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Recommendations for Adapting the TV Policy Approach for Computer Monitors and Digital Signage Displays

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Executive Summary

Background

This report was prepared by Pacific Crest Labs with funding support from the Northwest Energy Efficiency Alliance (NEEA). Findings and recommendations reflect the analysis conducted for this study and are intended to inform stakeholder discussion on the design of energy-efficiency policy for computer monitors and digital signage displays (DSDs). It extends an existing regulatory and testing framework, originally developed for televisions, to arrive at a unified approach to regulating all three display types under common test methods and metrics.

Why This Matters

The global computer monitor market is large and heterogeneous, with around 130 to 160 million units sold annually across consumer, business, gaming, and professional segments.[1] Most units are relatively affordable 21-inch–27-inch (diagonal; 53 cm–69 cm) models at Full High Definition (FHD) or Quad High Definition (QHD) resolution for personal and office use. However, fast-growing gaming and professional/creative niches favor larger 27-inch–34-inch (69 cm–86 cm) screens, have higher resolutions (up to 5K), and have notably higher prices. Digital signage is a higher-value market and is growing. While commercial monitors and single DSDs sell in the tens of millions of units, video walls (Direct View light emitting diodes (DVLED), tiled liquid crystal displays (LCD), and rear projection) are sold in hundreds of thousands of cabinets or square meters. These have very large screen areas, custom or 4K resolutions, and prices ranging from thousands to tens of thousands of dollars per installation.

Given their large and growing sales volumes, increasing screen sizes, high luminance; and long operating hours across homes, offices, and public spaces, computer monitors and DSDs represent a sizeable share of electronic display electricity demand, making them a priority for cost-effective energy efficiency policy measures.

This assessment estimates that electronic displays—televisions, computer monitors, LCD digital signage, and DVLED video walls—consume approximately 582 TWh per year globally (about 2% of global electricity) and 76 TWh per year in the EU. Long-term achievable savings from targeted efficiency and standby policies are estimated at 63 TWh per year globally (11%) and 16 TWh per year in the EU (21%), representing \$7.5 billion and \$4.5 billion in annual electricity cost savings, respectively, with corresponding CO_2 reductions of 31 Mt and 4 Mt per year. Table 1 and Table 2 summarize savings potential by product category.

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[1] See section MARKETS AND TECHNOLOGIES for the detailed data.

Global Long-Term Savings by Category and Mode

Table 1: Global long-term savings

Product Category	Current (TWh/a)	Active (TWh/a)	Non-Active (TWh/a)	Total (TWh/a)	Savings %	($B/a)	(Mt CO_2e)
Televisions	410	32.6	16.8	49.4	12%	5.9	24.4
Computer Monitors	62	4.7	0.0	4.7	8%	0.6	2.3
Indoor LCD Signage	14	1.2	0.0	1.2	8%	0.1	0.6
Outdoor LCD Signage	5	0.4	0.0	0.4	8%	0.1	0.2
Indoor DVLED Signage	16	0.0	2.6	2.6	16%	0.3	1.3
Outdoor DVLED Signage	75	0.0	4.5	4.5	6%	0.5	2.2
GLOBAL TOTAL	582	38.9	23.9	62.8	11%	7.5	31.0
Share of Total		*62%*	*38%*				

EU Long-Term Savings by Category and Mode

Table 2: EU long-term savings

Product Category	Current (TWh/a)	Active (TWh/a)	Non-Active (TWh/a)	Total (TWh/a)	Savings %	($B/a)	(Mt CO_2e)
Televisions	51	3.4	10.1	13.5	26%	3.8	3.4
Computer Monitors	9	0.7	0.0	0.7	8%	0.2	0.2
Indoor LCD Signage	2	0.2	0.0	0.2	8%	0.0	0.0
Outdoor LCD Signage	1	0.1	0.0	0.1	8%	0.0	0.0
Indoor DVLED Signage	3	0.0	0.5	0.5	18%	0.1	0.1
Outdoor DVLED Signage	10	0.0	1.1	1.1	11%	0.3	0.3
EU TOTAL	76	4.4	11.7	16.1	21%	4.5	4.0
Share of Total		*27%*	*73%*				

Savings fall into two categories with different policy timelines. Non-Active Mode savings—from eliminating smart wake standby penalties in televisions and implementing true standby in DVLED systems—are largely achievable within a few years of setting initial power limits. Active Mode savings—from efficiency improvements in LCD-based displays—require a longer timeframe, achievable after data collection and supply chain response to initial policy measures. The EU shows a higher share of Non-Active Mode savings (73%) compared to global (38%) due to greater smart wake feature penetration in European televisions.

Note that Active Mode savings represent avoided consumption at equivalent luminance levels. If future displays are set brighter than today's, absolute consumption reductions may be smaller—though such displays would still be more efficient than those without these policies.

Across both computer monitors and DSDs, power demand is shaped not only by headline specifications like resolution and screen size but also by their underlying light source technology and how it is controlled by the device in real use. Basic LCD screens with edge-lit or direct-lit backlights dominate shipping volumes, while new self-lit (emissive) displays such as Organic Light-Emitting Diode (OLED) computer monitors and Direct View LED (DVLED) signage displays are gaining market share.

Although emissive displays can be intrinsically efficient for darker scenes with bright highlights, their often large display sizes and dense pixel layouts can still result in substantial power use. For both LCD and emissive display types, local, dynamic light source control can deliver more light per unit of power (greater efficiency). In contrast, high luminance settings, long duty cycles, and additional capabilities (e.g., integrated operating systems, touchscreens, and decorative lighting) add to power demand, often in both Active and Non-Active modes.

For computer monitors, gaming and professional models tend to combine bright panels with high refresh rates (for better motion rendering), advanced picture processing and richer color settings (wide color gamut), which improve performance while increasing processing load and power demand. For signage, large-area DVLED and tiled LCD video walls and outdoor or window-facing displays combine extreme brightness with additional control electronics.

To determine the best approach to extending existing TV regulatory and testing frameworks to computer monitors and DSDs, it is first necessary to understand the context of the existing policy measures. Historically, international test methods have measured power during playback of a standard dynamic broadcast test clip without an effective means to measure luminance. The current European Ecodesign and Energy Label regulations measure screen center luminance in default settings using a test pattern with a spot photometer (light meter) at a single point. This approach rewards non-uniform screens with bright centers. It can also be gamed by manufacturers who may ship TVs with unrealistically low default luminance that consumers can subsequently override, which can diminish anticipated savings.

In contrast, ENERGY STAR® V9 for TVs first adopted the screen-average luminance-based approach in 2022, and the U.S. Department of Energy adopted a new TV test method in 2023 (ANSI/CTA-2037-D), also based on this approach. This approach involves simultaneous measurement of power and luminance using a camera photometer to measure average luminance across the whole screen. Luminance is incorporated directly into the metric. The fundamental Active and Non-Active Mode methods represented in ANSI/CTA-2037-D are being incorporated in the international TV testing standard IEC 62087-3, Edition 3, scheduled for publication in 2026.

