Nuances of High-Power UV LED Curing Systems

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Photopolymerization of inks, coatings, and adhesives occurs when formulations are exposed to a minimum threshold irradiance (Watts/cm^2) at wavelengths (nm) that are effectively absorbed by the specific photoinitiator package within the chemistry. While an optimum wavelength and irradiance combination generates free radicals that enable crosslinking, knowledge of wavelength and irradiance alone offers little insight into whether formulations can be crosslinked at the desired material handling speed. The component of UV output that most directly impacts how fast a production line will run while delivering an acceptable degree of cure is energy density (Joules/cm^2). Consequently, in order to fully define a process window and understand a UV LED curing system's output and performance potential, wavelength (nm), irradiance (W/cm^2), and energy density (J/cm^2) must be specified as a group along with applicable measurement conditions. Anything less is an incomplete characterization of a UV LED source.

Most UV LED equipment suppliers routinely provide information on wavelength and peak irradiance at the emitting window or at a specified offset distance from the emitting window, but they seldom reference the product's energy density at a given press or index speed. Instead, companies attempt to position themselves amongst a growing number of competitors by classifying their UV LED offerings as ***high-power***. A survey of 62 product listings from 11 UV LED system suppliers yielded 15 different promotional adjectives utilizing the qualifier ***high***. Minimal if any technical data or application context was included to support the claims. While high-power was the most frequently used promotional term, the full list included:

high-power	high-energy density	high-stability
high-output	high-dose	high-requirements
high-irradiance	high-performance	high-speed
high-intensity	high-efficiency	high-productivity
high-power density	high-specifications	high-end

Use of a qualifier such as ***high*** implies a relative value proposition without any commitment to specifics and often without reference to an identified baseline source. The intention is that a prospective user will assume the proposed high-power product meets or exceeds curing requirements for the process conditions when compared to lower-power alternatives. In other words, UV LED systems are generally marketed as capable of delivering adequate surface cure and through cure at the intended run speed and working distance dictated by the manufacturing line set-up solely because the lamp head is promoted as a high-power source. The problem, however, is that without technical specifics, it is nearly impossible to conduct a proper comparison with alternative sources or confirm that the output is sufficiently matched to the formulation and set-up requirements.

When suppliers across the industry follow suit and make the same high-power claims for all product offerings without disclosing relevant technical specifications or application context, the term high-power becomes meaningless. This leaves formulators, end-users, and OEMs struggling to properly match UV LED systems to application needs. Product sourcing essentially becomes a trial-and-error exercise with a fair amount of guess work. This ultimately impedes UV LED adoption, delays application innovation, and frustrates users and formulators when an installed UV LED system under-performs.

From a psychological perspective, promoting systems as high-power plays on the human tendency to believe that ***more of something is always better***. While there are numerous applications where a high-power UV LED curing system is necessary, the reality is that too much of something can also introduce unintended and undesirable trade-offs. For example, high-power UV curing systems require larger power supplies and larger cooling units than low-power systems. This leads to bigger installation footprints, greater initial investments, and higher running costs. If the method of generating high-power is through increased irradiance, then the result is a greater concentration of UV LED energy that transfers more heat to the substrate, part, or construction than a lower irradiance device. A greater peak irradiance can also generate more stress on diodes and shorten lamp head life. High-power systems definitely have a place in UV curing and should be used when necessitated by application needs and production set-up; however, systems that generate more output than required will likely lead to unnecessarily larger investment and running costs along with potentially greater scrap and shorter LED life.

What makes a UV LED system High-Power?

In order to properly understand the concept of high-power and its role in UV curing, it is helpful to review some basic terminology within the context of a human powerlifting analogy. The relevant definitions for the key terms that will be discussed are as follows:

> ***Work (Joules = Newton · Meters)*** is the use of force to move an object over a distance. Mathematically, work is force multiplied by distance.
>
> ***Strength (pounds or kilograms)*** is the ability to overcome resistance and produce work. It is typically measured as the greatest load that can be fully moved (lifted, pushed, or pulled) *one time* without failure or injury.
>
> ***Power (Watts = Joule/second)*** is a supply of mechanical or electrical energy. It is the potential to do work at a defined rate of time.
>
> ***Irradiance (Watts/cm^2)*** is the radiant energy or power (potential to do work) arriving at a surface per unit area. It is incorrectly but often referred to as intensity.
>
> ***Energy Density (Joules/cm^2)*** is the cumulative radiant energy or power (potential to do work) arriving at a surface per unit area. Energy density increases with exposure time and is the integral of irradiance over time. It is incorrectly but often referred to as dose. For clarification, energy density is delivered power; whereas, dose is absorbed power. The distinction is significant as not all delivered power is absorbed by a formulation, and absorption is very difficult to quantify.

In powerlifting, individuals build muscle mass, strength, and power by lifting, pulling, and pushing weight over a distance. In Figure One, a bodybuilder lifts a weighted barbell from the floor and presses it overhead in a single, dynamic movement. A minimum level of human strength is required for the individual to accomplish the task. A dozen randomly selected powerlifters may all possess enough strength to press a 50-pound barbell overhead; however, the time required to do so will typically vary by individual. The more powerful may perform the move in less than a second while others who are less powerful may take up to 5 seconds or more. In each case, the same work is accomplished in moving the weight from the floor to a location above the head. Those with more power simply perform the task more quickly.

The weightlifters in this hypothetical sample all exert similar human strength when raising the 50-pound load regardless of whether their individual effort is steady and controlled or wobbly and off-balance. This is because ***strength*** is defined solely as the ability to overcome the resistance of a weight and move it across a distance. Where the weightlifters differ is in their individual ***power*** which directly impacts the time required to complete the task.

