BY MIKE WOOD

Efficacy—How good can it get?

I'VE BEEN WRITING THIS COLUMN for nearly 10 years now and a perennial problem for me is deciding what to write about. Once I have a topic in mind, you just wind me up and let me go, but choosing a topic is sometimes tough. Often it's a project I've worked on recently, or a question I've been asked that triggers a thought, and that was the case this time. I was giving a seminar last month and was talking about the maximum efficacy for white light being around 250 lm/W (lumens per watt) when one of the audience reminded me that Cree, that very month, had issued a press release saying that they'd broken the 300 lm/W barrier with a new LED. How did I reconcile what I'd just said with the Cree press release? Surely one of us must be wrong (with the unspoken but understandable implication that the error was most likely mine!)

Fortunately for me, I'd seen the same press release, knew about the Cree breakthrough and was able to explain why we were both correct. The explanation is perhaps interesting and draws together some other recent topics we've discussed here, in particular the photopic curve we talked about in the Spring 2014 issue column.

Efficacy versus efficiency

We should start by considering what efficacy means. Why do we use the word efficacy rather than efficiency when talking about how good a light source is at turning electricity into light? The problem, as it so often is with photometrics, is that whenever we talk about light we must refer to the human eye, and what we are capable of seeing. Light measurements are not absolute, but are always referred to the capabilities of the average viewer. We measure electrical power in watts, and we could also measure electromagnetic radiation in watts as well. However, watts tell us nothing about how well we can see that radiation. For example, we can have as many watts of electromagnetic energy in the ultraviolet as we like, but we still can't see them, thus, to the human eye, there is no energy there. The name used for the visual equivalent of watts is "lumens." When we use the word lumens, we explicitly mean the power of a light that the human eye can see, and none of the other energy that might be present. If you can't see a light, then it is emitting zero lumens by definition, no matter how much invisible infrared, ultraviolet, or microwave energy might be coming out of it.

What we are often interested in when trying to work out how good a light source is at its job is the relationship between the electrical energy that it consumes versus the visible light energy that it emits. If those were both measured in the same units, then we can call the result the efficiency. For example, the efficiency of an electric motor might be related to the energy taken from the power supply, measured in watts, as compared to the mechanical energy produced by the output shaft, also measured in watts. If the motor consumes 100 W and produces 75 W then we say it is 75 W/100 W = 75% efficient. In the case of a light however, the input energy is in watts, but the output energy is measured in lumens. As these units are different, you can't just divide one by the other to come up with a percentage, that's meaningless. Instead we still divide the output energy by the input energy, but we keep the units separate and call it "efficacy" to distinguish it. An analogous light source to our motor might consume the same 100 W of power, and emit 7,500 lumens of light. We then say that the efficacy is 7,500 lm/100 W = 75 lm/W.

> "How many lumens per watt represent the perfection where every electron becomes a visible photon?"

What price perfection?

A key difference between efficiency and efficacy is that it's obvious in the case of efficiency of the electric motor what the upper limit must be. Perpetual motion is impossible thus the output power cannot be greater than the input power and, as the measurement units are the same, it follows that the efficiency cannot be greater than 100%. The same is true of an electric light, what you get out must be less than what you put in, but what efficacy corresponds with that 100% point? How many lumens per watt represent the perfection where every electron becomes a visible photon?

Because of the dependence of lumen

measurement on the human eye response, and the huge variation in how well the human eye sees different colors or wavelengths, the maximum efficacy of a light source is also dependent on the wavelength, or mix of wavelengths. **Figure 1** should be familiar from my Spring 2014 column on the currently used 1924 photopic curve. It represents the sensitivity of the human eye to different colors.