A key purpose of this study is to examine how the dynamic-luminance-centered approach can be expanded from televisions to computer monitors and DSDs. Testing combined with dataset analysis indicates how these metrics can be adapted for these display categories. Features identified as particularly important for Active Mode efficiency include panel technology (e.g., LCD, OLED, DVLED), dynamic light source dimming in response to picture content (local and global), color gamut capabilities, image contrast ratio, and refresh rate. In addition, the influence of features such as touchscreen controllers, USB charging, and RGB lighting are evaluated.

Further, Non-Active Modes such as Network Standby, Smart Standby,[2] and Standby with Hands-Free Wake[3] are only partially covered in current policy despite their growing share of lifetime electricity use. In addition, many DVLED cabinet-based systems do not implement true standby modes, instead maintaining internal electronics in an energized state while displaying a black screen. Therefore, evidence is also provided to support refined regulatory approaches for these modes.

What Is Proposed

The report concludes with recommendations on scope, test method, and metrics for computer monitors, DSDs, and televisions, including clarifications for setting up the unit being tested, refinements to the dynamic luminance measurement approach, and proposals to better account for the influence of additional features on power demand in non-Active and feature-enabled states. While the focus of this research is computer monitors and DSDs, this report includes several TV policy recommendations that build on earlier TV policy work in pursuit of a unified approach that harmonizes display policies that currently differ by display class and region.

Regarding scope, this proposal recommends that (with some exceptions noted) all display types be addressed by Minimum Energy Performance Standards (MEPS). In evaluating scope, this proposal considers several levels of potential product coverage; products may be out of scope (not included in the policy), or in scope under one of three escalating policy levels:

- **Information Reporting:** Testing and reporting requirements for data collection
- **Label:** Coverage by an energy label that communicates efficiency information to consumers, in addition to information reporting
- **MEPS:** Minimum Energy Performance Standards, which would also include energy labeling and information reporting obligations

The proposal's emphasis on Active Mode information reporting for some product classes reflects the diversity and rapid evolution of these products, as well as the need for broader data collection to support the future development of MEPS levels.

Battery-operated displays and outdoor/semi-outdoor DSDs are included in scope, in contrast with some current policy approaches that exclude such products. However, for certain product subtypes, Active Mode information reporting is recommended rather than MEPS, to allow data collection before setting efficiency limits. These include transparent OLEDs, DVLED video walls, and outdoor LCD signage. For outdoor LCD, engineering differences—including thermal management systems and optical losses from protective enclosures—make it premature to apply indoor-derived Active Mode limits; Non-Active Mode MEPS would still apply. Full exclusions from scope are recommended for standalone projectors (pending a suitable test method), integrated displays (such as automotive and portable console displays), medical displays, studio mastering displays, and displays for other very niche markets. It should be noted that

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[2] E.g., with wake via Chromecast, wake via smart speaker like Amazon Alexa, or wake via a remote-control smartphone app

[3] E.g., via voice activation, gesture recognition, or presence detection

some product categories can span multiple high-level classes (e.g., a security display can be a monitor or a DSD).

Displays above approximately 15.5 in^2 (~100 cm^2) of screen area are recommended for scope inclusion, in line with existing European rules. No upper bound on pixel density is proposed. Peak luminance is within scope up to 10,000 cd/m^2, reflecting the capabilities of modern high-brightness DSDs and the range of measurement that is possible in testing.

Recognizing the ongoing debate about which metrics best suit regional needs, this report provides guidance on the factors to consider when developing metrics and limits and offers an example set of metrics and limits to frame the discussion about these topics.

As the proposed test method measures power and screen-average luminance concurrently, it enables the use of luminance-based efficiency metrics that provide incentives to design displays that use less power across the full range of supported luminance levels. In addition to adapting methods, such as the distance at which luminance is measured, this study has shown that camera photometer systems can be used to measure screen-average luminance of ultra-wide curved computer monitors and bright outdoor displays.

Active Mode

In Active Mode, most display technologies draw more power as their light source setting (LSS) is adjusted to increase brightness. The relationship between power and luminance is typically linear, with a baseline level of power remaining when luminance is reduced to zero. This reflects power use of electronics that remain active when the display light source is off. To illustrate this relationship, “dimming line” plots are used in this report, which show power versus luminance for different displays across a range of light source settings. Once dimming lines are available for a sufficient number of displays, a limit equation can be developed for an Active Mode luminance-based metric. This metric would account for screen-average luminance, screen area, and resolution.

Some displays (or picture settings within a display) are tuned for use in bright indoor settings, like commercial offices or sunlit living rooms, while others are tuned for rooms with low ambient light levels, like home theaters. This picture quality tuning, or signal-to-light mapping, can significantly affect the relationship between power and luminance. Assuming that higher luminance per watt indicates higher efficiency for a given screen size, then displays tuned for bright ambient environments operate more efficiently than displays tuned for dark ambient environments. One of the risks associated with this policy approach is that makers of basic LCDs can change their signal-to-light mapping to achieve a better efficiency score by lifting midtones and shadow detail—in extreme cases, resulting in washed-out images—and consumers who use the display in a dark setting change the picture setting to attain optimal picture quality, defeating claimed savings. As explained in this study, this unintended consequence is primarily associated with basic LCD TVs, not with more advanced TVs that scale power to luminance.

On the other hand, this research suggests that ample opportunities exist to appropriately shift signal-to-light mapping and optimize dynamic light source control for basic LCDs to lead to improved energy efficiency with no degradation of picture quality. The risk of unintended shifts in signal-to-light mapping is low if near-term Active Mode MEPS levels are set to modest levels.

The general screen-average luminance-based metrics approach is technology-agnostic and is designed to reward more efficient components and effective power scaling, including the use of local backlight control. It places comparable performance pressure on large and small LCDs regardless of resolution, and the same underlying framework can be applied consistently to both SDR and HDR content. By remaining technology-neutral, the approach encourages adoption of more efficient display technologies without prescribing specific solutions or disproportionately disadvantaging lower-cost products. This helps preserve a range of price points in the market while still applying incremental efficiency pressure to less-efficient display types over time, such as basic LCDs.

This report explains the fundamental principles that underpin the screen-average luminance-based policy approach (methods and metrics) in section KEY CONCEPTS AND CORE PRINCIPLES. This research uses a set of TV metrics and "limits" developed by PCL with the support of NEEA in 2024 as a benchmark for making relative efficiency comparison in the energy efficiency driver assessment. In section EFFICIENCY DRIVER ASSESSMENT, these lines are referred to as reference lines rather than limits, because they are not proposed regulatory limits but are used solely as a means of relative comparison between products and technologies.