Figure One: Shoulder Press with Barbell Weights

As the barbell load increases to 100, then 150, and ultimately 200 pounds, more human strength is required to press the weight overhead. Greater human power is also required to complete the task in a controlled manner over a similar time period. Individuals who lack the required strength for the larger loads will be unable to finish regardless of allotted time. Individuals who possess enough strength for larger loads but lack suitable power will be able to press the barbell overhead but will require more time to do so and may have less control. Only individuals who possess both strength and power for the full 50 to 200-pound weight range will be able to smoothly complete the move in roughly the same time period for each increasing load. Since knowledge of an individual's strength provides little insight into their respective power, it is necessary to quantify both strength and power in order to have full understanding of a powerlifter's capabilities.

This powerlifting scenario serves as an analogy for UV curing where irradiance can be thought of as strength, and energy density can be thought of as power. When UV LED curing systems are selected for an application, it is necessary that the source deliver a minimum threshold irradiance (strength) necessary for crosslinking as well as surface and through cure. More heavily pigmented and thicker films as well as larger working distances generally require the UV source to emit a greater irradiance than when those factors are not present. Supplying the correct energy density (power) at the optimal wavelengths and above the established minimum irradiance, however, is ultimately what ensures cure at the desired production line speed.

Faster run speeds (with respect to each application and set-up) typically require more *emitted* power or total *delivered* energy since the cure surface is underneath the UV LED exposure window for a shorter time period. A need for more power is effectively a need for more total energy density to be delivered to the formulation or for the required energy density to be delivered more quickly. Conversely, slower line speeds for the same application typically require less emitted power as the cure surface is exposed to the UV LED source for a longer time period. As a result, it is this author's position that high-power means high-energy density, and low-power means low-energy density. It should be noted that regardless of terminology, energy density needs are not absolute and are always relative to each application and set-up. What is considered high-power for one market may in fact be low-power for another.

Just as high-strength does not guarantee high-power in weightlifting, high-irradiance does not always yield high-energy density in UV LED curing. Just as powerlifters may possess similar strength but different levels of power, different models of UV LED curing systems generating the same peak irradiance will likely emit different energy densities. Depending on the application and process set-up, the differences may have a negligible impact on cure, or they may have a very significant impact on cure. If it is significant, the less powerful systems will be unable to produce acceptable cure at the desired production speeds. This will force the line to run at slower speeds in order to allow the necessary energy density to build via a longer dwell time under the UV LED source. Alternatively, since energy density is cumulative, multiple UV LED systems at lower energy density outputs can be installed on the line to increase run speed.

The wide range of energy densities required for the various markets, applications, formulations, and production run speeds is one reason so many different UV LED systems exist. A single system will not effectively or efficiently meet the needs of all installations. While a given system may be ideally suited for some jobs and some markets, it will be over or under-engineered for the rest. The practical implication is that different UV LED curing systems rated at the same peak irradiance often do not deliver the same quality of cure at the same range of run speeds due to disparities in both energy density and application requirements.

Improperly matched UV LED systems are sometimes installed because energy density is not generally communicated on technical specification sheets and because the significance of energy density in driving cure at production line speeds is not considered by those sourcing the equipment. Instead, the industry is relying primarily on an incomplete specification of wavelength and peak irradiance as well as relative adjectives such as high-power to make recommendations and decisions. If the goal is to increase the manufacturing press speed without sacrificing degree of cure, the most direct way is to maintain a suitable irradiance and increase the energy density emitted by a single UV LED lamp head or install multiple lamp heads in series.

Deriving Energy Density from Irradiance Profiles

While energy density is the integral of irradiance over time, energy density is not easily calculated from commercially published peak irradiance values. This is because irradiance decreases with increases in working distance between the UV LED lamp head and the cure surface, and most UV LED system suppliers do not publish tables or graphs detailing how the two are correlated. Even when the irradiance at the cure surface is known, it is only possible to calculate energy density by multiplying irradiance and exposure time for static installations where the full cure surface is uniformly and continuously exposed. This simplistic scenario is illustrated by the rectangular profile in Figure Two. More commonly, the irradiance delivered to the cure surface is a dynamic variable as parts or substrates are constantly moving toward, under, and away from the UV source as depicted by the bell curve in Figure Three. The energy density for this second scenario is still represented by the area underneath the irradiance profile; however, it is no longer a simple multiplication exercise and requires mathematical integration obtained through radiometer readings.

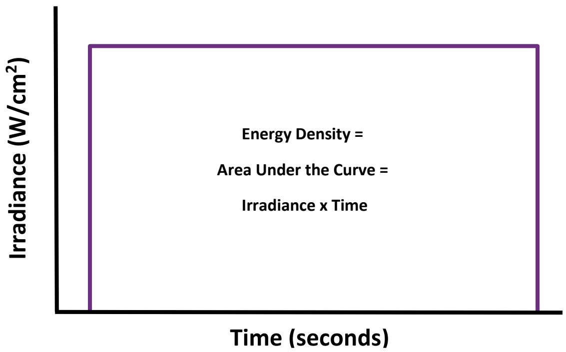

Figure Two: Irradiance profile for static, entire cure surface exposure with instant ON and instant OFF UV LED output.

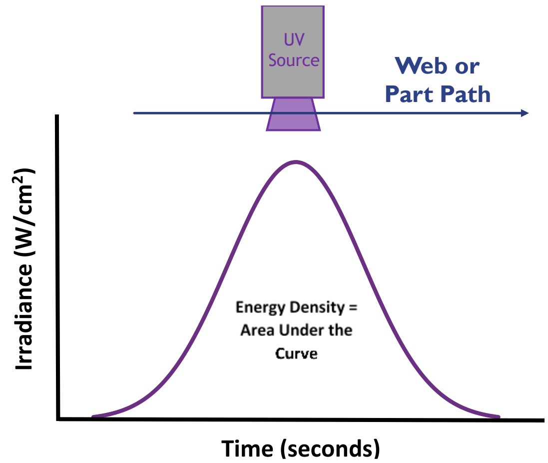

Figure Three: Irradiance profile for dynamic, partial cure surface exposure to a static UV LED system continuously powered.

