The Inconsistency of Dimmers with LED Lamps

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ABSTRACT

Modern dimmers are designed to work effectively with many light emitting diode (LED) lamps. Yet, testing has found that residential LED lamp dimming performance varies dramatically based on the dimmer that the lamp is paired with. Data presented in this paper shows that the same lamp can display up to a 25% difference in performance when dimmed with different dimmers. For example, an LED lamp rated for 800 lumens, when paired with an LED compatible dimmer, can experience a reduction in light output that would make the lamp more equivalent to a 40 W incandescent than a 60 W incandescent. These variances can impact overall system performance and consumer experience. Dimming performance has not been a reported aspect for efficiency ratings in the past, but given the impact a dimmer has on a lamp, more thought and effort needs to be put into standardizing dimmer compatibility and providing the consumer with an expectation of performance. This paper delivers information to utility and industry participants on the importance of assuring compatibility of paired lamps and dimmers. Proper performance increases the likelihood of improved consumer experience and results in higher energy efficiency program participation.

Background of Residential Lighting

Lighting is estimated to consume about 11% of total electricity in the United States (EIA, 2015). Residential lighting is estimated to be about 14% of the annual residential electricity consumption in the United States (EIA, 2015). A range of residential lighting technologies are included in these consumption numbers, but primarily, incandescent, halogen, compact fluorescent lamp (CFL), fluorescent, and LED are the notable residential lighting technologies. These technologies may be utilized in a variety of fixture types around the home such as table lamps, floor lamps, pendants, recessed cans, ceiling fixtures, chandeliers, and decorative fixtures. The majority of these residential fixtures contain sockets for A-type lamps[1] and directional lamps.[2]

[1] A-type lamps refer to the shape and size of the bulb. Common A-type shapes include A19 and A21. The number in A19 refers to the width of the lamp in eighths of an inch (A19 = 2 and 3/8 inches).
[2] Typical directional lamps include BR30, R20, PAR30, and PAR38. PAR stands for parabolic aluminized reflector. The number following the letters indicates the width of the lamp in eighths of an inch.

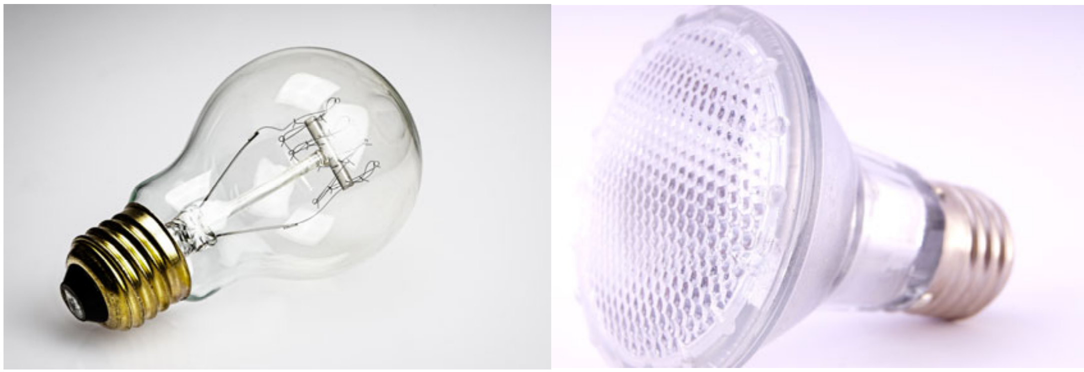

Figure 1. Example of an A-type lamp (left) and a directional lamp (right)

The large amount of electricity annually consumed by residential lighting means understanding the true performance of residential lighting is vital to assure consumer stratification with lighting technologies and to help energy efficiency programs be successful. As efforts to reduce energy consumption have increased, LED manufacturers have improved and expanded the variety of LED products to provide efficient replacements for virtually all residential lamp types. Though LED lamps are widely discussed and touted, as of 2014, LED A-type lamps had only reached 2.4% of sockets in the U.S. across all sectors (DOE, 2015). Similarly, the market penetration of directional LED lamps is only 5.8% (DOE, 2015). Utility rebating programs have helped push these numbers to where they are, but these small percentages show that there is still a large, untapped energy savings potential within the residential lighting marketplace.