Finally, section POLICY RECOMMENDATIONS goes beyond the 2024 light efficiency metrics to piece together a 2025 comprehensive example policy approach to include metrics, limits, and test sequence as they relate to MEPS and energy labels. This analysis includes thoughts about unit energy consumption and savings calculation approaches. This example has many moving parts; it is offered to help policymakers and other stakeholders to assemble alternative policy approaches that may or may not use elements of the example provided. This proposal includes a discussion of factors to consider when developing alternative policy approaches based on light efficiency metrics and new standby modes.

The 2025 example limit lines are based on 2024 proposed TV limits. They are structured so that the vast majority of displays pass (i.e., the default backlight test point for most displays would fall below the limit line). Conceptually, these limit lines were developed by identifying the average slope and intercept of TVs and then multiplying the line by a scaling factor to increase or decrease the pass rate:

Equation 1: Basic limit line equation

$$Limit\ Line = Scaling\ Factor * (m * x + b)$$

Where:

- m is the average dimming line slope
- x is a given luminance, also referred to as the grading point
- b is the average dimming line y-intercept for displays of a fixed screen area and resolution (e.g., 75" (191 cm) 4K displays)

If the limit line is set to the average slope and intercept, about half the displays pass. The scaling factor is chosen as a baseline against which to compare DSDs and computer monitors. It ensures a limit line that achieves TV pass rates of about 77% based on the current California dataset.

A limited set of Active Mode adders is included in this example for features such as contrast ratio and refresh rate for which PCL's analysis suggests they have a material impact on energy use. Example adders are listed in Table 3 below.

Table 3: Example recommended power adders

Category	Adder Amount
All Display Types in Scope	
Touchscreen setting	1 W [1]
Touchscreen technology type	TBD [2]
Computer Monitors Only	
Contrast ratio	2% per 1,000:1 increase in contrast ratio up to a 15% total
Screen curvature	7% [3]
Native refresh rate	0.04% per hertz over 60Hz
Maximum refresh rate	0.03% per hertz over 60Hz
Software-based Variable Refresh Rate supported	6%
Hardware-based Variable Refresh Rate supported	14%

[1] Only if touchscreen is enabled by default and therefore enabled during the test.
[2] More data needs to be collected about the energy efficiency performance of different touchscreen technologies to determine an appropriate adder as it is expected that some of them (particularly Projected Capacitive (PCAP)) may lead to a reduction in luminance emission.
[3] For flexible screens that can curve, only if the screen is curved by default in Active Mode and therefore curved during the test.

Section 1.1.1.37: ACTIVE MODE includes the full details of the 2025 example metrics and limit lines.

Given uncertainties around signal-to-light mapping and the risk that overly stringent limits could incentivize changes to image processing that lift midtones and shadow details, initial MEPS levels are recommended to be modest and relatively easy to meet for all product classes. This staged approach is intended to create early incentives for hardware and system-level improvements, while providing policymakers time to collect data and understand how the supply chain responds to the clear efficiency signals associated with this new policy approach. If component and operating system vendors advertise significant efficiency improvements with no loss or repositioning of picture quality, tougher limits would be warranted in future policy tiers.

Non-Active Mode

The example metrics for Non-Active Mode (as shown in Table 4) offer a simple approach to limiting Non-Active Mode energy consumption. A 0.5 W–1 W cap is applied across the main Non-Active Modes. A higher limit is specified only for hands-free-wake standby, reflecting the additional continuous power needed by best-in-class implementations today.

Table 4: Proposed metrics for Non-Active Mode

Non-Active Mode	Required function	MEPS
D3cold [1]	Reactivation by power button or remote control	≤ 0.5 W (Computer monitors)
D3hot [1] [2]	Input signal reactivation	≤ 0.5 W (Computer monitors)
Standby [3]	Reactivation	≤ 0.5 W (All in-scope display classes except DVLED cabinets) ≤ 4 W (DVLED cabinets) [6]
Networked Standby [3]	Network reactivation	≤ 1 W
Smart Standby [3] [4]	As many of the specified smart standby functions as possible [4]	≤ 1 W
Hands-free Wake [3] [5]	As many of the specified hands-free wake functions as possible	≤ 6 W

[1] For computer monitors only.

[2] When supported, computer monitors should be tested in the Non-Active Mode subtypes that include additional functions, using D3hot as the starting point. For example, if the monitor supports Smart Standby features, those features should be enabled when the monitor is in the D3hot power state, and the corresponding Non-Active Mode test (Smart Standby) should be performed.

[3] For TVs and DSDs where supported. For video walls, this limit applies at the LCD tile or DVLED cabinet level where applicable.

[4] The Smart Standby test is conducted in networked standby with additional Smart Wake features enabled. In this test, as many Smart Standby sub-functions as possible should be activated: reactivation, networked reactivation, wake-by-remote-control-app, wake-on-cast, wake-by-smart-speaker, and Bluetooth speaker link maintenance.

[5] In this test, as many hands-free wake sub-functions as possible should be enabled: voice activation, gesture recognition, presence detection, mobile-device proximity.

[6] In the case of Direct View LED (DVLED) cabinets, the reactivation function is typically provided by an external control box.

Conclusion

PCL’s analysis confirms the substantial long-term energy savings potential quantified in this report—63 TWh per year globally and 16 TWh per year in the EU. Standby-related savings from televisions and DVLED systems can largely be captured within a few years of setting initial limits, while active-mode efficiency gains will follow as the supply chain responds to clear policy signals.

The proposed framework is intended to provide policymakers with a coherent, evidence-based, and scalable approach for extending the light-efficiency policy paradigm from televisions to computer monitors and DSDs. It clarifies how product scope can be defined, which operating modes and metrics would be regulated, and how implementation could be phased over time. In addition, it highlights key strategic decisions—such as the appropriate stringency of requirements, the timing and phasing of MEPS, and the use of adders to address functional complexity—that are essential to capturing the identified savings potential but will require further policy deliberation.

Introduction

Pacific Crest Labs (PCL), a US-based consulting firm specializing in long-term global research and policy for electronic displays, is conducting this study with funding from the Northwest Energy Efficiency Alliance (NEEA). **The goal of this study is to adapt the camera-based dynamic luminance test methodology, originally developed for televisions, to computer monitors and digital signage displays, and to update the TV policy approach in pursuit of a unified approach for all three display classes.** This will enable more representative assessment of display energy-efficiency and provide a robust technical basis for future policy developments aimed at reducing energy consumption and associated carbon emissions. In addition, policy harmonization will reduce stakeholder engagement and compliance burden.

The proposed framework is based on an Active Mode test method that measures the light output (luminance) experienced by a typical viewer during broadcast video playback. Active Mode compliance is determined against power limits that are a function of the measured luminance. It also includes updated and more representative Non-Active Mode test methods and metrics. The proposed unified displays policy framework defines a policy approach rather than prescribing every detail, allowing flexibility in test sequence implementation. Where detailed policy options are discussed, alternative methodological approaches are presented to enable policymakers to select solutions suited to their regional context and regulatory objectives.