Variations in Emitted UV LED Energy Density

The following four illustrations demonstrate how peak irradiance cannot be used to accurately predict energy density. In the first image, four different irradiance profiles produced by four separate UV LED products are provided. Each profile has the same peak irradiance; however, the areas under each irradiance profile (energy density) are clearly not identical. In fact, profile 4 is greater than 3 which is greater than 2 which is greater than 1. Without prior knowledge of each product's emitted energy density or conducting a lab or field trial for each system, there is no way for a potential user to understand the variation in energy density values and how they relate to run speed before making a purchase. Profile 4 emits the highest power or energy density of all four profiles and will potentially enable the fastest production speeds. That said, depending on the line speed and application needs, profile 1 may be perfectly suitable and would consume less energy during operation.

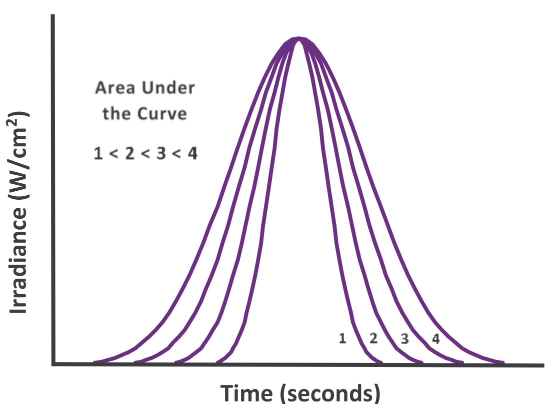

Figure Four: Profiles of four separate UV LED systems with the same peak irradiance but different energy densities.

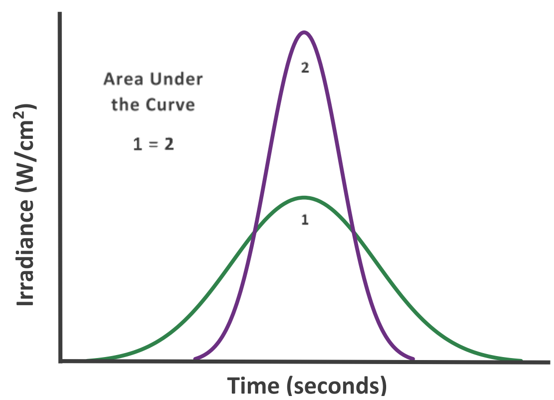

Figure Five: Profiles of two UV LED systems with the same energy density where the peak irradiance of (2) is twice the peak irradiance of (1).

Figure Five illustrates two irradiance profiles where the peak irradiance of (2) is twice the peak irradiance of (1). The designs of the two emitting sources, however, result in both profiles emitting the same energy density. In this case, further knowledge of the formulation and set-up would be required to determine which of the two profiles yields better cure. Provided both profiles exceed the minimum threshold irradiance for thickness, pigmentation, and working distance, then theoretically, both scenarios should produce the necessary polymerization at similar run speeds. Alternatively, a greater working distance might necessitate the need for profile (2); however, a more heat sensitive substrate would perform better under profile (1).

Figure Six offers some insight as to why the UV curing industry fixates on peak irradiance. In the early years of development, UV LED curing systems were very low in output (irradiance and energy density) and limited to 395 nm. This is represented by profile (1) in the graph. At the time, few formulators were willing to modify existing chemistry to optimize the photoinitiator package for longer 395 nm wavelengths. As the technology evolved and UV LED system suppliers began producing devices at increasingly higher irradiances (represented by profiles 2 through 8), existing mercury formulations began to react better to the relatively monochromatic UV LED output. The conclusion drawn by most of the industry, which is perpetuated to this day, was that increases in irradiance were the key to making UV LED curing feasible. While a greater irradiance does provide benefits to oxygen inhibition at the cure surface as well as better penetration through the formulation, the reality is that by increasing peak irradiance for a UV LED lamp head, a comparable increase in energy density also occurs. This is demonstrated by the 8 separate profiles in Figure Six which show how increases in irradiance from the same lamp head produce proportional increases in energy density (area under the curve) as one gravitates from the lowest peak profile (1) vertically up through the highest peak profile (8).

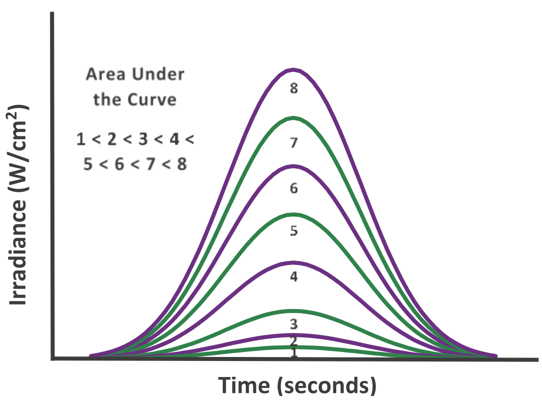

Figure Six: Profiles of one UV LED system at eight different peak irradiance levels.

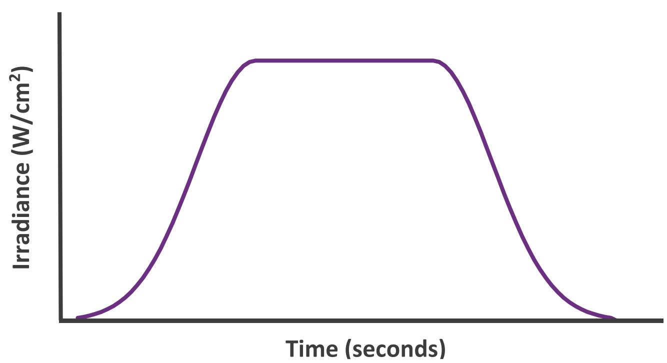

Figure Seven: Profile of a UV LED system with a wider emitting window compared to the profiles of Figures 4, 5, and 6.