In the past few years, LED residential market share numbers have been rising, but there are still many barriers to overcome before mass adoption. Hurdles routinely vary by the individual but can also vary from by region due to state and local regulations and public perception. Some states have raised awareness regarding limited energy availability in the region while other states have little need of reducing energy consumption. While price is generally the largest barrier (DOE, 2015), other barriers to residential LED adoption may be:

- lack of understanding regarding total value of product (Osram, 2015)
- complexity of choices (too many features/options to choose from)
- negative experiences with other energy efficient products
- unattractive shape or color temperature of the product
- lack of dimming or poor dimming quality

Some of these barriers may stem from lack of education regarding LED technology, while other barriers may stem from issues with other energy efficient products. With unfamiliar choices to consider – including color temperature, dimmability, color rendering index (CRI), lifetime, and shape - the customer can easily feel overwhelmed and revert to selecting, lighting products they are more familiar with. Utility energy efficiency programs have proved to be a valuable resource for customers to help make informed decisions and to remove some of the barriers such as high cost and product unfamiliarity. Whatever the barrier, LED adoption still remains relatively low throughout the lighting marketplace. The following sections will focus on defining and addressing one of these barriers – dimming incompatibility.

Dimming, Dimmers, and Dimmability

Dimming

Dimming is an important feature of modern lighting that many consumers value. The ability to reduce light levels offers several benefits to the user. First and foremost, dimming can provide a specific level of desired illumination to the occupants of a space which increases the comfort level of the occupant. Dimming a lamp or fixture allows the user to vary and set the exact amount of light desired or needed for a specific application. Dimming can also be used when there is daylight supplementing the space or when a certain mood is desired for the room. Second, dimming a lamp provides reduces the power consumption of the lamp and provides energy savings. Via dimming, the customer reduces their electric bill while the utility sees a reduction in energy demand on the grid. Both of these impacts are important in areas with high energy costs. Lastly, having a dimmer in the circuit versus not having a dimmer in the circuit can often provide 5% energy savings even when the dimmer is set to full brightness. This is due to the voltage clipping which is described further in the following section. These are not the only benefits of dimming light, but are some of the primary reasons dimming exists.

Dimmers

Dimmers for residential lighting have been in regular use since the early 1960s. In 1959, Joel Spira of Lutron is credited with inventing the first solid state dimmer for residential light control. By incorporating the use of a thyristor, Spira created a solid state dimmer that would replace the rheostat dimmer, a technology traditionally used for controlling lights in a theater. The solid-state dimmer, as opposed to the traditional rheostat dimmer, has the ability to lower the RMS value of the voltage by clipping the sine wave. The primary component of the modern dimmer is a triode alternating current switch (TRIAC). The TRIAC switch controls at what phase angle the voltage to the lamp is switched on. Compared to a rheostat dimmer, the TRIAC is physically smaller and more efficient from an energy standpoint. Most of today's residential dimmers are TRIAC dimmers and are generally leading-edge dimmers which means the dimmer clips the front edge of the voltage waveform after the zero crossing. An example of the voltage waveform clipping from a leading edge dimmer can be seen in Figure 1 below.

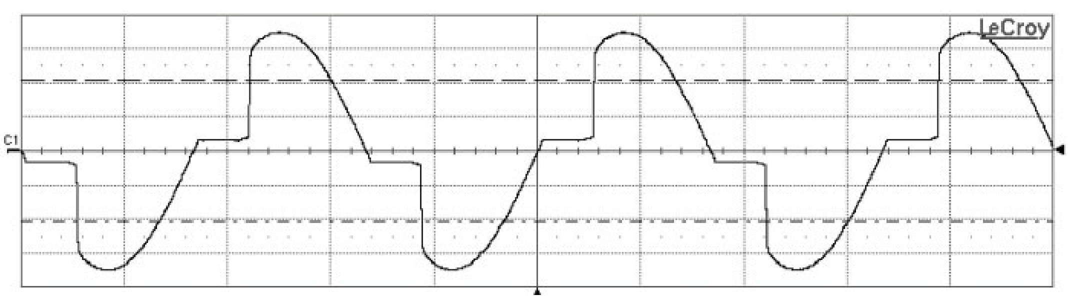

Figure 2. Example of the voltage waveform after a leading-edge dimmer.

Traditionally, dimmers have controlled incandescent or halogen lamps, but with the emergence of CFL and LED products, residential dimmers are now being required to control a new generation of technologies. To address these new technologies, manufacturers have designed "universal" dimmers that are made to work with both electronically ballasted lamps

(LED and CFL) and resistive lamps (halogen and incandescent). These new universal dimmers are 3 wire dimmers (adds a neutral line connection to detect the zero-crossing of the AC waveform) instead of 2 wire dimmers and have more complex circuitry to alleviate problems such as flicker, buzzing, and reduced dimming range.

