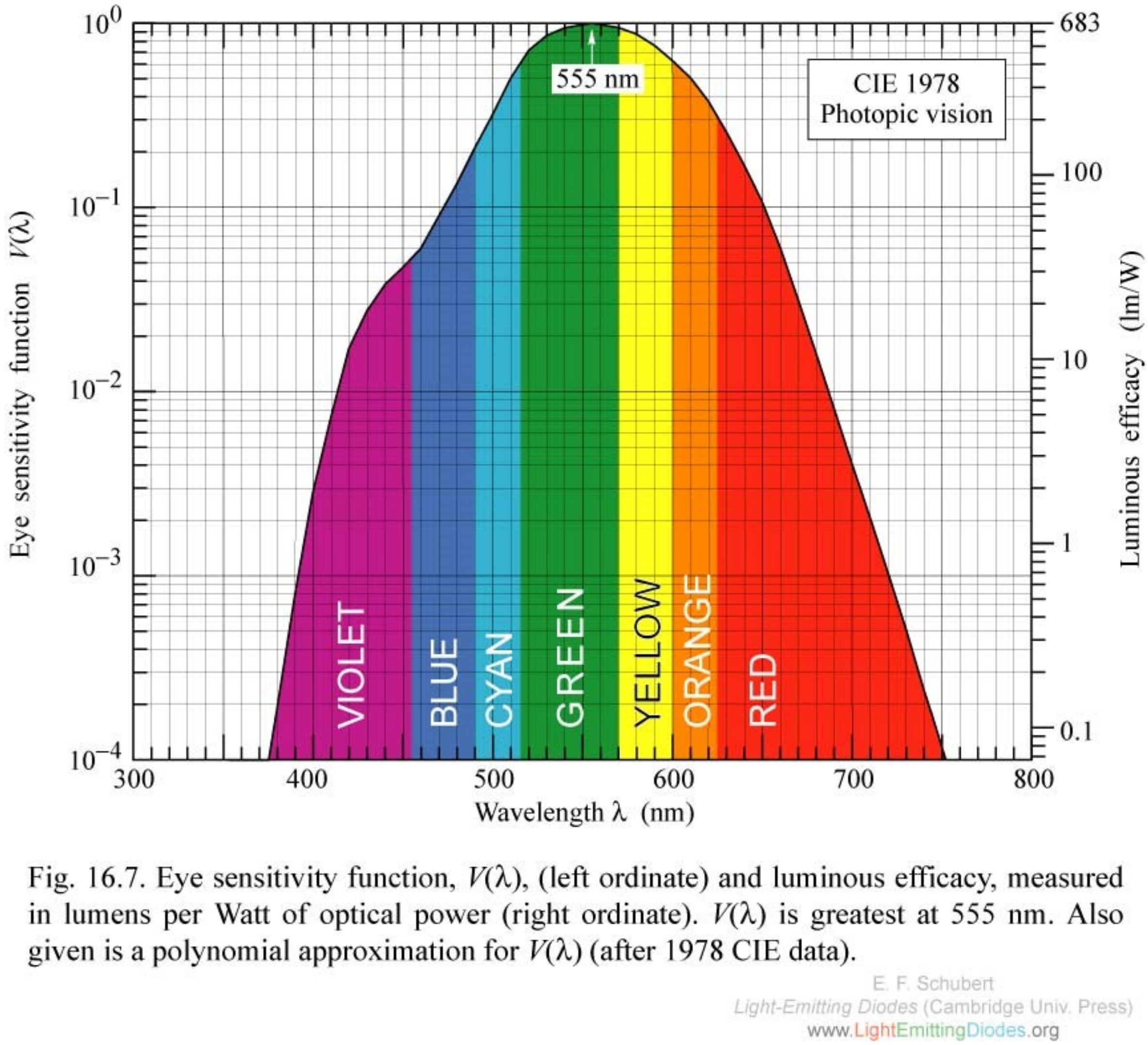

Figure 1. The visible spectrum of light [7]

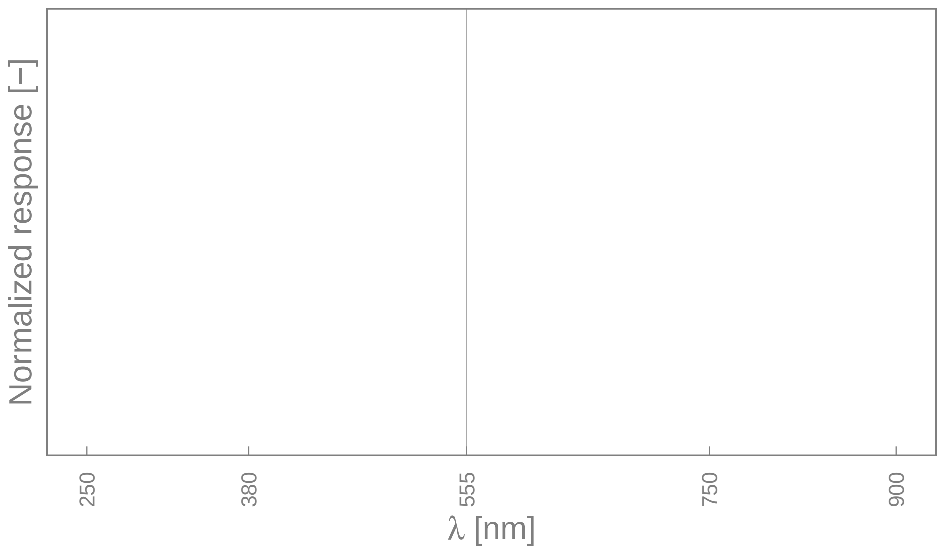

Figure 2. Alternative visible range figure that matches style of later figures.