The relationship between power and luminance for a display is called its “dimming line,” the line that defines how much power the display will use at any given luminance, where luminance is the screen-average luminance averaged over the duration of the international standard broadcast test clip.

Using the extensive TV dataset collected by the California Energy Commission (CEC), average dimming lines can be determined for TV categories grouped by size and resolution. These average dimming lines allow comparison of the efficiency of a specific display relative to category averages at any luminance level. They can also be used as the basis for defining aspirational or mandatory power limits.

This framework, which includes a test method and a policy approach, incentivizes technologies that enhance light-emission management and power scaling, including:

- Power scaling through global or local dimming in LCD displays, or sub-pixel-level dimming in emissive display (e.g., OLED)
- Quantum dot technology
- Reflective polarizer films
- Light source, power supply and other hardware component efficiency improvements

Historically, international test methods have measured power during playback of a standard dynamic broadcast test clip without an effective means to measure luminance. Because efficiency is expressed in watts per unit of screen area, manufacturers can reduce default brightness to meet regulatory limits, while consumers often select brighter modes. This reduces the potential savings that can be achieved by regulatory measures.

The luminance-based efficiency approach carries certain risks. For example, excessive stringency in regulatory requirements could prompt manufacturers of basic LCD displays to increase luminance by brightening midtones and dark areas, producing washed-out images. Although user picture quality constraints make this outcome unlikely, to mitigate this risk PCL proposes initially modest Active Mode limits, targeting only small energy savings for new displays. Greater reductions could be pursued as manufacturers adopt technical solutions to achieve efficiency while preserving picture quality.

This study uses hypothetical TV limits that PCL developed with NEEA's support in 2024 as a benchmark to evaluate the relative efficiency of computer monitors and digital signage displays (DSDs) for the purpose of analyzing key energy efficiency drivers like local dimming. This analysis is used to recommend Active Mode adders. This study offers an updated policy approach that is broad enough to encompass TVs, computer monitors and DSDs. The proposed product scope for displays is shaped by PCL's assessment of typical camera system and other test lab capabilities (e.g., maximum measurable screen area) and by cost-effectiveness considerations, such as excluding low-volume classes with limited total savings potential.

Finally, the research and development conducted proves that camera photometer-based test systems that underpin this luminance-based policy approach can be adapted for use with computer monitors and DSDs.[4] Details on this research and development are available in ANNEX D: MODIFYING THE PCL CAMERA SYSTEM.

PCL's high-level research goals are:

- **Understanding potential policy drivers:** PCL's research efforts focus on understanding market trends, technological developments, and user settings that may impact energy consumption in computer monitors and digital signage in both Active Mode and Non-Active Mode. This report analyzes industry reports, usage patterns, and secondary sources, with the goal of ensuring that PCL's findings reflect real-world product usage and market conditions.
- **Developing policy recommendations:** To support effective energy efficiency regulations, clear policy guidelines are established based on laboratory testing and previous policy analysis. This includes recommending the scope of products covered, test methodologies, and a metrics framework, and providing preliminary guidance on appropriate power limits and allowances for different display technologies.

These are the methodologies used to accomplish these goals:

- **Secondary Research:** Reviewing technical literature, industry reports, and consulting with experts to understand display industry market trends and technologies.

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[4] PCL developed the first camera photometer dedicated to measuring display screen-average luminance while playing broadcast video to explore the potential application of camera photometers to TV energy efficiency policy. PCL continues to expand this system's capability and to share learnings with other camera vendors to achieve a robust supply chain for camera-based test systems that can be used across a broad range of display types.

- **Dataset and Policy Analysis:** Examining existing regulatory frameworks, such as the EU Ecodesign and EU Energy label regulations, California Energy Commission's (CEC's) Title 20, and ENERGY STAR® for Displays 8.0, along with associated datasets.[5]
- **Laboratory Testing:** Conducting a broad range of research-focused energy efficiency tests on a diverse set of computer monitors and digital signage displays to inform policy recommendations.

Table 5 below outlines how these methodologies are used to achieve the research goals and contains links to the relevant sections in this document (if viewing it digitally). Blue cells indicate the relevant methods for each goal.

Table 5: Research goals and methodology

	Research Methodology		
Goals	Secondary Research	Dataset and Policy Analysis	Laboratory Testing
UNDERSTANDING ENERGY EFFICIENCY DRIVERS			
MARKETS AND TECHNOLOGIES	X		
EFFICIENCY DRIVER ASSESSMENT	X	X	X
DEVELOPING POLICY RECOMMENDATIONS			
PRODUCT SCOPE	X	X	
METRICS, POWER LIMITS		X	X
TEST METHOD		X	X

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[5] The CEC Title 20 dataset includes test data on models covered by the U.S. TV Voluntary Agreement, which this study does not analyze separately.

Markets and Technologies

This section provides an overview of the monitor and DSD markets, introduces the display technologies evaluated in this study, and outlines their technical characteristics.

Display Technologies

Table 6 details an initial classification of panel technologies based on light source type.

Table 6: Panel technologies classified by light source type

Technology	Light Source Type
Liquid Crystal Displays (LCD)	Edge-lit backlight
	Direct-lit backlight
Emissive	OLED
	Direct View LED (DVLED)

These technologies are:

- **Liquid Crystal Displays (LCD):** A technology that uses liquid crystals to control light from a backlight
    - **Edge-lit backlight:** LEDs are placed along the screen's edges to light the panel
    - **Direct-lit backlight:** LEDs are placed directly behind the screen for more uniform lighting
- **Emissive:** A display type where each pixel generates its own light
    - **OLED:** Uses organic materials that emit light at a pixel level
    - **Direct View LED (DVLED):** Uses individual LEDs as pixels

Since emissive displays do not have backlights, the more widely used term "backlight level" is replaced with "light source setting" throughout this report, following the IEC 62087-3 draft Edition 3 committee's definition of the term. Light source setting refers to the luminance setting available for adjustment by the user.

Both LCD and emissive displays may have Quantum Dot technology. Quantum Dot technology uses tiny semiconductor particles—called quantum dots—that emit precise colors when illuminated by a light source, typically a blue LED backlight. These dots produce highly pure red and green light, which, combined with the blue backlight, results in a wider color gamut and more accurate, vibrant colors compared to traditional LCDs. This technology improves both color accuracy and energy efficiency.

The following sections provide simplified explanations of each technology type to convey their key technical aspects.