Dimmability

Dimmability remains a point of conflict in the lighting industry. Some lamp manufacturers, lighting advocacy groups, government regulators, energy efficiency programs and consumer advocates contend that all LED products should be dimmable since the incandescent technology is inherently dimmable. Proponents of this position use the fact that only 12% of residential lights are controlled via dimmers (DOE, 2012), and therefore, the customer should be given the choice of having a less costly, non-dimmable lamp. These stances argue that providing a low-cost, non-dimmable LED lamp can be used as an entryway for the majority of consumers into the LED technology. By removing dimmability (and sometimes other features and components) from LED lamps, manufacturers have been able to sell LED lamps in the $1.50-$3.00 range without rebates. While this is a fast way to increase market penetration of LEDs, this is a potentially risky approach and is similar to CFLs when they were first introduced. Even today, most CFLs are not dimmable and many consumers are still dissatisfied with the technology since it does not offer all of the same features as incandescent. LED lamps have the potential to fall into that same trap if consumers are not educated about dimming compatibility.

In indoor applications where a lamp is operated in an on/off fashion, a low cost, non-dimmable LED product can be fine. In fact, in most cases the elimination of the additional circuitry needed for dimming will actually reduce the consumption of the lamp by a watt or more, further helping with energy savings. However, when a lamp is needed in an application where dimming is required, that low cost product, will likely result in product failure if dimming is attempted. Non-dimmable electronically ballasted lamps have been known to flicker, overheat, and create unwanted harmonics when placed in a dimming circuit. Dimming a non-dimmable lamp can be catastrophic for the lamp and other electronics on the circuit. Because of these issues, most consumers would need to maintain a stock of both dimmable and non-dimmable lamps to address different applications. This further adds to the confusion and complexity of converting consumers to LED based products.

Addressing the Dimmer Compatibility Issue

Accurately selecting the correct lamp for a dimmer (or dimmer for a lamp) has become a complicated process that many consumers are unaware they even need to consider until they install a wrong combination. Even if a consumer purchases a dimmable lamp and a universal dimmer, compatibility and full dimming operation is not guaranteed. Many consumers end up resorting to the trial-and-error method to find a lamp and dimmer combination that works for their application. This often leaves the consumer frustrated because of extra costs and wasted time. Few tools exist to help consumers make informed decisions. Most lighting manufacturers maintain lists on their websites of approved products that their product works with. However, many consumers are not aware that these lists exist because the website is usually printed on the back of the package of the lamp or dimmer in small font.

Some leaders in the industry are aware of this problem and are actively trying to resolve the dimmer compatibility issue. The DOE has been a leader in documenting LED performance with its CALiPER (Commercially Available LED Product Evaluation and Reporting) reports. CALiPER report entitled *Retail Lamps Study 3.1* specifically addresses to LED dimming performance (DOE, 2014). Also, PNNL authored a guideline document that details a recommended procedure for pairing LED and dimmers help reduce issues with dimming installations (PNNL, 2013). Furthermore, in 2013, the National Electrical Manufacturers Association (NEMA) released a standard entitled "Phase Cut Dimming for Solid State Lighting: Basic Compatibility." The standard, SSL 7A-2013, begins to address the compatibility issue by defining compatibility and introducing test procedures for compatibility compliance. Dimmer compatibility is defined in SSL 7A as

- "The reliability of the dimmer and the LED Light Engine are not affected by combining them.
- Dimming behavior meets or exceeds the behavior specified in sections 3 and 4 (NEMA, 2013)."

The definition provides some basic guidelines, but since it is self-referencing, it is difficult to fully grasp and apply in this form. The rest of the standard goes on to describe LED Light Engine (LLE) and dimmer testing to enable predictable functionality between the two. Sections 3 and 4 specifically outline tests pertaining to inrush current, repetitive peak current, overload, off-state operation and more.

Manufacturers may follow the guidelines if they desire to be more compatible with a variety of manufacturers lamps or fixtures, but this is not currently viewed as an industry requirement. That being said, the California Energy Commission (CEC) has recently released its 2016 energy codes and the SSL 7A standard is referenced. The energy code says, "All forward phase cut dimmers used with LED light sources shall comply with NEMA SSL 7A (CEC, 2015)." This phrase applies specifically to new construction and renovation residential projects. This standard goes into effect on January 1, 2017, and California will be the first state to require SSL 7A compliance. Even though Title 24-2016 is less than a year away, it is difficult to find dimmers that are SSL 7A compliant. The packages and specification sheets of today's dimmers make no mention of SSL 7A and there is no online list of compliant products. This is a significant gap in the industry, which makes it difficult for anyone to comply with the code.

While SSL 7A addresses many of the power requirements for compatibility, it does not address the light performance of the dimmer. There have been discussions of NEMA releasing SSL 7B to address light performance. This standard would theoretically provide dimming curve requirements and minimum cutoff requirements. A standard such as this would further increase the predictability of the LLE and dimmer combination so that the customer can achieve repeatable results with various products. However, this standard does not exist yet and currently there is no means of easily comparing repeatable dimming results.