1.3. Diverging approaches to lighting efficiency

From this point, however, we stumble into various key sources of confusion surrounding the conversion efficiency (η) of light. A conventional term is luminous efficacy (in lumens/watt, or lm/W), which is the luminous flux produced (light output, in lm) for a given electricity energy input (in W). The first source of confusion is that some practitioners equate luminous efficacy with luminous (or light) efficiency. For example, [8] provides estimates of historical lighting efficiencies from the earliest time of open wood fires (0.002 lm/W), through to candles (0.1 lm/W), tungsten filament lamps (10 lm/W) and compact fluorescent light bulbs (68 lm/W). Tsao and Waide [9, p. 265] are very clear, stating "[l]uminous efficacy represents the efficiency with which energy is used to produce visible light." Fundamentally this is not correct, as although luminous efficacy is a proxy commonly taken to represent energy efficiency, they are not equivalent. **** Can we be more specific? Luminous efficacy is a final-energy-to-service efficiency, not an energy efficiency. —MKH ****

Others (***REF***),), more correctly define efficiency of light provision on a thermodynamic basis, as follows:

$$\eta = \frac{\text{actual lamp efficacy [lm/W]}}{\text{theoretical maximum efficacy limit [lm/W]}} \,. \tag{2}$$

However, that takes us straight into two further sources of confusion. One—as set out by [10]—is the calculation of the numerator (actual lamp efficacy), both in terms of the luminous flux output (the total lamp lumens produced versus the directional output that emerges from the lamp) and electrical energy input (electrical energy input to the wall plug versus a reduction to include plug conversion and other losses?).

The other, and perhaps most controversial of all, is the denominator: *what is the theoretical maximum efficacy limit* (in lm/W)? Within the literature, three common values are adopted: 220 lm/W [11,12, Table 5.6.9], 400 lm/W [4,13–15], and finally 683 lm/W [16,17].

Even within technical lighting papers, there are divergences over the theoretical maximum efficacy limit of lamps, due to differing decisions of what "luminosity function" to adopt, as the eye is sensitive to different wavelengths within the visible range (380 nm $< \lambda <$ 750 nm). Such differences are still very recent [18–21]. Due to the introduction of LED lamps, which have much higher efficacies, the issue has urgency, as shown in Figure 3.

A final source of confusion is the differences between first law (energy) and second law (exergy) efficiencies. Few authors make the distinction, most indirectly adopt a second law efficiency as given earlier in Equation 2. Schaeffer and Wirtshafter [22] and Nakicenovic et al. [23] provide rare exceptions, by defining both final-to-useful energy efficiency of lamps (ranging from incandescent, 5 %, to fluorescent, 20%) and energy-to-exergy useful stage efficiency of 90–93%.

1.4. Paper structure

The article proceeds as follows. In Section 2, we set out the energy and exergy fundamentals of light. In Section 3, we show results for example weighting functions and lamps before presenting a discussion in Section 4. Section 5 concludes. Our key finding is that the maximum efficacy limit of lamps should be taken as 400 lm/W.

2. Methods (2250 words)

2.1. Exergy theory (MKH, 1000 words)

Energy and exergy are two methods to quantify the physical property that, when transferred to an object, heats it or performs work on it. (For this discussion, we can't call the "physical property" energy or exergy, because the concepts need to be separated. So, we must use the generic term "physical property.") We discuss energy and exergy quantifications of the physical property in the sections below, beginning with heat and work, the concepts for which energy and exergy originated. Thereafter,