In recent years, chemistry for many applications has been sufficiently optimized for UV LED output such that a lower minimum irradiance threshold is now feasible provided a suitable level of energy density is also delivered for the intended run speed. Despite this fact, system suppliers, formulators, OEMs, and end users are still focused on increasing peak irradiance. This fails to capitalize on the unique ability of UV LED technology to optimally deliver the required peak irradiance, energy density, and wavelength combination through different product designs and the fact that energy density can be increased in ways other than driving a higher irradiance.

As UV LED technology moves into applications that require greater energy density (higher-power) for faster line speeds, emitting windows are growing in width in order to accommodate more diodes and provide greater total exposure for the cure surface. Figure 7 highlights the trend toward UV LED curing systems that incorporate an increasingly wider emitting window. Maintaining the peak irradiance over a longer exposure window naturally produces greater energy density and avoids some of the negative trappings associated with increasingly higher irradiance levels.

Practical Implications of Irradiance

A minimum level of irradiance at the cure surface is essential for creating free radicals and enabling the photopolymerization process. As illustrated in the previous section, increasing the irradiance emitted from the same or similarly designed lamp head produces a comparable increase in emitted energy density. More energy density gives operators the option of generating more crosslinking at slower run speeds or running at faster line speeds.

A higher irradiance benefits the photopolymerization process by countering oxygen inhibition at the cure surface and providing greater through cure for thicker and more heavily pigmented formulations. Because irradiance decreases with distance traveled, a higher peak irradiance at the emitting window is advantageous for delivering more irradiance to the cure surface when larger working distances exist.

Mathematically, the inverse square law stipulates that irradiance is inversely proportional to the square of the distance from the emitting source. In layman's terms, this means that rays of light quickly diverge from one another as they travel away from their point of origin. The result is significantly lower irradiance values at the cure surface when large working distances are involved. From the inverse square law, if the irradiance at one location is known, then the irradiance at a second location can be calculated using the following equation:

$$\text{Irradiance}_2 = \frac{\text{Irradiance}_1 \cdot (\text{Distance}_1)^2}{(\text{Distance}_2)^2}$$

At very close working distances, UV LED systems do not closely follow the inverse square law. This is because a line of diodes or a matrix of diodes represent numerous point sources and not a single point source as stipulated by the inverse square law. At a certain offset distance from a UV LED product's emitting window, the discrete output from each of the LEDs in an assembly uniformly blends. It is at this location where the origin of the source as defined by the inverse square law exists. While the offset distance varies by product, it is generally between 5 and 15 mm depending on diode spacing and use of optics.

In order to illustrate how rapidly irradiance decreases with working distance, the output from a hypothetical UV LED curing system with diodes arranged in a matrix pattern without optics was plotted using the inverse square law. The lamp was assumed to measure 20 Watts/cm^2 at a location 5 mm (0.2 inches) from the emitting window. A plot of the lamp head's decreasing irradiance at working distances between 5 (0.2 inches) and 100 mm (4 inches) is provided in Figure Eight. The difficulty in maintaining UV LED irradiance at large working distances is one of the reasons that UV LED application development originated in web, sheet, and flat part applications where the cure surface could be easily positioned within 15 mm (1/2 inch) of the emitting window.

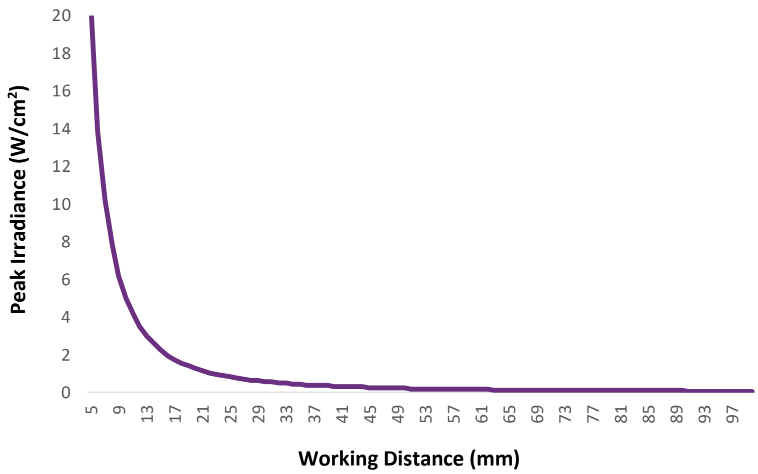

Figure Eight: Relationship between irradiance and working distance using the inverse square law.

Optics, reflectors, mirrors, and collars are often integrated into UV LED lamp heads to circumvent the inverse square law by collimating or containing the light spread. Specific reasons for incorporating optics include producing a slightly higher irradiance without utilizing more supply power, maintaining a greater irradiance over larger working distances, and preventing stray UV light from reaching unintended surfaces. Simple illustrations of common optical enhancements are provided in Figure Nine.