The goal of this research is to help the industry acknowledge and eliminate dimming compatibility issues that might decrease the market penetration of LED lamps. The following sections of this paper will summarize research that EPRI has performed to illustrate the need for a light performance standard for dimmers.

Test Plan and Product Selection

To explore the problem of dimmer compatibility, twenty different LED lamps and five different model dimmers were studied. Prior to the beginning of dimming testing, EPRI tested the electrical and photometric performance of the LED products. Each of the 20 lamps was a different model, and the lamps were from a variety of manufacturers. Of the 20 LED lamps, three different lamp types were tested: twelve A19, seven PAR30, and one PAR38. Also included in the 20 products were three color shifting lamps that are often referred to as "dim-to-warm" lamps. These lamps more accurately reflect the color temperature of incandescent lamps when dimmed. Table 1 shows some product details of the 20 lamps including claimed wattage versus measured wattage with no dimmer in the circuit.[3]

Table 1. Lamps types and wattages

Number	Lamp Type	Claimed Wattage	Measured Wattage	Wattage Difference
1	A19	8.5	8.45	-1%
2	A19	9.0	9.40	4%
3	A19	9.5	10.12	7%
4	A19	9.5	9.40	-1%
5	A19	10.0	10.99	10%
6	A19	10.0	9.56	-4%
7	A19	10.0	10.34	3%
8	A19	10.0	10.40	4%
9	A19	11.0	11.79	7%
10	A19	11.0	11.30	3%
11	A19	13.5	14.20	5%
12	A19	13.5	12.95	-4%
13	PAR 30	9.0	8.86	-2%
14	PAR 30	9.0	8.58	-5%
15	PAR 30	9.5	9.83	3%
16	PAR 30	10.0	9.92	-1%
17	PAR 30	12.0	11.12	-7%
18	PAR 30	14.0	14.07	1%
19	PAR 30	14.0	14.29	2%
20	PAR 38	16.0	17.75	11%

[3] The wattage of a single lamp is often different from the claimed wattage by a small percentage because the rated wattage is based on an average of hundreds of lamp samples. That being said, several of the lamps exhibited a greater difference in rated wattage than expected, but that is not a primary focus of this paper.

The 20 lamps were each tested with 5 different dimmers. The dimmer characteristics are listed in Table 2 below. Based on manufacturer provided compatibility sheets, many of the dimmer and lamp products were not listed as compatible with each other. The dimmers were loaded with just a single lamp which fell within the minimum load recommendations as listed by the manufacturers (some did not have any minimum requirements).

Table 2. Dimmers types and maximum loads

Number	Dimming Type	Lamp Types	Maximum Loads (resistive/electronic)	Quantity of Listed Compatible Lamps
1	Leading Edge	Universal	600/300 W	3
2	Leading Edge	Resistive	600 W	4
3	Leading Edge	Universal	600/150 W	12
4	Leading Edge	Universal	600/150 W	4
5	Leading Edge	Universal	600/150 W	10

To begin the dimming testing, each of the 20 lamps was individually placed into an integrating sphere and powered without a dimmer to get a baseline reading. Then, one of the dimmers in the circuit, and the lamp was then dimmed from 100% down to the lowest light output in 10% power increments. At each 10% increment along the dimming curve, power and light measurements were recorded. After the full operational range was recorded, the dimmer exchanged with a different dimmer and the test was repeated until all five dimmers were tested. This process was repeated for each of the twenty lamps. Overall, 100 different lamp-dimmer combinations were tested.

Testing Results

Though the test plan was straightforward, the data collected provided answers to various questions. First, how does the same lamp operate across different dimmers? Second, does a compatible lamp (as listed by the manufacturer) perform differently than a non-compatible lamp on the same dimmer? Third, how will a non-LED rated dimmer perform against LED rated dimmers? Relevant data from the tests is shown below.

Figure 2 (left) shows the light output dimming curve of Lamp 1 with each of the five dimmers. The chart shows a fairly linear decline in light output as power is decreased, regardless of dimmer. At 100% light output, the lamp ranges from 820 lumens to 600 lumens depending on the dimmer. This is a large range that illustrates that some dimmers clip a significant percent of the voltage waveform even at 100%. While the dimmer that delivers 600 lumens at full brightness provides energy savings, the end-user may not be happy with the lack of light. With a rated light output of 800 lumens, the user would experience a 25% reduction in light output at full brightness which puts the LED lamp more equivalent with a 40 W incandescent than a 60 W incandescent. Figure 2 (right) shows the minimal decline in Correlated Color Temperature (CCT). This is different from incandescent lamps that decline in CCT as they are dimmed which creates a “warm” ambiance. For LEDs to achieve the warmer color temperature, additional amber LEDs must be mixed in with the white LEDs to mimic the desired color shift.