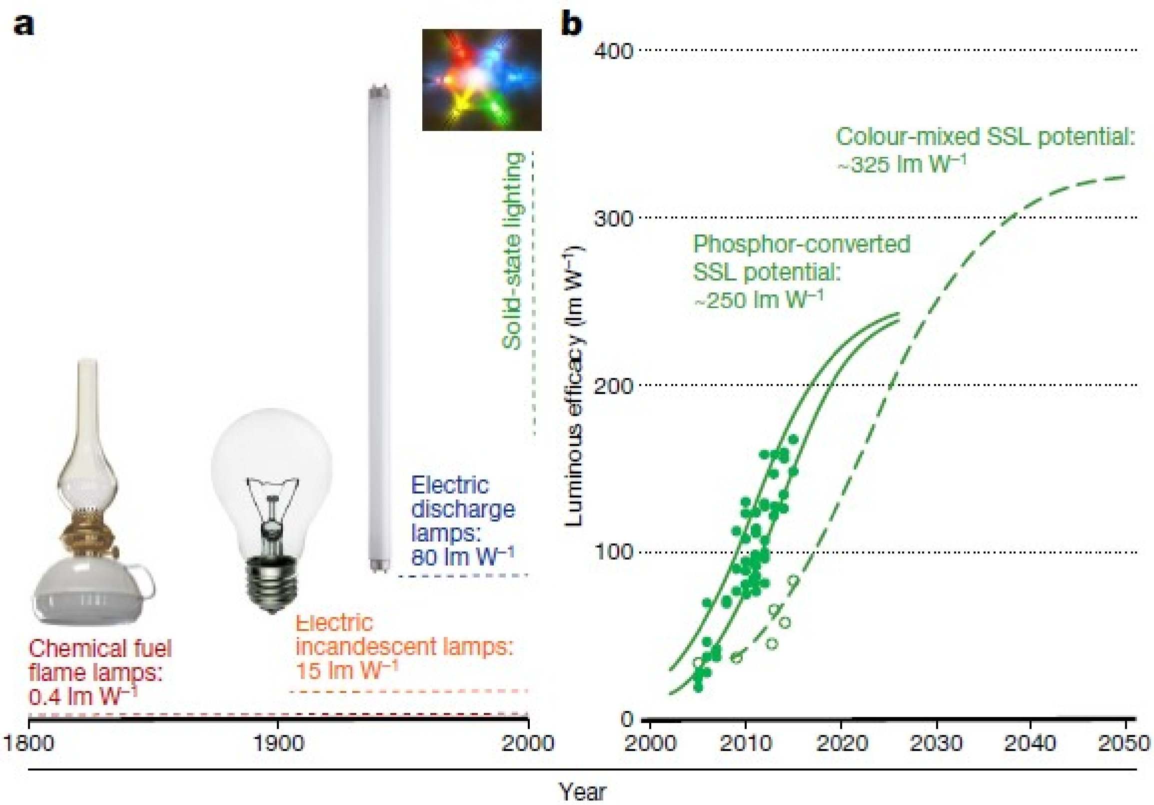

Figure 3. A history of lighting technology luminous efficacy (1800–2050): taken from [19].

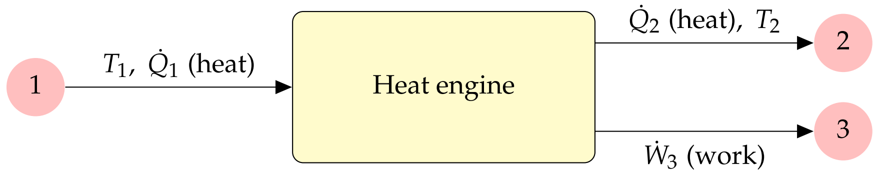

Figure 4. A heat engine that produces heat and work.

we develop a framework for the energy and exergy of light in a parallel manner to the energy and exergy of heat and work.

2.1.1. Energy and exergy ($\dot{E}$ and $\dot{X}$) of heat and work

Energy quantifies the physical property by its heat content. Thus, heat is pure energy. Thanks to Thompson's cannon experiment [24], we know that work can be converted, without loss, into heat.

Figure 4 shows a heat engine that converts heat at 1 to work at 3 with a waste heat byproduct at 2. All streams can be counted as energy, such that

$$\dot{E}_1 = \dot{Q}_1, \ \dot{E}_2 = \dot{Q}_2, \text{ and } \dot{E}_3 = \dot{W}_3 \,. \tag{3}$$

Energy efficiency is defined as $\eta_E \equiv \frac{\text{energy out}}{\text{energy in}}$. For the example of Figure 4,

$$\eta_E = \frac{\dot{E}_2 + \dot{E}_3}{\dot{E}_1} = \frac{\dot{Q}_2 + \dot{W}_3}{\dot{Q}_1} = 1 \,. \tag{4}$$

Energy efficiency (η_E) is 1, because the first law of thermodynamics states that energy is conserved ($\dot{Q}_1 = \dot{Q}_2 + \dot{W}_3$).

That said, typically only one of the products in Figure 4 is deemed valuable: the work produced by the heat engine ($\dot{W}_3$). Thus, the *valuable* energy efficiency ($\eta_{E,v}$) is

$$\eta_{E,v} = \frac{\dot{E}_3}{\dot{E}_1} = \frac{\dot{W}_3}{\dot{Q}_1} < 1 \,. \tag{5}$$

On the other hand, exergy quantifies the physical property by its work potential. Exergy provides the answer to the question, "what is the maximum work we could obtain from a stream of this physical property?" Thus, work is pure exergy.

The Kelvin-Planck statement of the second law of thermodynamics states that heat cannot be converted to work without loss. To find the maximum possible work that can be created from heat (and, therefore, the exergy of heat), we consider the Carnot heat engine which operates at the maximum possible valuable energy efficiency,

$$\eta_C = 1 - \frac{T_0}{T_{sys}} \,. \tag{6}$$

The exergy of each stream in Figure 4 is then

$$\dot{X}_1 = \phi_1 \dot{Q}_1 = \left(1 - \frac{T_0}{T_1}\right) \dot{Q}_1, \tag{7}$$

$$\dot{X}_2 = \phi_2 \dot{Q}_2 = \left(1 - \frac{T_0}{T_2}\right) \dot{Q}_2, \text{ and} \tag{8}$$

$$\dot{X}_3 = \cancelto{1}{\phi_3} \dot{W}_3 = \dot{W}_3 \,. \tag{9}$$

In this context, the Carnot efficiency (η_C) becomes the exergy-to-energy ratio for heat streams ($\phi_Q = \eta_C$). The exergy-to-energy ratio for work is $\phi_W = 1$, because work is pure exergy.