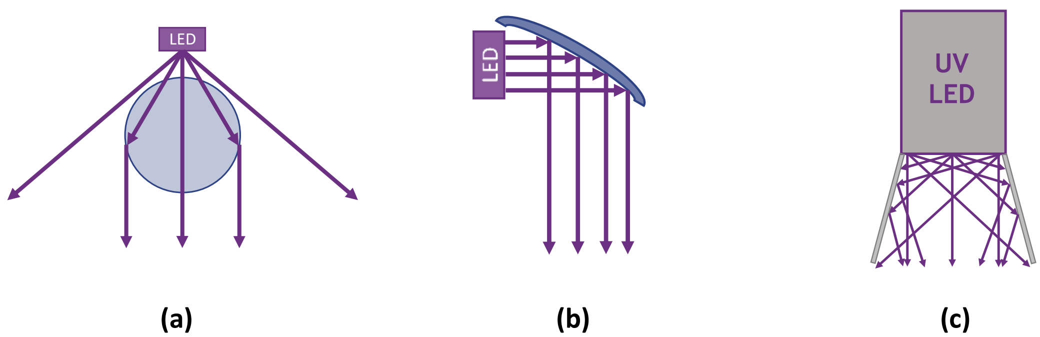

Figure Nine: (a) rod lens optics, (b) reflectors and mirrors, and (c) collars are often integrated into UV LED lamp head assemblies to direct or contain output.

It should be noted that excessively high-irradiance is not always preferred. Too high of an irradiance at the cure surface can result in diminishing returns to cure as it has the tendency to create too many polymerization chains that terminate prematurely and diminish final cure properties. Operating at a higher irradiance can also stress the diodes and decrease system life. Finally, greater irradiance leads to a greater concentration of UV light which transfers more heat to the substrate, construction, or part. This can be very problematic for heat sensitive materials particularly at slower run speeds and close working distances. High-irradiance UV LED curing systems are essential for certain applications; however, opting for a high-irradiance source when not necessitated by the needs of the formulation and set-up can be detrimental to cure or simply a waste of energy.

Survey of Commercial UV LED Systems
Commercially available information was analyzed for 62 different UV LED lamp heads from 11 different system suppliers. Of the 62 lamp heads, 53 were specifically promoted as ***high-power*** offerings. None of the 11 suppliers promoting products as high-power or any of the various other adjectives listed on page one defined what was meant by the claim. The interpretation is left entirely to the prospective user. For simplicity and to avoid redundancy, systems available in multiple wavelengths, irradiance levels, and lengths were counted only once in the analysis. Whenever possible, information was documented for the highest irradiance system in each model at 395 nm. In some cases, information for 385 nm products was used when 395 nm was not offered.

The most common perspective in the industry is that high-power means high-irradiance as opposed to high-energy density. This is because high-irradiance has been the single most promoted metric for UV LED curing during the past 15 years, and energy density is not generally specified on product data sheets. If high-power means high-irradiance, then clearly the industry is not in agreement regarding the magnitude of high-irradiance as the surveyed products ranged from 4 to 50 Watts/cm^2 with the most numerous being 16 Watts/cm^2. Figure Ten is a graph illustrating the peak irradiance distribution of 56 out of the 62 high-power UV LED products surveyed. It should be noted that 6 products in the sample were excluded from the bar chart. While all 6 were advertised as high-power, a peak irradiance value was not provided on the respective website or product brochure.

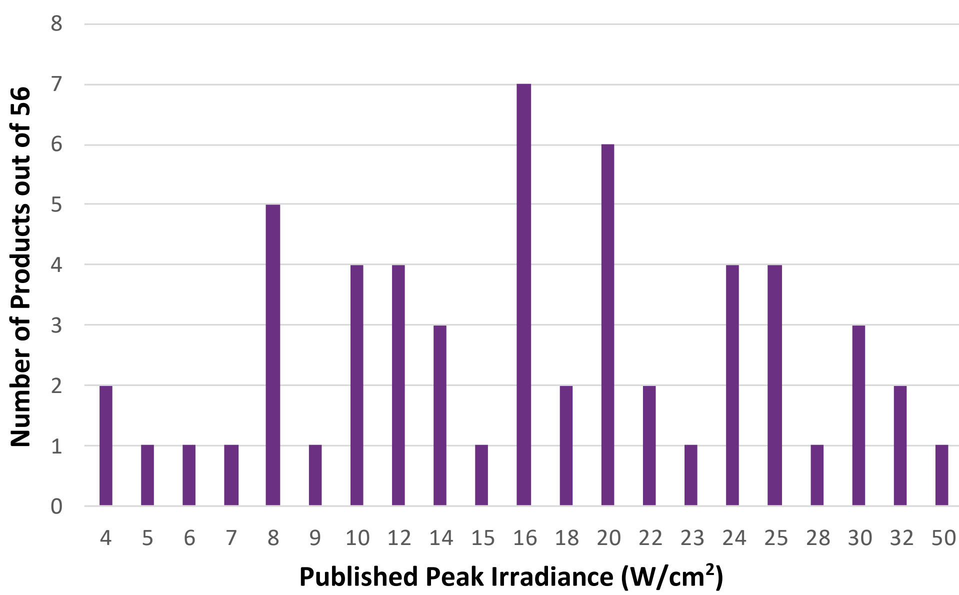

Figure Ten: Distribution of peak irradiance levels for 56 UV LED products promoted as high-power.

A likely reason for the drastic range in values in Figure Ten is that companies are using the term high-power to make a relative comparison to an earlier product offering from the same company and not to all industry offerings or specific applications. This is further distorted when subsequent products are released at even higher-output levels and earlier documentation for older and now lower-output models by comparison is not updated. All this does is render the term high-power meaningless when it is not clearly defined and backed-up with specific numerical values or given suitable context by noting the intended application and respective line speed, energy density, and integration configuration.

The table in Figure Eleven summarizes the commercially available information for all 62 LED lamp heads in the study while the table in Figure Twelve summarizes the range of values for each category evaluated. It should be noted that only commercially available information was used. As a result, this was not a fully comprehensive study as many companies in the industry do not publish this essential information.