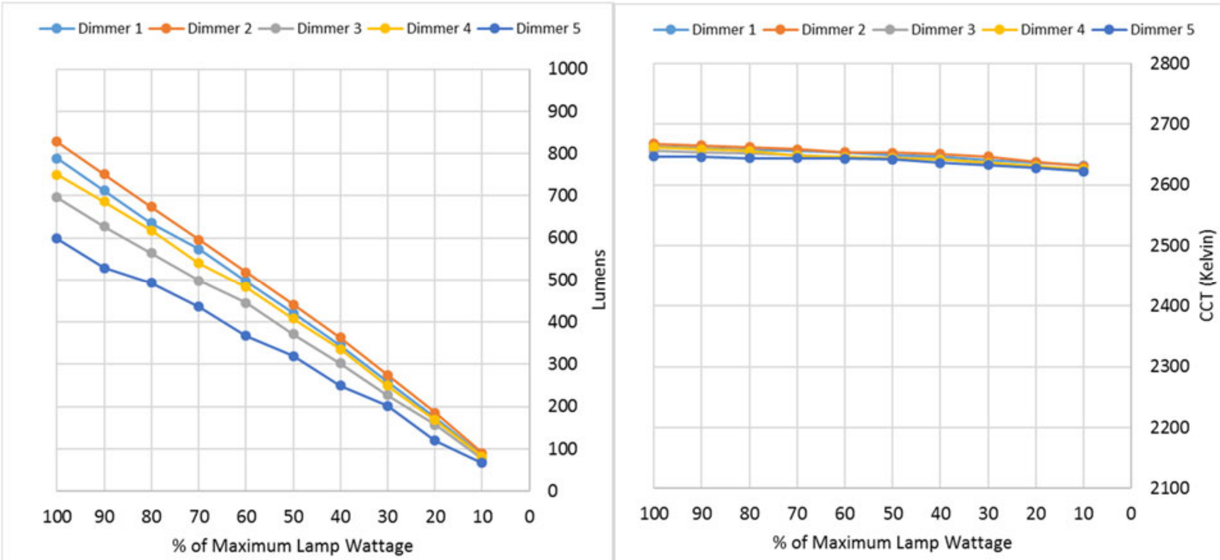

Figure 2. Dimming curves of Lamp 1 with each dimmer; Lumens (left), CCT (right)

Figure 3 below shows the light output and color temperature shifting curves for Lamp 15 with each of the five dimmers. Lamp 15 is a PAR30, color-shifting (or "dim-to-warm") lamp. Notice that the color temperature transitions from 2700 K down to 2100 K. Additionally, notice the sharp drop-off in the middle of the curve where the lamp transitions from yellow to orange. This chart shows that different dimmers transition at different times which results in some dimmers having more color granularity than others. Efficacy is shown on a later chart, but the collected efficacy data for this lamp reveals that the efficacy declined throughout the dimming curve. The lighting industry will likely need to devise separate performance standards for color changing lamps when determining dimming curve restrictions for LED dimming compatibility.