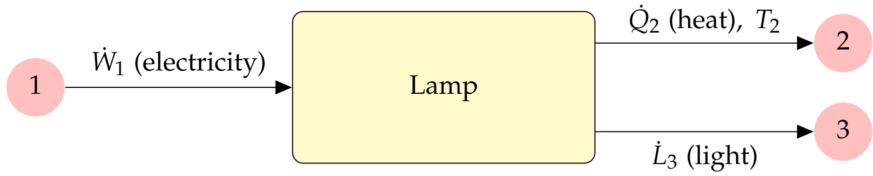

Figure 5. A lamp that produces heat and light.

Exergy efficiency is defined as $\eta_X \equiv \frac{\text{exergy out}}{\text{exergy in}}$. For the heat engine in Figure 4,

$$\eta_X = \frac{\dot{X}_2 + \dot{X}_3}{\dot{X}_1} = \frac{\dot{Q}_2\left(1 - \frac{T_0}{T_2}\right) + \dot{W}_3}{\dot{Q}_1\left(1 - \frac{T_0}{T_1}\right)} < 1\,. \tag{10}$$

Exergy efficiency (η_X) is less than 1, because the second law of thermodynamics states that exergy is always destroyed ($\dot{X}_1 > \dot{X}_2 + \dot{X}_3$).

Assuming, again, that work is valuable gives

$$\eta_{X,v} = \frac{\dot{W}_3}{\dot{Q}_1\left(1 - \frac{T_0}{T_1}\right)} < \eta_X\,. \tag{11}$$

Note that both $\eta_{E,v}$ and $\eta_{X,v}$ are independent of human presence. The work created ($\dot{W}_3$) could be a spinning driveshaft on an automobile carrying four passengers down the freeway or the same spinning driveshaft on dynamometer in an unoccupied laboratory. Both (a) the energy and exergy of the work and heat ($\dot{Q}_2$ and $\dot{W}_3$) and (b) the efficiencies of the heat engine ($\eta_{E,v}$ and $\eta_{X,v}$) would be the same, regardless.

In other words, both (a) the energy and exergy of work and heat and (b) the efficiencies of the heat engine are independent of human presence and the energy service provided by the heat engine.

We now turn to the production of light instead of work at 3.

2.1.2. Energy and exergy ($\dot{E}$ and $\dot{X}$) of light

Figure 5 replaces the heat engine with a lamp that produces light instead of work at 3. Waste heat is still produced at 2, and electricity powers the lamp at 1. Both electricity and light can be converted to heat without loss, so they are pure energy. Thus,

$$\dot{E}_1 = \dot{W}_1 = \dot{W}_1,\ \dot{E}_2 = \dot{Q}_2,\ \text{and}\ \dot{E}_3 = \dot{L}_3\,. \tag{12}$$

Energy efficiency for Figure 5 is

$$\eta_E = \frac{\dot{E}_2 + \dot{E}_3}{\dot{E}_1} = \frac{\dot{Q}_2 + \dot{L}_3}{\dot{W}_1} = 1\,, \tag{13}$$

and valuable energy efficiency for Figure 5 (assuming that light is the valuable output from the lamp) is

$$\eta_{E,v} = \frac{\dot{E}_3}{\dot{E}_1} = \frac{\dot{L}_3}{\dot{W}_1} < 1\,. \tag{14}$$

Because electricity can be converted to work without loss in a frictionless motor, electricity is considered pure exergy, i.e., $\phi_{elect} = 1$. Thus, the exergy of each stream in Figure 5 is given by

$$\dot{X}_1 = \cancelto{1}{\phi_{elect}}\dot{W}_1 = \dot{W}_1,\ \dot{X}_2 = \left(1 - \frac{T_0}{T_2}\right)\dot{Q}_2,\ \text{and}\ \dot{X}_3 = \phi_L \dot{L}_3\,, \tag{15}$$

where ϕ_L is the exergy-to-energy ratio for light.

Recent work by Delgado-Bonal [18] provides a method for calculating ϕ_L. (See Section 2.3 for details.) Delgado-Bonal's estimate is $\phi_L = 0.931$ for solar spectrum electromagnetic radiation [18, Figure 3]. A similar estimate comes from the maximum efficiency of converting blackbody electromagnetic radiation (at 5800 K, the temperature of the sun) to electricity (pure work and, therefore, pure exergy), rejecting waste heat to an ambient temperature of 300 K:

$$\phi_L \approx \eta_C = 1 - \frac{T_0}{T_{sun}} = 1 - \frac{300\text{ K}}{5800\text{ K}} = 0.948\ . \tag{16}$$

Other values for ϕ_L are needed when the spectra of emitted light is different from the spectra of blackbody radiation, as discussed in Section 2.3.