Note: As much as I hate to use the 1924 curve and would much rather use the newer ANSI E1.48 *curve which more accurately represents human vision, I've chosen not to for this article because the Cree product, and others cited here, use the CIE 1924 curve. It would be both churlish and confusing to insist on changing them. Everything discussed here is equally applicable (albeit with some changes in the numbers) if the* ANSI E1.48 *photopic curve were used instead.*

Starting at the short wavelengths, we have no sensitivity to UV, and we see blue fairly poorly, with increasing sensitivity as we get into green. Our eyes peak at 555 nm in the yellow-green, then we drop off again into the reds until we get into the IR, which is again invisible to us. The lumen is defined such that 1 W of monochromatic green light at the 555 nm peak of the curve would appear to our eyes as 683 lumens. This definition is essentially arbitrary, but forms the basis for all color photometry. We can now scale off the photopic curve and see that 1 W of light at 650 nm would be visible as approximately 68 lumens, and 1 W at 500 nm would be visible as approximately 200 lumens. We have our basis for understanding what 100% efficiency means with a light source.

For 555 nm green light, 100% efficiency would mean 683 lm/W, for the 650 nm red light just 68 lm/W would represent 100%, and for the blue-green 500 nm that 100% would be 230 lm/W. There isn't just one answer! Because efficacy is dependent on lumens, which in turn are dependent on human vision, maximum efficacy varies with wavelength or color.

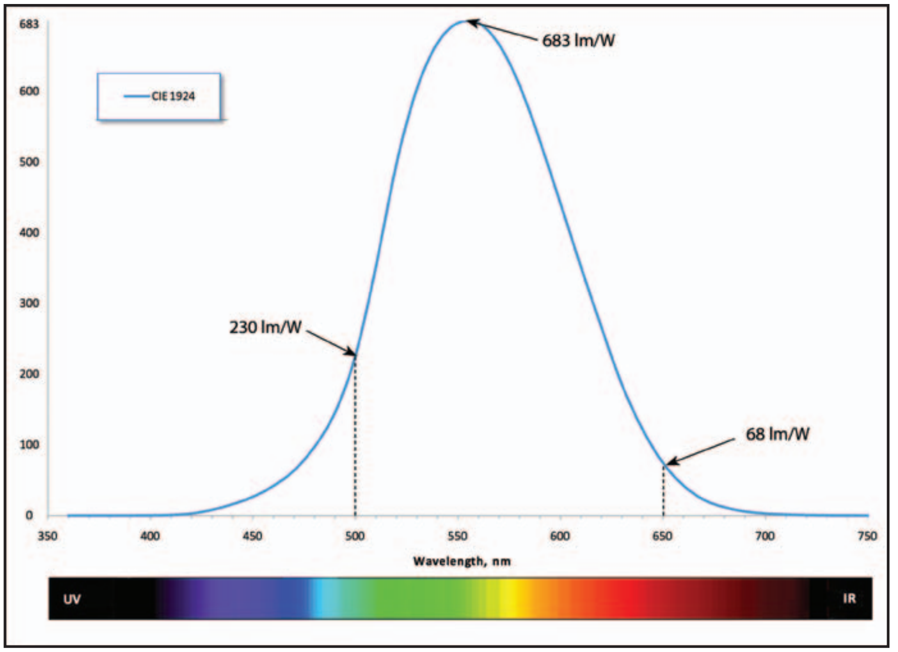

Figure 1 – Photopic curve

White light

That's relatively straightforward with a monochromatic light with a single wavelength, but what about a broadband light source which contains many different colors, perhaps a continuous spectrum? What about white light?

What we have to do is to conceptually break down the light source into its individual wavelengths, work out the efficacy for each one, and then add them up again in the right proportions. (This is mathematically equivalent to convolving the light spectrum with the photopic curve.) Fortunately the math isn't that complex, and Excel handles it very easily. Let's look at a few examples of real light sources, and the maximum possible efficacy for each.

First, a low-pressure sodium (LPS) light, horribly familiar to us as that awful yellow light in old parking lots. This is a trivial example as it essentially consists of a single spectral line (actually two very close together) so our simple model gives us a direct result.