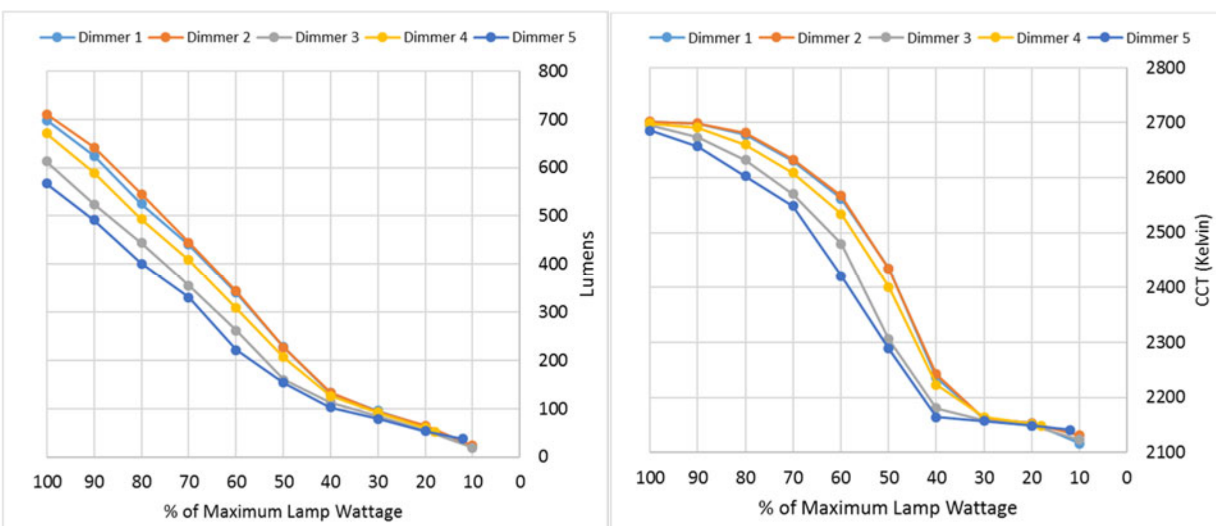

Figure 3. Dimming curves of Lamp 15 with each dimmer; Lumens (left), CCT (right)

In Figure 4 below, the efficacy (lumens per Watt) curve of each lamp is shown when operated with Dimmer 1. Most of the lamps improve in efficacy as dimming is increased down to a certain point. This is opposed to other technologies such as CFL and incandescent which decline in efficacy when dimmed. The LED lamps that do decline in efficacy with dimming are the color temperature shifting, “dim-to-warm” lamps. These lamps use less efficient, warm CCT LEDs to achieve the 2200K color temperature that mimics incandescents. *Another interesting finding in this chart is that almost all of lamps dimmed fully (to 5% or below) with Dimmer 1, which was the dimmer listed to be compatible with only three of the twenty tested lamps (Lamp 1).* Lamp 14 was incompatible with Dimmer 1 and did not dim at all. Overall, this conclusion from this data is that most manufacturers do attempt to produce lamps and dimmers that are compatible with various products, whether they report the compliance or not.