The exergy efficiency of lighting for Figure 5 is given by

$$\eta_X = \frac{\dot{X}_2 + \dot{X}_3}{\dot{X}_1} = \frac{\left(1 - \frac{T_0}{T_2}\right)\dot{Q}_2 + \phi_L \dot{L}_3}{\dot{W}_1} < 1\ . \tag{17}$$

The valuable exergetic efficiency of lighting for Figure 5 is given by

$$\eta_{X,v} = \frac{\dot{X}_3}{\dot{X}_1} = \frac{\phi_L \dot{L}_3}{\dot{W}_1} < \eta_X\ . \tag{18}$$

Note that both η_X and $\eta_{X,v}$ are independent of human presence; the efficiencies (η_X and $\eta_{X,v}$) would be the same whether the lamp is illuminating an unoccupied room or a crowded bar, whether the illumination stimulates the rods and cones of a human eye or excites band gap electrons in an amorphous silicon solar cell.

Strictly speaking, the energy and exergy efficiencies of a lamp are evaluated at the useful stage of the energy conversion chain (where light energy and exergy exist), prior to the *energy service* stage (where illumination exists). Both (a) the energy and exergy of light and (b) the energy and exergy efficiency of lamps are independent of the energy service provided by the lamp.

2.2. Theoretical challenges and analyst decisions with application to societal exergy analysis (MKH, 250 words)

There are two challenges facing the societal exergy analyst regarding the exergy of light, including (a) how to account for waste heat from lamps and (b) how to account for the human perception of light. We discuss each challenge in the sections below.

**** Are there any other challenges we want to address in this paper? —MKH ****

2.2.1. Waste heat from lamps

**** Do we want to include this section? —MKH ****

**** Absolutely, I've added two sentences detailing the niche use of heat lamps for various purposes. —ZM ****

Every lamp produces waste heat ($\dot{Q}_2$ in Figure 5) as it converts electrical energy into light energy. In Section 2.1.2 waste heat was deemed the un-valuable product of the lamp. However, in some circumstances, the waste heat from lamps is, in fact, valuable, because it displaces energy for space heating, especially in winter climates. In summer climates, waste heat from lamps adds to space cooling loads. For locations where both summer cooling and winter heating are performed, the winter/summer effects of lamps cancel, to first order.

Furthermore, some lamps, commonly termed heat or infrared lamps are explicitly designed to produce heat, and are used for various purposes including: space heating, incubator heating, plastic manufacture, food preparation, and warming animals in captivity. As the infrared portion of light emitted by these lamps is considered useful they typically display high efficiencies.

**** Where is the line between an electric heater and an incandescent lamp? Is it just the design purpose? —ZM ****

The societal exergy analyst must decide how to treat waste heat from lamps when determining the quantity of useful energy delivered to a society. To our knowledge, societal exergy analysis has, to date, ignored waste heat from lamps, implicitly assuming that winter and summer effects cancel. We contend that the issue deserves further study, but that is a topic for another paper.

2.2.2. Human perception of light

We noted above that both (a) energy and exergy of light and (b) energy and exergy efficiency of lamps are independent of human presence. But what about human *perception*?

Human eyes perceive only a portion of the electromagnetic spectrum emitted by lamps (approximately 380 nm < λ < 750 nm). (Human skin can perceive the thermal radiation portion of the broader electromagnetic spectrum, approximately 100 nm < λ < 10,000 nm.) Furthermore, the wavelength sensitivity of the human eye is uneven, peaking at 555 nm (green), with reductions in sensitivity at both longer and shorter wavelengths.

Human perception of light exhibits nuances that are not present when considering human perception of work and heat, and the nuances are important for societal exergy analysis. Specifically, when considering work and heat, there is no analogue to the sensitivity of the human eye to wavelengths of light. Neither heat nor work present to human beings as differentiated by wavelength or other characteristics. (Strictly speaking, the absorption spectrum of human skin is differentially sensitive to wavelengths of thermal radiation, but this effect is usually small and neglected by societal exergy analysts, because convection is usually the dominant mode of heat transfer experienced by humans in heated spaces.) So there is no need to consider human perception when accounting for work and heat in societal exergy analysis.

In contrast, the analyst must decide how to account for human perception of light. Three options are apparent.

First, the analyst can account for the human perception of light in the useful-to-services efficiency. In this approach, the useful energy and exergy of light is unaffected by human perception, and the energy or exergy *service* provided by light is deemed to be the possibility that light excites rods and cones in the human eye. For the purposes of accounting at the *useful* stage of the energy conversion chain, all energy and exergy in electromagnetic radiation emitted by a lamp is counted, regardless of its wavelength. When choosing Option 1, $\dot{X}_3$ is unchanged from the analysis in Section 2.1.2, i.e., $\dot{X}_3 = \phi_L \dot{L}_3$.

The second and third options account for human perception of light at the useful stage. In the second option, light is deemed useful only if it *could* stimulate rods and cones, regardless of the sensitivity of the human eye to any given wavelength of light in the range 380 nm < λ < 750 nm. In this option, the analyst simply excludes the energy or exergy content of light in wavelengths outside the range of perception by the human eye when determining the useful energy or exergy of light. I.e., the analyst counts only light in the range 380 nm < λ < 750 nm as useful, assuming that the human eye perceives all wavelengths in that range equally. When choosing Option 2, the exergy of light becomes (with reference to Figure 5)

$$\dot{X}_3 = g \phi_L \dot{L}_3 \, , \tag{19}$$

where $g \in (0, 1)$ accounts for neglecting the energy beyond the visible portion of the electromagnetic spectrum.