Figure 2 shows the single orange spike

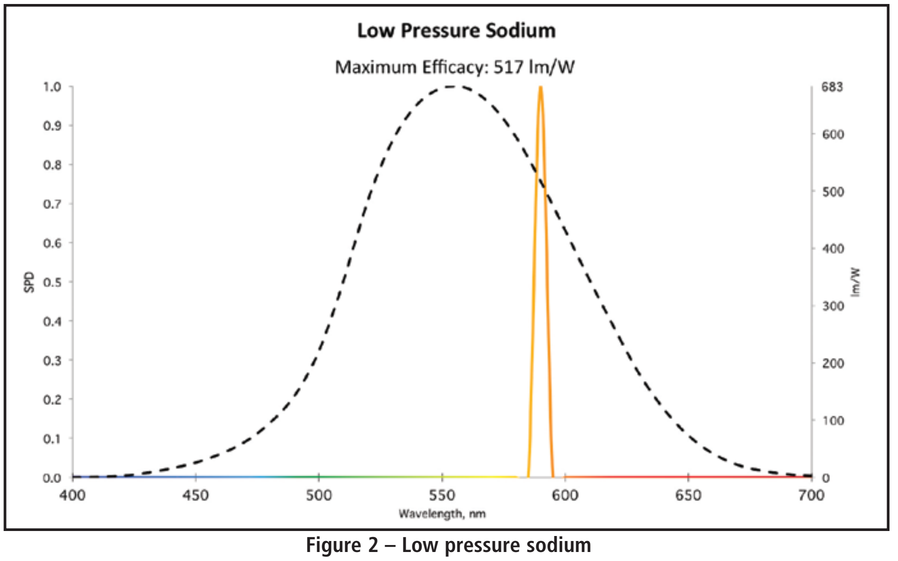

Figure 2 – Low pressure sodium

superimposed on the dotted photopic curve for reference. At this wavelength a 100% efficient lamp would produce 517 lm/W. That is, 517 lumens of visible radiation for every watt of power consumed. That sounds like a very good result, but we know the color rendering of that LPS source is appalling.

Next, the familiar incandescent lamp; this has great color rendering but, unfortunately, emits a lot of energy in areas of the spectrum that are invisible to us. Even if we limit our analysis to the energy between 400 nm and 700 nm, we still get a result that, at 153 lm/W, is considerably less than the LPS.

In other words, no matter how good we are at making new light sources, if they have the same spectrum as an incandescent lamp then they can never have an efficacy higher than 153 lm/W. (*Note: This is nothing to do with the underlying technology, this is the incandescent spectrum we are talking about, not incandescent lamp technology. An LED, or any other light source, with this same spectrum would still be limited to 153 lm/W.*)

Daylight is a little better at 247 lm/W and, indeed, a figure of approximately 250 lm/W is often cited as the standard maximum efficacy for a white light source, and was the figure I was talking about in the seminar. So how did Cree make a white light LED that had an efficacy of 300 lm/W? Is that press release just marketing rhetoric?

Better than daylight?

What we can do to get better than 250 lm/W is to stop looking at continuous spectra, particularly those which extend into regions of the spectrum where we can't see very well, and instead concentrate on producing light at wavelengths we see the best, and try and make it look white. Looking back at **Figure 1**, we have to design lights to maximize their response within the photopic curve.

Figure 5 shows the spectrum of a typical phosphor converted white LED with a blue pump LED and a broad yellow phosphor giving the familiar twin peaks.