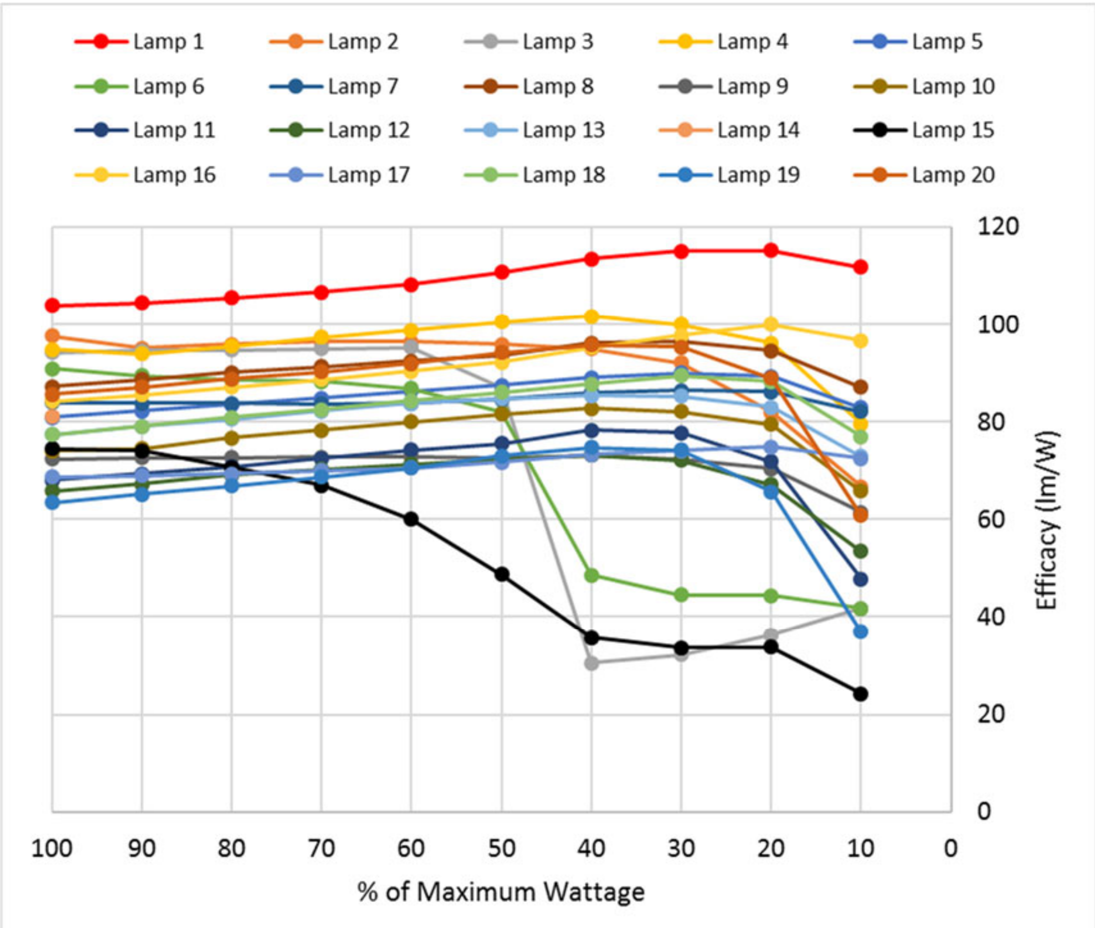

Figure 4. Efficacy curves for all lamps with Dimmer 1

Other compelling results can be seen in Figure 5 and Figure 6 below. Figure 5 is a plot of minimum power cutoffs for all of the lamps with each dimmer. Dimmers 4 and 5 resulted in more than half of the lamps cutting off above 10% of lamp power. This was likely due to the fact that these dimmers do not have a low-end trim dial. Without the adjustable low-end trim, the user has no customization of lamp cutoff. Also notable was lamp 14 which was not compatible with Dimmer 1 and dimmed very poorly with Dimmer 5. Based on testing results like this, performance standards for dimming compatibility should be encouraged to require a low-end trim feature so that the user can customize their setup to have a fuller range of dimming.

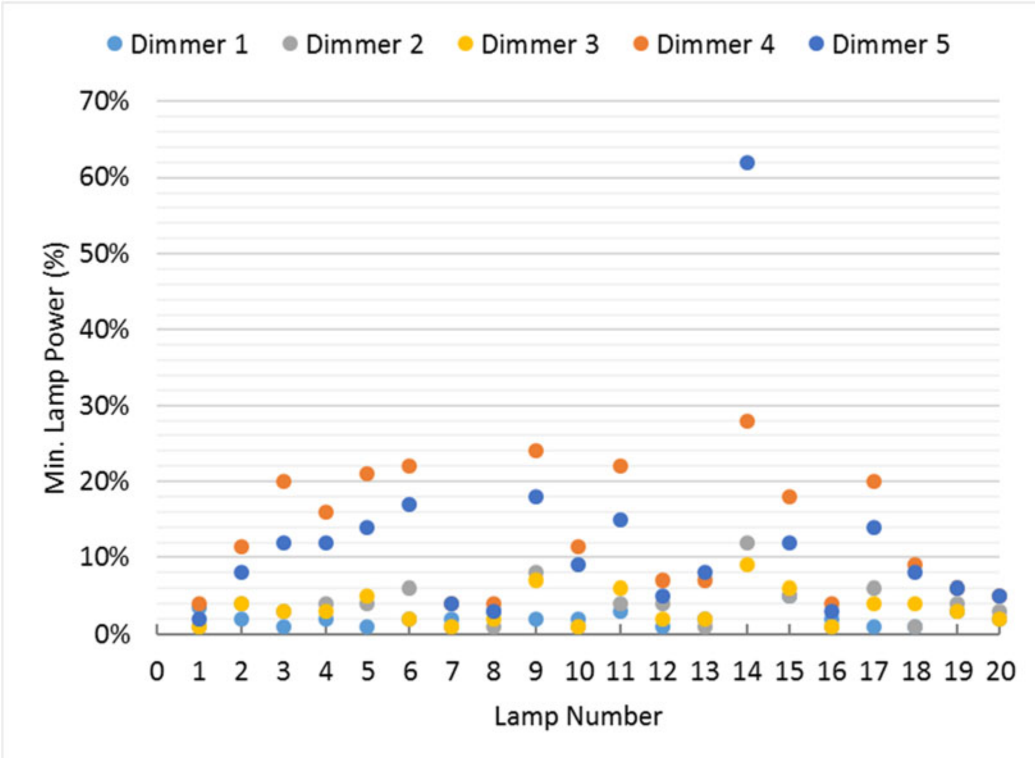

Figure 5. Lamp cutoff levels for each dimmer

Figure 6 shows the variance in power with no dimmer in the circuit versus full brightness with each dimmer. As expected, without a dimmer in the circuit, the lamps consume the most power since the voltage waveform is not being clipped. Another observation includes the fact that Dimmer 5 is consistently the lowest power allowing dimmer across the board. Furthermore, it is interesting to see that some lamps have a tight grouping whereas other lamps have a wide grouping. This shows that some lamps have better input voltage tolerance than others. Overall, this graph illustrates that energy savings can be achieved with many lamps just by installing a dimmer in a circuit without actually dimming the lamps.