**** Should we include Option 2? Options 2 and 3 could be combined easily. —MKH ****

**** Yes I definitely think we should include Option 2! —ZM ****

The third option adds wavelength sensitivity of the human eye to the second option, weighting the energy or exergy content of light by its ability to excite rods and cones at each wavelength. When choosing Option 3, the exergy of light becomes (with reference to Figure 5)

$$\dot{X}_3 = f \phi_L \dot{L}_3 , \tag{20}$$

where $f \in (0,1)$ accounts for the spectral sensitivity of the human eye.

**** My idea here is that Zeke can develop specific expressions (involving integrals) for f and g in sections that follow. —MKH ****

In summary, the analyst must make at least one and possibly two choices: (a) whether to account for the spectral sensitivity of the human eye at the services stage (Option 1) or the useful stage (Options 2 and 3) of the ECC and (b) if accounting for human perception at the useful stage, whether to weight by the spectral sensitivity of the human eye (no for Option 2, yes for Option 3) when determining the useful energy and exergy content of light.

Sections 2.3 and 3 provide more details about the implications of Options 1, 2, and 3.

**** Where to insert the issue of which model of human eye perception should be used? ****

**** I believe the best place for this would be at the end of section 4 in the discussion (see below) —ZM ****

2.3. The physics of light (Zeke and Emmanuel, 1000 words)

**** ZM: Discuss various integrations over wavelength and our conclusions that some features don't matter. Maybe discuss sources of data Include discussion of [18]. ****

To understand how the measurement of a lamps efficiency varies according to which wavelengths of light induce the strongest response in the human eyes light receptors, or more broadly the response of any mechanism to light, data for the spectral power distribution of a lamp is required.

Firstly, and representing Option 1, the calculation of $\dot{L}_3$, the light (or radiant power/flux) emitted by a lamp is given by

$$\dot{L}_3 = \int \dot{P}_\lambda d\lambda , \tag{21}$$

where $\dot{P}_\lambda$ is the spectral power distribution of a lamp, representing the radiant power (W) per unit wavelength (nm) of the lamp.

If Option 2 is adopted the upper and lower bounds of the integral are set by the upper and lower limits of the visible spectrum (380 nm < λ < 750 nm).

$$\dot{L}_{vis} = \int_{380\text{ nm}}^{750\text{ nm}} P_\lambda d\lambda . \tag{22}$$

If Option 3 is adopted the above equation becomes

$$Luminous\ flux = 683\ \text{lm/W} \int \dot{P}_\lambda V_\lambda d\lambda , \tag{23}$$

where V_λ is the photopic luminosity function, as defined by the Commission Internationale de l' Éclairage (CIE) most recently in 2006(?), and representing the sensitivity of the human eye to daytime light levels. The above equation is the SI derived unit for the quantity of visible light (luminous flux or power) - the Lumen. The constant of 683 is applied in accordance with the definition of the lumen and candela, which states that a monochromatic lamp emitting light at a wavelength of 555nm (the wavelength at which the human eye is deemed to be most sensitive) has a luminous efficacy of 683 lumens per watt.

The use of the photopic luminosity function been subject to much criticism for its long-wave bias, as it represents the sensitivity of the long-wave and medium-wave cones to daytime light levels, whilst neglecting the differing sensitivities of the human eyes other light receptors. Namely the short-wave cones, rods and intrinsically photosensitive retinal ganglion cells (ipRGCs), which are responsible for vision in low-light settings and physiological functions such as the regulation of circadian rhythms respectively.

Given that the industry-standard measure of lighting efficiency is the luminous efficacy (the quotient of the lumen output and power input of a lamp), the use of the photopic luminosity function to measure light output under-represents the power of wavelengths other than 555nm emitted by a lamp, and in the case where other uses of light are desired the utility of these wavelengths of light are also under-represented.

For the analyst interested in examining what proportion of a spectral power distribution is 'useful' for any given purpose an appropriate weighting function must be selected (including the photopic luminosity function). The useful light ($\dot{L}_{useful}$) emitted by a lamp is then given by

$$\dot{L}_{useful} = \int \dot{P}_\lambda W f_\lambda d\lambda \ , \tag{24}$$

where Wf_λ is equal to a given weighting function, with values between 0 and 1.

Depending on the option taken and the weighting function selected the valuable energy efficiency of a lamp to the useful stage is given by

$$\eta_{X,v} = \frac{\dot{L}_{useful}}{\dot{W}_1} = \frac{\int \dot{P}_\lambda W f_\lambda d\lambda}{\dot{W}_1} \ . \tag{25}$$

To demonstrate how the use of selection of various weighting functions alters the measurement of the efficiency of a lighting device we choose to compare the following lamps and weighting functions

**** Which lamps are we assessing? —ZM ****

In addition to examining the energy efficiency of these lamps, we also calculate the ratio of the useful light (as determined by a given weighting function), to both the radiant power and the electricity consumption of the device.

**** Insert additional metrics here —ZM ****

Zeke: Here is the way to include chunks of R code.