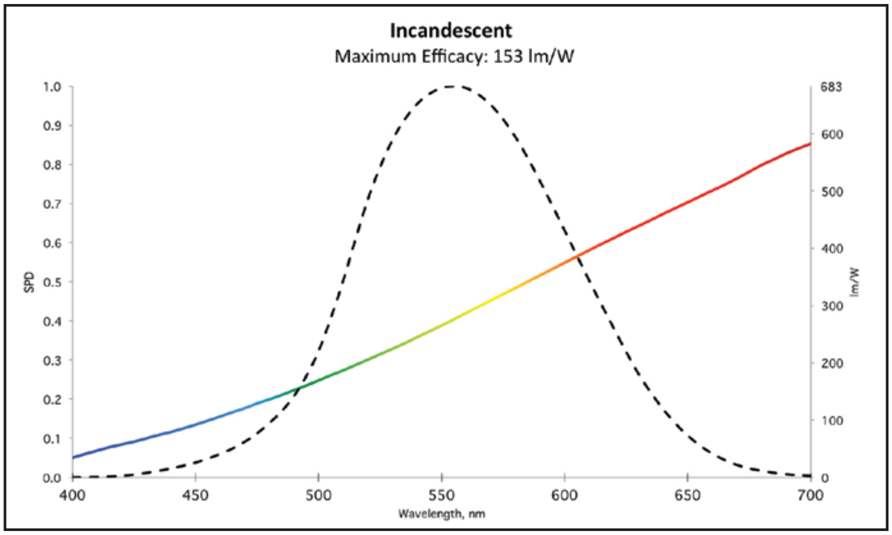

Figure 3 – Incandescent

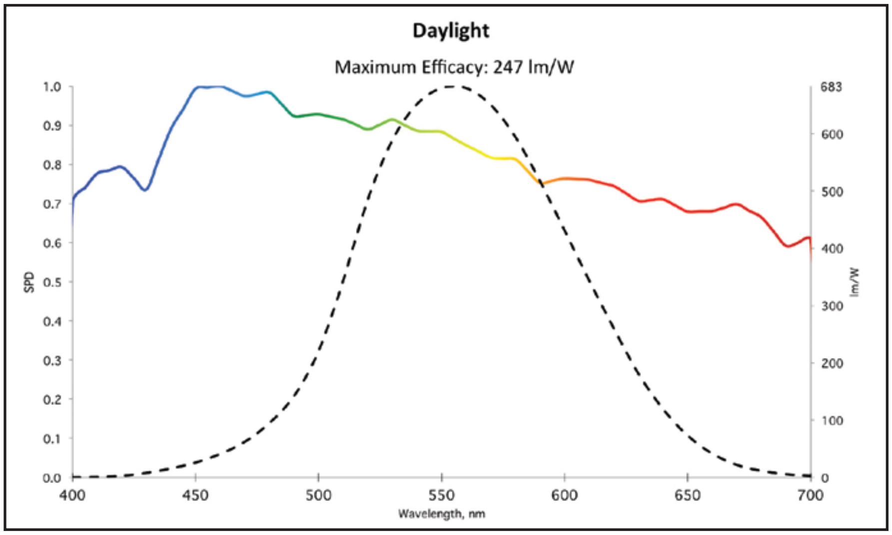

Figure 4 – Daylight

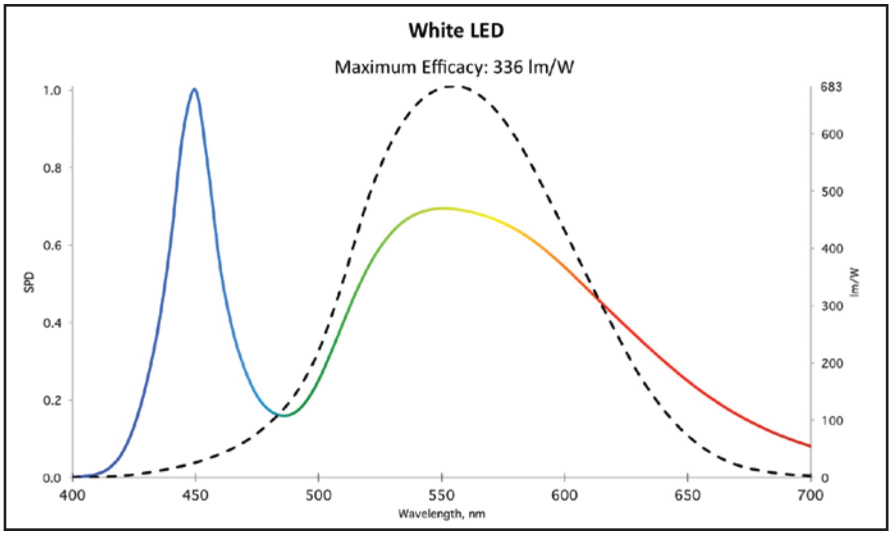

Figure 5 – White LED

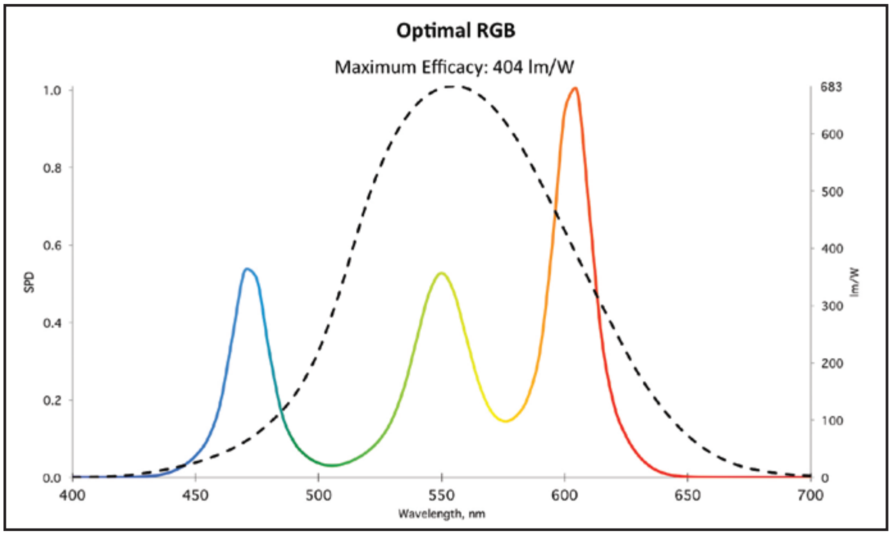

Figure 6 – Optimal RGB

Look at the shape of that yellow peak, it's been carefully chosen to mimic the peak in the photopic curve, giving highest output at the green-yellow color where the human eye is most sensitive with less wasted energy in the areas where we don't see well. By designing to the curve like this, we get a maximum possible efficacy, if everything else were perfect, of 336 lm/W. The light still looks white, but we've beaten the 250 lm/W barrier. The color rendering isn't perfect (and never can be—we have to give up something to get high efficacy, and rendering is the unfortunate victim) but is acceptable in many cases. Cree hasn't released details of the spectra of their 300 lm/W product, but I'm sure it will look something like **Figure 5**.

> "Is that press release just marketing rhetoric?"

How good can we get?

Is the 300 lm/W achieved by Cree with their phosphor white LED as good as it's going to get? Well, not quite. By gaming the system even more we can get a little better. Funnily enough, by returning to using three emitters in a familiar RGB layout, and picking three colors so that they maximize our return from the photopic curve we can get outputs with efficacies above 400 lm/W. **Figure 6** shows one example of a close to optimal result of 404 lm/W.

To achieve this result, each of the emitters would have to be 100% efficient at producing its own color; the red emitter would have to be 100% efficient at producing its 610 nm light, similarly the green and the blue. Once again we would be giving up color rendering to get this high efficacy, and it's up to us how much we are prepared to give that up in the interests of saving energy. However, no matter how poor the color rendering we are prepared to live with, it just isn't possible to make a white light source that is much better than 400 lm/W. That's an absolute limit.