Liquid Crystal Displays (LCD)

Basic LCDs have a white LED backlight that includes several individual light diodes which operate as a single light source. The two most common methods for implementing this backlight are edge-lit and direct-lit (or full array) backlighting. Edge-lit backlights use LEDs placed along the perimeter of the screen, with a light guide plate distributing the light across the display. This design allows for thinner panels and is typically more cost-effective. In contrast, direct-lit backlights (Figure 1) position an array of LEDs directly behind the entire display panel. A diffuser plate is placed in front of the light diodes, so the individual light sources are diffused and the light seen by the viewer is as uniform as possible across the screen area.

Figure 1: A 3x6 LED direct-lit backlight array

In basic LCDs, the luminance level of the backlight does not vary based on content brightness, either individually or at a macro level. Backlight power is determined solely by the manual backlight luminance setting. Thus, the unit uses more power with higher backlight settings, but power does not vary with the dynamic luminance of content.

Every pixel in a basic LCD consists of red, green, and blue (RGB) subpixels (Figure 2). Each of these subpixels has either a red, green, or blue light filter that blocks all the white light spectrum except for the desired color. White light consists of all the primary colors combined across a broad array of light wavelengths, so each color filter blocks the other two primary colors and the wavelengths between them. Color filters let through only about 5%–20% of the light depending on the color in question. This results in 80%–95% of the light generated by the backlight being “wasted” by the color filter for all content regardless of the backlight level or content brightness.[6]

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[6] The use of the word “waste” here is cautious, as no equivalently low-cost ways exist to separate the primary colors. So light is wasted relative to more expensive emissive technologies that do not rely on color filters (which are described later in this report). Light is wasted relative to an ideal usage of all the light emitted. In reality, color filters are an effective and inexpensive way to make RGB subpixels.

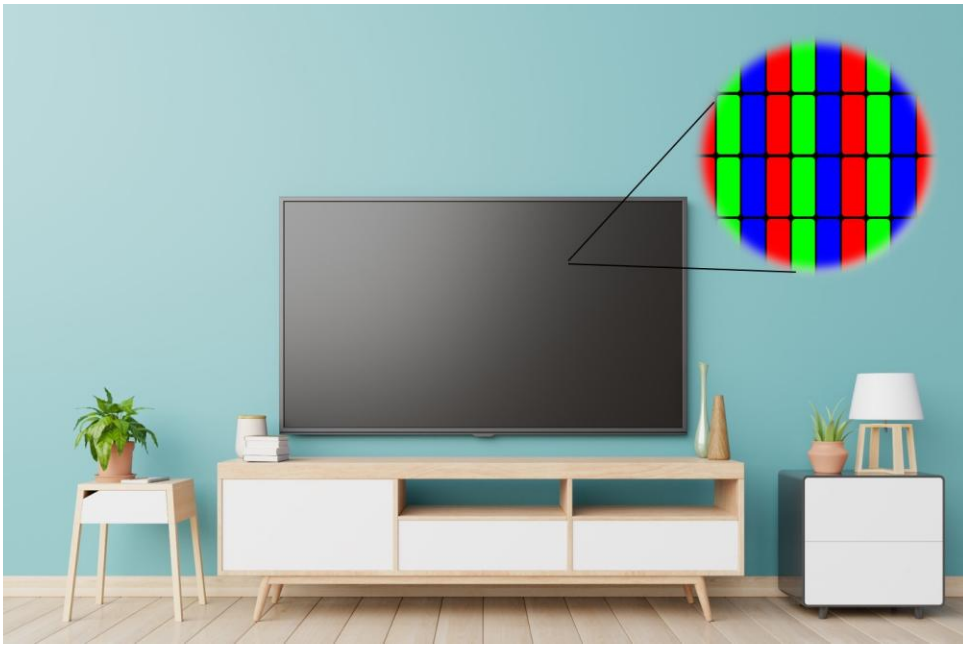

Figure 2: RGB color filters from artience on a TV

LCDs control the light output of each subpixel with a liquid crystal stack that leverages light polarization to let a controlled amount of light pass through. LCDs pass the white light from the backlight through a polarized film, then through a liquid crystal layer that can twist the polarization of the already polarized light at a subpixel level. If it twists the polarization one way, the light passes through a second polarized film. If it twists it the other way the second polarized film blocks it almost entirely. If the liquid crystal layer twists subpixel light partially, then part of the light passes through.

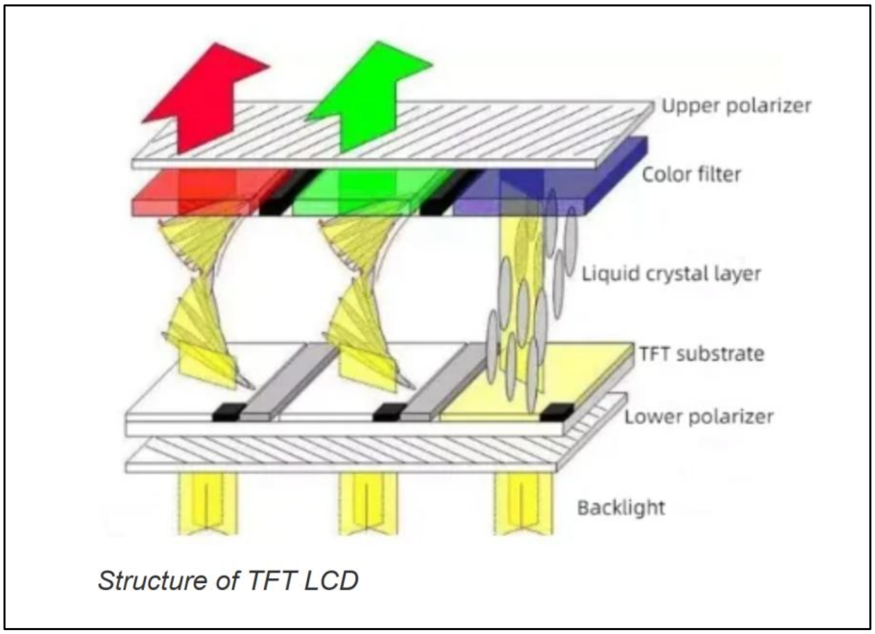

Figure 3: Illustration of a liquid crystal stack from Hongguang Display

Figure 3 illustrates how LCD displays use polarized light to control how much light is emitted by each subpixel. Modern LCDs use a Thin Film Transistor (TFT) approach. Unpolarized light has electric field components oscillating in multiple planes perpendicular to the direction of travel. Figure 3 illustrates this by showing the backlight as crossed planes. A polarizer filters the light so that only the component oscillating in one plane remains. Here, the lower polarizer alters these waves so that they oscillate in a diagonal plane only. When a subpixel is intended to emit light (red and green subpixels in this case), the liquid crystals, activated by the TFT substrate, twist the light waves so that they pass through the upper polarizer that is oriented 90 degrees from the lower polarizer. Since the desired pixel color is yellow in this case, the backlight is allowed to pass through red and green subpixels. The TFT orients the liquid crystals behind the blue color filter to leave the polarization as-is, which means that it is misaligned with the upper polarizer and light cannot pass through it. So, the blue subpixel effectively emits no light. While this diagram shows the liquid crystal “gate” either open or closed, the liquid crystals can be set to let a fraction of the light through by partially twisting the light waves.