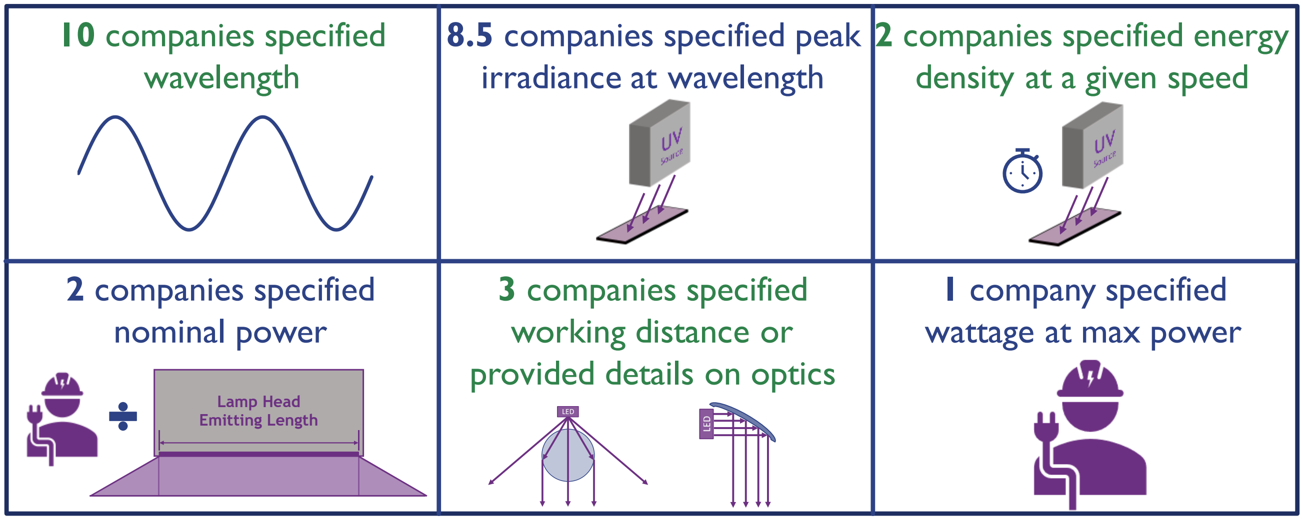

Figure Eleven: Statistics for 62 different UV LED lamp heads available from 11 different system suppliers.

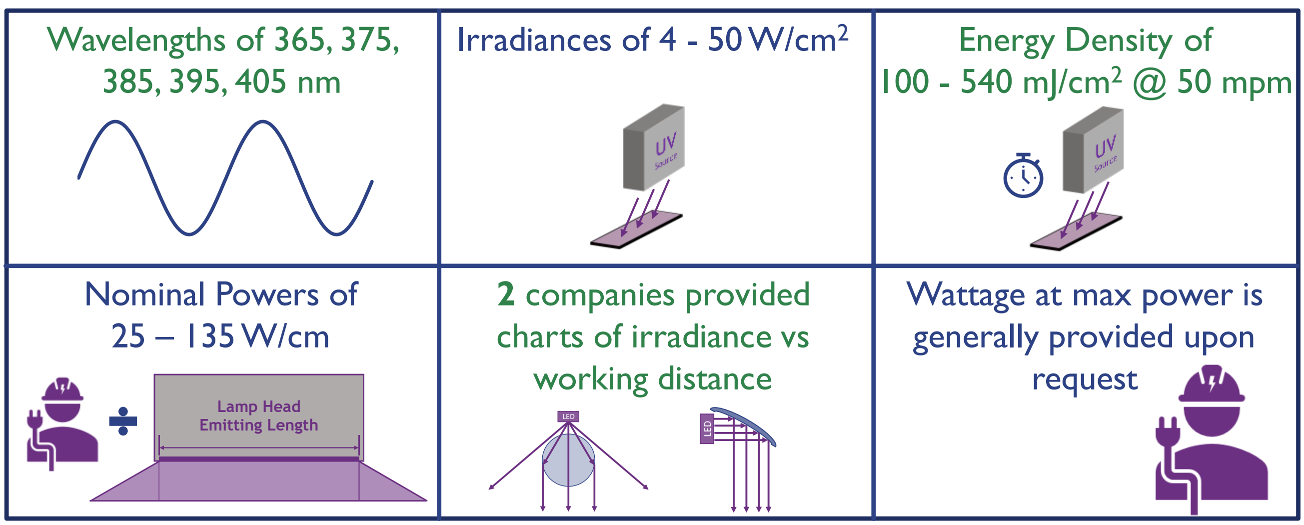

Figure Twelve: Range of values for 62 different UV LED lamp heads from 11 different system suppliers.

While wavelength and peak irradiance are the two most referenced metrics, 1 company out of 11 elected not to publish the wavelength(s) being used. Despite the critical role that energy density plays in run speed, only 2 companies out of 11 referenced a value at a given line speed, and only 1 of those 2 companies specified the radiometer that was used for the measurement. Regarding peak irradiance, 8 out of 11 companies specified values at the emitting window or at a specified offset distance. A ninth company specified the peak irradiance for roughly half its products, which is why the rating in the table is 8.5. Omitting a peak irradiance specification tends to occur when companies intentionally design their

UV LED products at a peak irradiance they believe is suitable for an intended market and application but at a magnitude that is lower than comparable products. To avoid being excluded by OEMs and end users based on published data alone, companies engineering lower peak irradiance products are purposefully not publishing the values. Instead, companies should be helping the market understand the role of the various parameters in driving the desired cure.