When you put this in that context, the 300 lm/W achievement by Cree and the other LED manufacturers is, to me, even more impressive. Compared with the roughly 400 lm/W maximum, this device produces about 75% of the maximum possible for white light. That's astounding! We've gone from incandescent light bulbs at 15 lm/W efficacy (or 10% of the maximum possible with the spectrum) to 300 lm/W efficacy (75% of the maximum possible with that spectrum) in a very short space of time. The results also suggest that the current blue plus phosphor-yellow white LEDs are likely a short-lived design that will eventually be replaced by designs with three or more mixed colors.

What does this mean in the real world? Current shipping products are a long way from 400 lm/W, or even the 300 lm/W that is being achieved in the laboratories, however 200 lm/W devices are already in production. (*The US Department of Energy based their initial 200 lm/W target for energy efficient lighting on 50% of the 400 lm/W that was theoretically possible, a sensible goal.*) The incredibly steep curve we've seen over the last ten years as LEDs have got better and better, and brighter and brighter must inevitably flatten out. I look forward to that, as the LED race will then switch to better quality and better pricing rather than just raw power. ■

Mike Wood runs Mike Wood Consulting LLC, which provides consulting support to companies within the entertainment industry on product design, technology strategy, R&D, standards, and Intellectual Property. A 35-year veteran of the entertainment technology industry, Mike is the Immediate Past Chair of the PLASA Governing Body and Co-Chair of the Technical Standards Council. Mike can be reached at mike@mikewoodconsulting.com.