For basic LCDs, subpixel light output is controlled exclusively by TFT control of the liquid crystals. Light output is controlled by blocking light, not by modulating the light source itself.

1.1.1.1 LCD Subtypes

LCD panels are divided into several subtypes based on the liquid crystal alignment technologies they use, each offering distinct performance characteristics. Among the many variants, the most common are **Twisted Nematic (TN)**, **Vertical Alignment (VA)**, and **In-Plane Switching (IPS)**.

TN is the oldest and typically the most affordable LCD technology. It is known for exceptionally fast response times, making it popular in high-refresh-rate displays. TN suffers from limited viewing angle (especially vertically) and often shows noticeable shifts in color, brightness, and gray levels when viewed off axis.

VA technology offers much higher contrast ratios and better viewing angles than TN panels. VA panels provide more uniform gray-level performance and only moderate color shift at different viewing angles. However, these panels generally have slower response times.

IPS panels are favored for their excellent color accuracy and for having the widest viewing angles of the three major types. They deliver highly consistent gray-level performance. Though IPS panels tend to be more expensive than TN and usually have lower contrast ratios than VA, they are widely regarded as the most balanced option for general use and color-sensitive work.

Several proprietary IPS subtypes exist, developed by different manufacturers to refine or optimize IPS behavior. Samsung’s **Plane-to-Line Switching (PLS)** offers viewing angles and color performance comparable to traditional IPS while providing slightly higher brightness and improved energy efficiency. Innolux’s **Azimuthal Anchoring Switch (AAS)** is another IPS-derived technology designed to enhance viewing angles and color accuracy, making it suitable for large screens and laptop displays. BOE’s **Advanced Super Dimension Switch (ADS)** is a cost-optimized IPS variant that maintains competitive color reproduction and wide viewing angles.

1.1.1.2 Dynamic Dimming in LCD Displays

Dynamic dimming in LCD displays allows for some level of power scaling when an image contains darker areas. A dimming zone refers to an area of the screen a display can dim according to the brightness of the content displayed in that zone. Table 7 describes the types of dynamic dimming based on a display's number of dimming zones.

Table 7: Types of dynamic dimming based on dimming zone count

Approximate Number of Dimming Zones	Type of Dynamic Dimming
1 zone	Global Dimming
2–500 zones	Local Dimming
> 500 zones	Mini-LED (<300 µm LED chips and local dimming)

In the case of an LCD with a 3x6 array of light emitting diodes with local dimming, if the bottom third of the image is darker than the top two-thirds, the local dimming function would reduce the backlight power to the bottom row of diodes and the liquid crystal layer could be left in a more open state to achieve the desired (reduced) light output level. In other words, less light blocking by the liquid crystal stack is needed.

Figure 4: A high-end TV with local dimming from Toshiba

Local dimming requires additional processing and display driver power. In displays with local dimming, the TCON board, which handles display timing and control, requires higher processing power to coordinate dimming in each zone and to adjust the content accordingly, while the backlight driver circuitry is more complex because each zone needs its own dedicated driver rather than a single driver across the entire display. While this increases the overhead power usage of a display, it also diminishes the display's overall power usage since power better scales to image light level, thereby reducing the average power level over the duration of the test clip. For typical in-home backlight settings, local dimming results in less power (and better contrast ratios) than a basic LCD with no dynamic dimming capability.

Generally, the more dimming zones a display has, the greater the efficiency gain is for typical backlight levels. However, the number of local dimming zones also tends to correlate with price. Table 8 shows incremental bill of materials (BOM) costs for different dynamic dimming implementations. Note that at the lower end of the display market, profit margins are low, so even small price increments can make a product uncompetitive.

Table 8: Incremental cost of different dimming architectures

Dimming Architecture	Zone Count Range	Validated BOM Incremental Cost (USD)[7]	Primary Technical Cost Driver
Global Dimming	1 zone	< $1	Control circuit/firmware integration. Mostly TCON firmware.
Basic Full Array Local Dimming (FALD)	3–180 zones	$25–$150	Mandatory Direct-Lit Array hardware, backplane, and volume of driver integrated circuits (ICs)
Mini-LED Entry	200–800 zones	$100–$250	Massive chip volume (100k+), advanced driving schemes
Premium Mini-LED	800–5,000+ zones	$200–$400+	Non-linear scaling complexity, specialized thermal management

ANNEX G: INCREMENTAL COST ANALYSIS FOR GLOBAL AND LOCAL DIMMING IN LCD Displays details the analysis completed to obtain the estimates on Table 8.

The term "local dimming" generally does not apply to emissive displays; however, these displays achieve the most granular level of local dimming possible, as they can control light emission at the subpixel level.

Emissive Displays

Emissive displays differ from basic LCDs in one fundamental way: each subpixel is its own light source. Instead of modulating light output by blocking white backlight with a liquid crystal stack, emissive displays generate light directly at the subpixel level. Every red, green, and blue subpixel is an independently controlled light source that emits light only when needed and only at the intensity required to render the image. As a result, emissive displays do not waste light by blocking it to modulate light output, and their energy usage is directly tied to the brightness and color composition of the content.

Because light originates at the subpixel level, emissive displays scale power dynamically and continuously in response to how many subpixels are illuminated, how brightly they are driven, and which colors are present on each frame. Bright scenes with large areas of high luminance require substantially more power, while darker scenes require significantly less. This produces over time a power profile that closely follows

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[7] Depends heavily on the display size and number of zones. Requires a backlight driver capable of handling multiple zones, as well as TCON firmware to control the dimming.

frame-average luminance, unlike basic LCDs, which often show nearly flat power traces during changing scenes due to fixed backlight output.

The fundamental advantages of emissive displays, which are currently dominant in the high-end market, include:

- **Perfect black levels:** A pixel can be fully turned off (0% light emission), resulting in an infinite contrast ratio.
- **Near-instant response time:** Pixels can switch almost instantly, minimizing motion blur.
- **Wider viewing angles:** Picture quality remains consistent even when viewed off-center.

The present market is primarily defined by various types of OLED and large-format Direct View LED (DVLED) systems. Table 9 shows which emissive technology types are dominant for different product types.