Things to consider:

1. `library(X)` statements go in the `setup-R` chunk, early in the document.
2. Name chunks with capital letters, no spaces, _ to separate words (by convention).
3. `ggplot` figures go in their own chunks, one graph per chunk.
4. Variables in previous chunks are available to `R` code in later chunks.
5. Use `::` syntax to identify `package::function` to eliminate ambiguity.
6. Data and calculations go in their own chunk.
7. Graphs go in a separate chunk.
8. R-generated graphs will be automatically stashed in the `figure/` directory. Don't put anything else in `figure/`, because `figure/` is excluded from GitHub.

3. Results (Zeke and Emmanuel, 2000 words)

**** ZM: Develop examples with two lighting technologies, one old and one LED. Do calculations with various permutations and show graphs. ****

4. Discussion (ZM, PB, 1000 words)

Authors should discuss the results and how they can be interpreted in perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

**** ZM: Discuss how our results for the examples vary from results that would have been obtained with previous methods of determining the exergy of lighting. ****

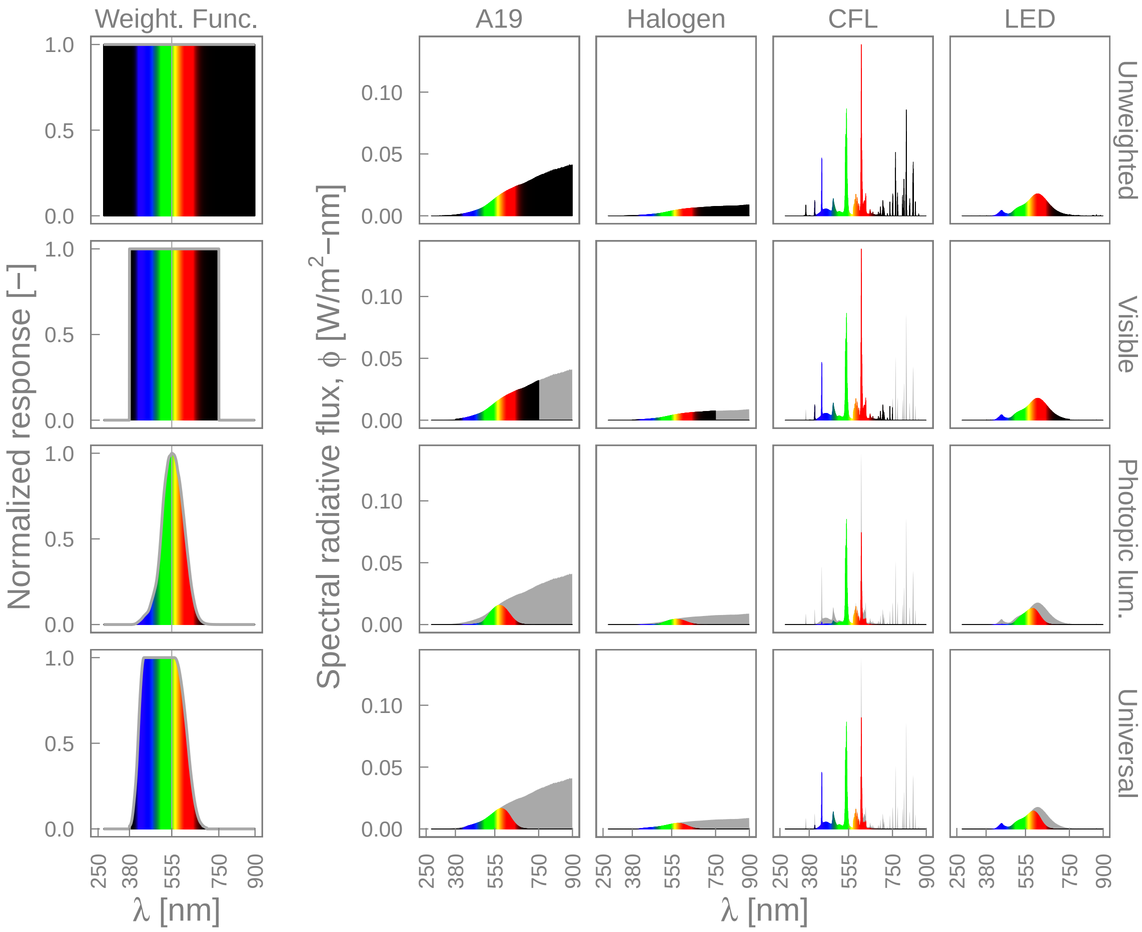

Figure 6. Weighting functions, lamp emission, and weighted responses. Gray regions show lamp emission. Colored regions give weighted responses and indicate human perception of color. "A19" is a 100 W incandescent A19 globe. "Halogen" is a 29 W halogen R20 globe. "CFL" is a 15 W EnergyStar twister compact fluorescent. "LED" is an 11 W Phillips A19 LED. "Unweighted" spans the entire wavelength range of the graph, 250 nm $< \lambda <$ 900 nm. "Visible" restricts to visible wavelengths, 380 nm $< \lambda <$ 750 nm. "Photopic lum." is the standard photopic luminosity weighting function. "Universal" is the universal weighting function. **** What symbol do we want for vertical axis? It is not precisely radiative flux if it is per-nm. **** **** Provide references for each of the weighting functions and lamps? **** **** Yep! I'll add the reference for the LPSDD database in the .bib —ZM**** **** Shall we add luminous intensity annotations to each graph? **** **** Yes, we should add the weighted 'spectral radiative flux' for each graph, me and Emmanuel are working on these calcs! —ZM

4.0.1. Comparison with previous approaches in Societal Exergy Analysis

The luminous (or second law) efficiency of lighting has previously been calculated in SEA by taking the quotient of the minimum energy required to produce a given output, and the energy required to produce a given output by the device in question.