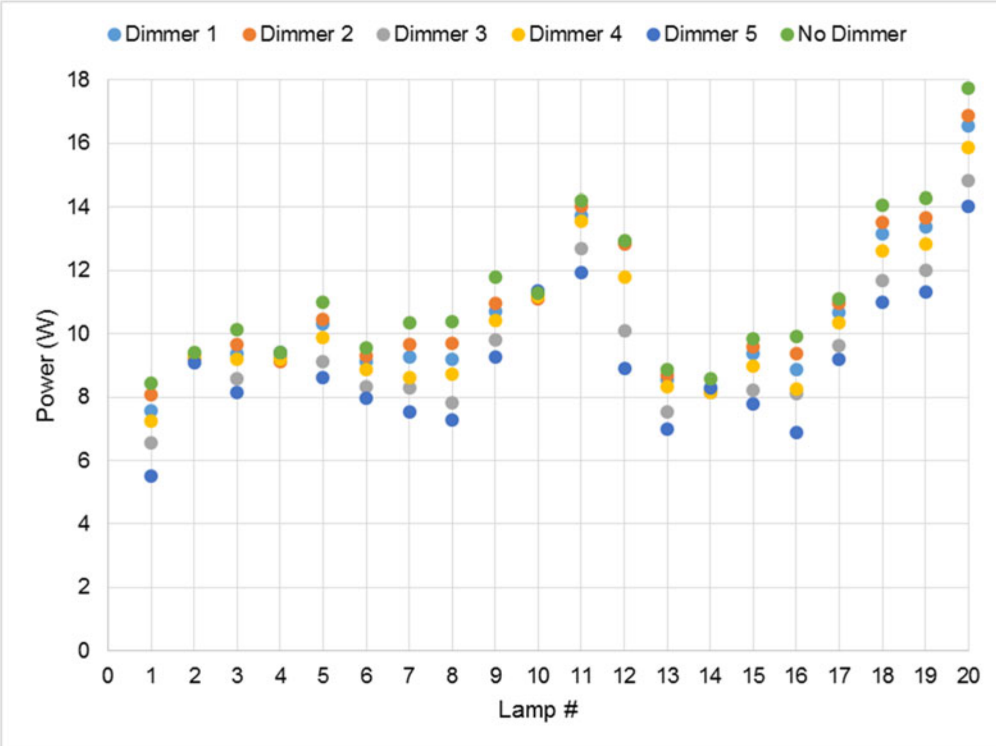

Figure 6. Lamp power comparison at 100% brightness with each dimmer versus no dimmer

Conclusion

The data provided in this paper show that combining dimmers and dimmable LEDs generally results in an operational pair, but a range of outcomes and performances can be expected depending on make and model. Only one of the dimmable lamps selected, Lamp 14, did not function with the majority of the dimmers selected. The rest of the lamps dimmed down to low levels as expected although some did display flickering or buzzing at the low ends. While many of the lamps were not listed as compatible on the manufacturer lists, there did not appear to be a significant difference between listed and non-listed lamps. It could be the manufacturers have not yet tested and approved these lamps since the compatibility lists are maintained voluntarily by the manufacturers.

The data presented in this paper demonstrates several inconsistencies across dimming products. First, the consumer may not receive the full amount of light at 100% brightness that they expected. Some of the dimmers saw as much as a 25% drop in light output because of the voltage wave clipping at 100%. Another inconsistency was that the consumer may not experience low dimming levels (below 10% output) which they may have been accustomed to with incandescents. Some of the dimmers did not have an adjustable low-end trim which means that they have no control of the dimming range. Furthermore, most LEDs do not shift in color temperature like an incandescent when dimmed. The three variable color temperature lamps that were tested exhibited color shifting similar to an incandescent lamp, however, the efficiency of these variable color temperature LEDs dropped significantly at the lower light output.

Inconsistency in LED performance with dimmers has the potential to frustrate and deter consumers from using LED technology. Though NEMA SSL 7A is a good start, the standard is future-looking and does not address the problem between dimmers that are already in homes and LEDs currently on the market. California is helping push the standard forward by including it in the 2016 energy codes which should hopefully raise more awareness to dimming incompatibility. Furthermore, SSL 7A is limited to only basic compatibility and not light level / dimming performance.

The industry also needs to consider improved reporting and education of dimmer compatibility. Currently, the consumer has to go online to a website to identify potential compatible products, which is a burdensome task. If the consumer had a reference guide in the store with compatible product options, either in the form of a printout or a kiosk, the consumer would be able to make a more educated decision with less likelihood for failure. Manufacturers could even consider putting a QR code on the box that directs the user straight to the list instead of requiring the user to scour around the website. The industry needs to take more aggressive action to remove this barrier from the consumer in order to achieve higher LED market penetration. CFL technology has shown how consumers respond to products that do not meet their requirements, and if deeper energy efficiency is to be gained in residential buildings, LEDs need to meet or exceed the customer's expectations.

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