While nominal power, which is power (Watts) drawn from the electrical supply during operation divided by the length of the emitting window (cm or in), is ineffective for comparing conventional mercury lamps to UV LED lamps, it can provide valuable insight when comparing UV LED systems to each other. Unfortunately, only 2 of the 11 companies referenced nominal power in their documentation for a grand total of 5 out of 63 products. Whenever two systems are marketed at the same peak irradiance level, the system with the greater nominal power will tend to have the greater energy density. Although nominal power does not account for diode packaging inefficiencies, cooling performance, or the use of optics in the lamp heads being compared, it is the best predictor of energy density when the actual value is unknown. Fortunately, nominal power is easy to calculate when not specifically stated. All that is needed is the wattage drawn by the UV LED system at maximum power and the length of the emitting window. While only 1 company out of the 11 listed the wattage at max power in its published materials, most companies will readily provide this information when asked. It should be noted that using the maximum available wattage of the actual power supply as opposed to the wattage drawn during operation will over-estimate the value for nominal power.

Hypothetical Product Comparison

Figure Thirteen presents technical specifications for three hypothetical UV LED curing products labeled A, B, and C. This three-way comparison is meant to highlight the disparity in performance data of UV LED market offerings and how a fully comprehensive set of data is necessary to properly source a curing system. Please note that while the specifications listed for the three fictitious products are plausible, all the information is fabricated. The purpose of this example is to demonstrate how to compare products and not to promote one company's technology over another.

Specification	Product A	Product B	Product C
1 – Cooling	Air	Liquid	Liquid
2 – Wavelength (nm)	395	385	395
3 – Emitting Window Dimensions	450 x 20 mm	450 x 50 mm	450 x 50 mm
4 – Emitting Window Type	Flat Glass	Flat Glass	Optical Enhancement
5 – Peak Irradiance (W/cm^2)	25	20	16
6 – Peak Irradiance (W/cm^2) @ 50 mm	1.4	2.5	6.7
7 – Energy Density (mJ/cm^2) @ 20 fpm (6 mpm) and 500 fpm (150 mpm)	1,280 (51.2)	2,035 (81.4)	3,868 (154.7)
8 – Wattage (W) Drawn at Max Power	2,925	4,650	8,840
9 – Nominal Power (W/cm)	65	103	196

Figure Thirteen: Technical specifications for a hypothetical, three-way, UV LED product comparison.

As detailed in the previous section, the information presented in lines 1 – 5 of the table is readily available from most UV LED system suppliers while the information in lines 6 – 9 is not typically provided. Using only lines 1 – 5, the three products appear somewhat similar. One minor difference is that two products are liquid-cooled while one is air-cooled. For most applications, 385 and 395 nm will perform comparably which makes wavelength a non-factor in this scenario. While the lamp heads are the same length (450 mm), one is 20 mm wide and two are 50 mm wide. Product C offers optical enhancement, but it is not known from the information in the first five lines what that entails and what impact it has on the product's emitting angle and working distance. The most noticeable difference is in the peak irradiance values which are 25, 20 and 16 Watts/cm^2 for products A, B, and C respectively.

Limited by the information in lines 1 – 5, a sourcing selection would come down to the decision maker's preferences on the parameters he or she understands as well as total system price and vendor relationships. It would most likely not be based on the performance of the UV LED system as it relates to the application requirements unless a trial had been conducted or a recommendation was made by the formulator. To be more specific, the decision would likely be influenced by an individual's personal inclinations on cooling type and wavelength and whether the 20 mm wide or 50 mm wide emitting windows would fit within the available lamp head space on the machine. If the decision maker had no leanings or limitations on these first three features, then the decision would ultimately rest on peak irradiance, and when the role that irradiance plays in photopolymerization is not sufficiently understood, human nature drives us toward the higher number. This would be product A at 25 Watts/cm^2. The optical enhancement would likely not factor into the decision because without more information, there is no way to understand the role it plays in curing, and people are rarely willing to pay for features they don't appreciate.

As the evaluation is expanded to include lines 6 – 9, the optimal UV LED system for the application starts to become more obvious. For example, if the application required cure at a 50 mm working distance as opposed to 5 mm and the required minimum irradiance for the formulation was 5 Watts/cm^2, then Product C would be the only viable choice. If instead, the minimum required irradiance at this working distance was 2 Watts/cm^2, then either Product B or C would be suitable with Product C offering a bit wider irradiance window. Product A, which had the greatest peak irradiance when working distance wasn't considered (25 Watts/cm^2) would fail to cure the intended formulation at 50 mm.

Line 7 details energy density at two run speeds (20 and 500 fpm / 6 and 150 mpm). Whenever energy density is known for one linear process speed, it can be extrapolated for any other speed. As a result, Line 7 allows the decision maker to coordinate with the formulator to determine which product or products will cure at the desired machine speed. If 75 mJ/cm^2 was required at a speed of 500 fpm (150 mpm), then both products B and C would suffice; however, if 120 mJ/cm^2 was needed, then only Product C is viable. If the end user had previously purchased and installed product A only to determine that cure was not achievable at 500 fpm, then the only options would be to 1) run production at a slower speed, 2) subject the cure surface to multiple passes underneath the current UV LED source or another off-line source, 3) add additional UV LED lamp heads in series assuming there is available space, or 4) replace Product A with Product B or C based on the energy density value required by the formulation at the desired run speed.

If the UV LED supplier is unwilling or unable to provide an energy density value at a given speed, then there are two alternative methods of estimating performance. One relies on wattage drawn at maximum output and the other is nominal power. For systems of identical or very similar peak irradiance values (16 to 25 Watts/cm^2 in this scenario) and lengths (450 mm in this scenario), the wattage required to run the UV LED systems at 100% output provides insight into their respective energy densities. Since supply wattage is utilized to drive irradiance and energy density, for systems of similar irradiance and length, the higher wattage value will result in a greater energy density value. While it is not possible to calculate energy density based on supply wattage, it does allow the three products to be ranked in order of increasing energy density. For example, it is reasonable to conclude that 2,925 Watts (Product A); 4,650 Watts (Product B); and 8,840 Watts (Product C) would result in Product C having the greatest energy density followed by Product B and then A.