This approach has been recommended for outputs such as light, sound and information ″because the useful output cannot or is not typically measured in energy units" [25].

For lighting this constitutes taking the quotient of the theoretical minimum quantity of energy required to emit one lumen, and the actual energy used to emit one lumen of light by the lamp, values which are derived by taking the inverse of the luminous efficacy values, with the equation therefore equivalent to the quotient of the devices luminous efficacy and the maximum luminous efficacy.

$$\frac{1}{\epsilon_{max}} / \frac{1}{\epsilon_{lamp}} \equiv \frac{1}{\epsilon_{max}} \cdot \frac{\epsilon_{lamp}}{1} \equiv \frac{\epsilon_{lamp}}{\epsilon_{max}} \, , \tag{26}$$

where ϵ_{max} is equal to the maximum luminous efficacy (683 lm/W), and ϵ_{lamp} is equal to the luminous efficacy of the lamp.

As detailed above in 2.1.2 the valuable exergy of the light emitted by a lamp if given by

$$\eta_{X,v} = \frac{\phi_L \dot{L}_3}{\dot{W}_1} \, . \tag{27}$$

Considering the equivalency of the previous SEA approach when using a maximum luminous efficacy figure of 683 lm/W, and the approach detailed in this paper when using the photopic luminosity function, any future studies which select different weighting functions are likely to produce considerably different results. For example, the use of 400 lm/W as the maximum luminous efficacy figure by Ayres et al (2005) and Guevara et al (2016) results in lighting efficiencies being overestimated by a factor of $\frac{683}{400}$ = 1.71, *if* it is decided that light has the greatest utility at a wavelength of 555nm, and is the desired work output. The choice of any weighting function is a subjective decision for the analyst, however to provide consistency for SEA community moving forward we propose to adopt the universal luminosity function in accordance with Rea and Biermann (2018), *if* the assumption is made that lamps are solely used for illumination in society. A more comprehensive approach would be to select a representative range of uses for lamps, which are then assessed based on their respective weighting functions.

**** ZM and PB: Be sure to spike the set from the introduction. ****

5. Conclusions (MKH, 500 words)

**** MKH: Recommend using our method for SEA going forward. ****

**** MKH: Include a future work section. Do we want to include something about waste heat from lamps? ****

Supplementary Materials: The following are available online at http://www.mdpi.com/1996-1073/xx/1/5/s1, Figure S1: title, Table S1: title, Video S1: title.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used:

Conceptualization, X.X. and Y.Y.; methodology, X.X.; software, X.X.; validation, X.X., Y.Y. and Z.Z.; formal analysis, X.X.; investigation, X.X.; resources, X.X.; data curation, X.X.; writing–original draft preparation, X.X.; writing–review and editing, X.X.; visualization, X.X.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript.

Please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

Funding: Please add: “This research received no external funding” or “This research was funded by NAME OF FUNDER grant number XXX.” and and “The APC was funded by XXX”. Check carefully that the details given are accurate and use the standard spelling of funding agency names at https://search.crossref.org/funding, any errors may affect your future funding.

Table 1. Symbols and abbreviations.

Symbol	Meaning [example units]
E	Energy [MJ]
f	Multiplicative factor accounting for spectral sensitivity of the human eye [–]
g	Multiplicative factor accounting for spectral range of the human eye [–]
Q	Heat [MJ]
T	Temperature [K]
W	Work [MJ]
X	Exergy [MJ]
P	The spectral power distribution of a lamp [W/nm]
Wf	A weighting function which details the normalised response of a mechanism to light [–]
V	The photopic luminosity function

Table 2. Greek letters.

Greek letter	Meaning [example units]
ϵ	luminous efficacy [lm/W]
η	efficiency [–]
λ	wavelength of electromagnetic radiation [nm]
ϕ	exergy-to-energy ratio [–]

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Abbreviations

The following abbreviations are used in this manuscript:

MDPI	Multidisciplinary Digital Publishing Institute
DOAJ	Directory of open access journals
TLA	Three letter acronym
LD	linear dichroism

Nomenclature

Table 1 shows symbols and abbreviations, their meanings, and example units. Table 2 shows greek letters and their meaning. Table 3 shows symbol decorations and their meanings. Table 4 shows subscripts and their meanings.

Table 3. Decorations.

Decoration	Meaning [example units]
$\dot{X}$	rate of X [units of X/s]

Table 4. Subscripts.

Subscript	Meaning
0	ambient temperature
C	Carnot efficiency
$elect$	electricity
E	energy
$lamp$	the lighting device (lamp) under assessment
L	light
max	maximum luminous efficacy
s	energy services stage of the energy conversion chain
sys	system operating temperature
u	useful stage of the energy conversion chain
$useful$	the portion of a spectral power distribution considered useful
v	valuable
vis	visible spectrum
X	exergy

Appendix A. First appendix

Appendix A.1. appendix subsection 1

Appendix A.2. appdendix subsection 2

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