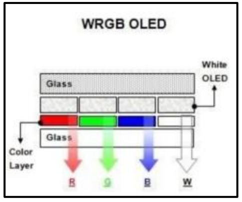
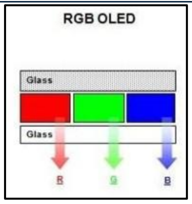
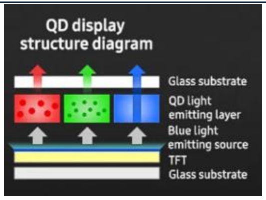
Table 9: Types of dominant emissive technologies by product type

Product Type	Dominant Emissive Technology	Key Strengths
Desktop Monitor	OLED and QD-OLED	Perfect blacks, fast response times, high color saturation
Consumer TV	WRGB OLED and QD-OLED	Cinematic contrast and slim design
Digital Signage	DVLED	Extreme brightness, scalability to any size, and durability
Mobile/Wearable	RGB OLED (AMOLED)	Flexibility, low power consumption, and high pixel density

1.1.1.3 Organic Light Emitting Diode (OLED)

OLED technology uses thin films of organic material that glow when an electric current is applied. Table 10 summarizes the different OLED subtypes and their most common applications.

Table 10: OLED subtypes according to their primary application

OLED Subtype	Primary Applications	Core Mechanism		Key Market Status
WRGB OLED (WOLED)	Large TVs, some monitors	Uses an all-white OLED emitter behind red, green, and blue color filters (plus a white sub-pixel)		Used for high-end **TVs**
RGB OLED (AMOLED)	Smartphones, Smartwatches	Each red, green, and blue sub-pixel is created from a separate organic compound and emits its own color directly		Standard for **mobile devices** and **wearables**
Quantum Dot OLED (QD-OLED)	Premium monitors, TVs	Uses a **blue OLED emitter** as the light source, which excites a layer of **Quantum Dots** to produce pure red and green light		The newest high-end standard for **computer monitors** and **TVs**, offering superior color volume and brightness over WRGB OLED

1.1.1.4 Direct View LED (DVLED)

In the Direct View LED display technology, the LED chips themselves form the pixels.

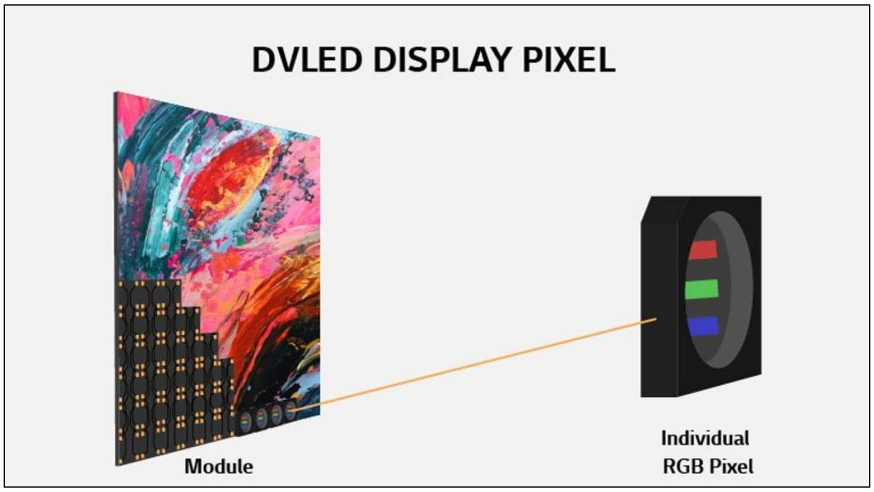


Figure 5: View of an individual DVLED pixel from [LG]

Note: Each RGB subpixel shown on the right of this figure is an independently controlled light emitting diode (LED) that natively emits the desired color.

DVLED displays are commonly used in applications such as digital signage, video walls, and ultra-luxury home theaters. They are constructed from individual modules that are typically grouped into subassemblies called cabinets to form large displays. Because the distance between the LED chips (known as pixel pitch) is still too large for close-up viewing, DVLED technology results in pixel densities that are too low at smaller sizes, making it unsuitable for standard computer monitors.

The vast majority of DVLED displays use multiplexed scanning architectures with driver integrated circuits (ICs) that continuously scan the LED array at high frequencies (typically 3840Hz) to avoid visible flicker, even when displaying black. As a result, they consume significant power regardless of light output, leading to high overhead power even when emitting no light. Active-matrix DVLED displays using TFT backplanes are intended to improve this efficiency by eliminating continuous scanning; however, some early implementations still rely on driver IC architectures similar to conventional scanning DVLED, meaning the cabinet electronics remain fully active and continue to consume power when the display is dark.

Micro-LED shares the emissive LED architecture of DVLED but uses miniaturized LEDs to achieve the high pixel densities required for closer viewing distances. Although it offers significant performance potential, micro-LED is not yet commercially available as a standard computer monitor or mainstream consumer TV because of extremely high manufacturing costs and production complexity, particularly the challenge of "mass transfer," which involves placing millions of microscopic LEDs with precise accuracy. As a result, micro-LED remains limited to ultra-expensive, modular luxury TVs, often exceeding 100 inches diagonal.

Automatic Brightness Control (ABC)

Automatic Brightness Control (ABC) technology adjusts a display’s luminance based on ambient light conditions. It uses built-in light sensors to continuously monitor the surrounding environment and increases brightness in bright environments while reducing it in darker ones. The goal of ABC is to optimize the viewing experience while improving energy efficiency. ABC is found in both LCD and emissive display technologies.

ABC is widely used across a range of applications. In consumer electronics (such as smartphones, tablets, laptops, and TVs), it can improve battery life in portable electronics and provide more natural viewing under changing lighting conditions. In digital signage, including outdoor and semi-outdoor or “window” displays, ABC helps ensure images remain readable even under harsh or variable lighting.

Niche Display Technologies

The following sections detail several emerging or niche panel technologies and contain extended technical detail that may be of interest primarily to technical audiences.

1.1.1.5 Dual-layer LCD

Figure 6: The Sony BVM-HX310 Professional Master Monitor

Dual-layer LCDs (also known as dual-cell or stacked LCDs) are built by stacking a full-resolution color LCD in front of a lower-resolution monochrome LCD that acts as a luminance modulator. The front panel provides all the image detail, while the rear monochrome layer (typically of a lower resolution) shapes the brightness for blocks of front-panel pixels, effectively creating millions of local dimming zones. This architecture delivers exceptionally deep blacks and very high contrast because the rear layer functions like a finely detailed grayscale mask behind the color image.

These displays are expensive to manufacture due to the need for two TFT stacks, precise optical alignment, and very bright backlights; they are typically priced in the $20,000–$30,000 range. As a result, they are almost exclusively used in professional mastering environments, such as color-grading suites and high-end post-production facilities, where consistent HDR performance and reference-grade accuracy are required.

A major tradeoff of dual-layer LCD technology is its very low optical efficiency. With two LCD cells, four polarizers, and a full set of color filters, total light transmission is typically in the range of 2%–4%, assuming the use of reflective polarizers, which are the most common choice in these systems. Without reflective polarizers, the transmission would fall even lower. This means that only a small fraction of the backlight's output reaches the viewer, forcing manufacturers to use exceptionally bright and high-powered backlight assemblies to achieve HDR-capable peak luminance.