Nominal power offers the same insight with the added benefit that it eliminates the variable of lamp head length. For example, it is reasonable to conclude that 65 Watts/cm (Product A); 103 Watts/cm (Product B); and 196 Watts/cm (Product C) for these three items of similar irradiance would also result in Product C having the greatest energy density followed by Product B and then A. It should be noted that since the irradiance values for the three lamp heads are not equal, the maximum wattage and nominal power methods of ranking energy density provide only a reasonable but educated guess. That said, it is better than not considering energy density at all.

Line 8 also provides clarity on energy consumption. For these three products of similar peak irradiance and head length, the wattage drawn at maximum power is an indicator of how the systems rank in terms of energy consumption. If all three products were determined to be technically suitable for the intended application, then Product A might be the wiser choice since it requires the least power to run (2,925 Watts) compared to Product B (4,650 Watts) and Product C (8,840 Watts). It may be possible to turn down the power of Product B or C to reduce running costs; however, this would not eliminate the higher initial investment and may result in the irradiance falling to an insufficient level. This is a great example of Product C being the higher-power system of the three as well as the consequential trade-offs that power creates. In other words, product C has the greatest energy density (highest power), but if all three systems are viable options for the application under consideration, going with Product C would typically result in larger than necessary investment and running costs.

Concluding Comments on High-Power UV LED Systems

A wide range of UV LED systems are necessary to meet the diverse needs of all curing applications; however, UV LED system suppliers are not providing enough information for users to make informed purchasing and development decisions. Lack of technical data on product spec sheets makes it difficult for formulators, end uses, and OEMs to effectively source UV LED technology, drive innovation, advance adoption, and troubleshoot insufficient cure. As a result, the onus is on customers and co-suppliers to request the necessary information from LED suppliers and get clarification on what is meant by ***high-power***. High-power systems definitely have a place in UV curing and should be used when necessitated by application needs and production set-up; however, systems that generate more output than required will likely lead to unnecessarily larger investment and running costs along with potentially greater scrap and shorter LED life.

Without adequate technical specifications, the only option for formulators, machine builders, and end users is to borrow or purchase multiple UV LED systems for personal evaluation in head-to-head trials. This can be incredibly time consuming, especially for rapidly evolving technology. Unfortunately, in today’s LED curing market, lab and field product comparisons are generally an unavoidable exercise since without a complete set of specifications, UV LED systems cannot be thoroughly compared, judiciously selected, and properly integrated for the application, process set-up, and formulations being considered.

As stated, formulation requirements, run speed, and working distance are the primary drivers of the spectral output, irradiance, and energy density that must be delivered to the cure surface for suitable polymerization. Consequently, wavelength, peak irradiance at a known location, and energy density at a defined line speed should be specified by UV LED system manufacturers for each product offered along with applicable measurement conditions. Additionally, wattage drawn at full power, nominal power, variation in irradiance with working distance, and the impact of integrated optics on beam angle provide deeper insight into a product's potential curing performance and should also be included.

It is this author's position that ***high-power*** means ***high-energy density*** (not high-irradiance), and low-power means low-energy density (not low-irradiance). Greater energy density delivered above the minimum irradiance threshold is what enables manufacturing lines to run at faster production speeds or to produce better cure at slower speeds. It is equally acceptable to use the terms high-energy density and low-energy density as well as high-dose and low-dose in place of high-power and low-power. It should be noted that regardless of terminology, energy density needs are not absolute and are always relative to each specific application. For added clarification, when referring to peak intensity, high-irradiance or low-irradiance as well as high-intensity and low-intensity are the preferable qualifiers while high and low-output are more general terms that can mean irradiance, energy density, or both.

The applicable marketing terms for UV LED output are grouped in three boxes in Figure Fourteen. All words within each box are interchangeable with each other; however, their use is only significant when given suitable application context and quantified. Without context and supporting data, these commonly used promotional terms are rendered meaningless and only serve to confuse and disappoint users when products do not perform as expected.

High-Energy Density	High-Irradiance	High-Output
High-Power	High-Intensity	High-Energy Density (Dose) or High-Irradiance (Intensity)
High-Dose	High-Penetration	High-Energy Density (Dose) and High-Irradiance (Intensity)
High-Speed	High-Working Distance	High-Penetration
High-Productivity	Integrated Optics	Integrated Optics / High-WD
High-Nominal Power		High-Speed / High-Productivity
High-DC Wattage		

Figure Fourteen: Promotional terms grouped within each color-coded box are interchangeable; however, their use is only meaningful when given suitable application context and quantified. High-Energy Density and High-Irradiance are preferred. High-Output is not specific.

One of the greatest benefits of UV LED technology is that it enables systems engineers, within technical limitations, to purposefully and independently select the peak irradiance, energy density, and wavelength for each product being designed. The result is a much larger number of permutations than is possible with conventional curing technology where these three parameters are much more closely aligned with each other and limited by the physics of vaporized mercury. The trade-off of having so many design options is that product diversity creates significant industry confusion when specifications aren't clearly communicated, fully understood, and universally applied.

Ideally, matching the optimal UV output in terms of wavelength, irradiance, and energy density to the needs of the application and integration set-up allows UV LED curing processes to be much more efficient and environmentally friendly than conventional mercury-based technology. As UV LED technology continues to evolve and systems are increasingly designed with specific applications in mind, realization of even greater manufacturing efficiency and energy savings will be achieved. To get to this point, however, suppliers need to be much more transparent with the technical performance of the products they are promoting. This can be accomplished by providing complete sets of UV LED specifications as outlined in this paper to formulators, OEMs, and end users and avoiding the use of misleading terminology that is not supported with data and application context.