Although inefficient, this combination of a finely controlled modulator and a standard high-resolution LCD layer allows dual-layer systems to approach OLED-like black levels while maintaining the brightness and stability advantages of LCD.

1.1.1.6 Micro-LED

Micro-LED technology is an advanced display solution that leverages arrays of microscopic, self-emissive inorganic LEDs as individual pixel elements, offering superior contrast, extreme brightness, and long lifespans.[8,9] This technology is a subset of DVLED that features a much finer pixel pitch (often below 1 mm) to create high-resolution displays. The inherent energy efficiency potential of micro-LED stems from its self-emissive nature, in which light is only emitted where needed, although actual efficiency performance can vary as the efficiency of certain colored LEDs is still low.

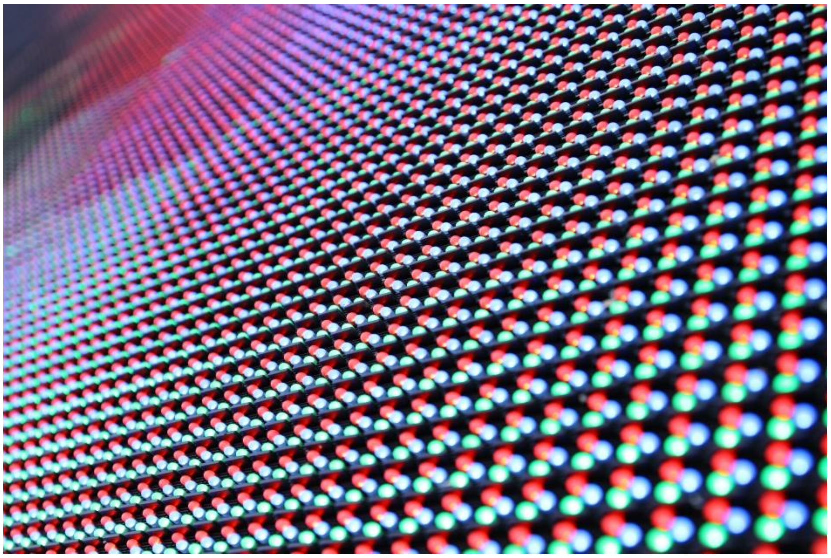


Figure 7: Close-up of a micro-LED screen from Dexerials

The display's architecture often employs a passive matrix with driver integrated circuits (ICs) to refresh small sections of the wall at high rates, commonly 1920Hz or 3840Hz. However, the development of active-matrix displays—which use a Thin-Film Transistor (TFT) backplane instead of driver ICs—is in progress, as active-matrix displays are expected to be significantly more energy efficient. Furthermore, the technology often utilizes common-cathode drive technology to supply each red, green, and blue LED at its own forward voltage, which can reduce power consumption by approximately 20%–40% in some implementations. Despite these technical advantages, the overall market availability of micro-LED displays is currently limited due to the high cost and complexity of production.

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[8] 848 ppi high-brightness active-matrix micro-LED micro-display using GaN-on-Si epi-wafers towards mass production. Optica Publishing Group, accessed November 20, 2025, https://opg.optica.org/abstract.cfm?uri=oe-29-7-10580

[9] LEDinside: Observing the Development Trend of Micro LED Display from Micro LED Technology Challenges. TrendForce, accessed November 20, 2025, https://www.trendforce.com/news/2019/02/13/ledinside-observing-the-development-trend-of-micro-led-display-from-micro-led-technology-challenges/

1.1.1.7 Transparent OLED

Figure 8: Picture of a transparent OLED display from Pro Display

Transparent OLED (T-OLED) technology uses organic light-emitting diodes built on a specialized, transparent substrate, allowing for displays that appear clear when inactive and can display content with high clarity and brightness when active. These displays achieve transparency by utilizing transparent cathodes and anodes (often made of materials such as Indium Tin Oxide or very thin metal layers), along with transparent encapsulation layers, enabling light to pass through the panel from both directions. The self-emissive nature of the OLEDs provides excellent contrast, while the overall panel structure makes them ideal for applications such as augmented reality storefront windows, clear digital signage, and heads-up displays, in which simultaneously viewing the digital content and the real environment behind the display is necessary.

1.1.1.8 3D Displays

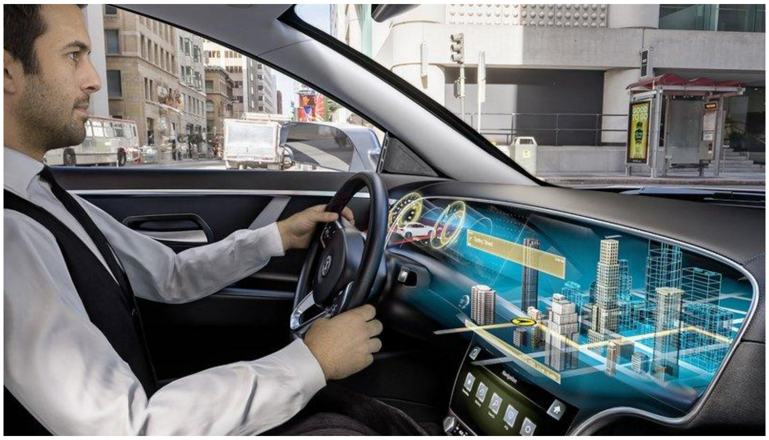

Figure 9: Picture of a light field 3D display from Continental

Stereoscopic 3D displays create the perception of depth by delivering two slightly offset images to the viewer, one for each eye. This effect can be achieved through various methods, including active shutter glasses, which rapidly open and close in sync with the display; polarized passive glasses, which use different polarizations for each eye; or glasses-free techniques like lenticular lenses or parallax barriers that manage the light's direction. Because the display is essentially processing and showing two images simultaneously, and often needs to compensate for the light blocked by the glasses or directional optics, more processing power and higher luminance levels are typically required to maintain image clarity, which leads to higher power consumption than for standard 2D displays.

1.1.1.9 Field Sequential Color (FSC)

Figure 10: Picture of a Field Sequential Color display from Omdia

Field Sequential Color (FSC) is a promising LCD backlight technology that replaces the standard combination of a white LED backlight and a color filter with an RGB LED backlight. Unlike other RGB backlights, FSC displays show each color (Red, Green, and Blue) sequentially—one at a time, in rapid succession—and rely on the user's eye to blend the colors. Because no color filter is blocking the light, this method offers high energy efficiency; early measurements suggest it can achieve around 50% lower power consumption than traditional white LED backlights. Therefore, FSC is expected to be highly energy efficient according to display metrics, although this benefit could be partially offset by the high overhead energy consumption required for the increased processing power needed to rapidly switch and control the sequential frames.

1.1.1.10 RGB Mini-LED Backlight

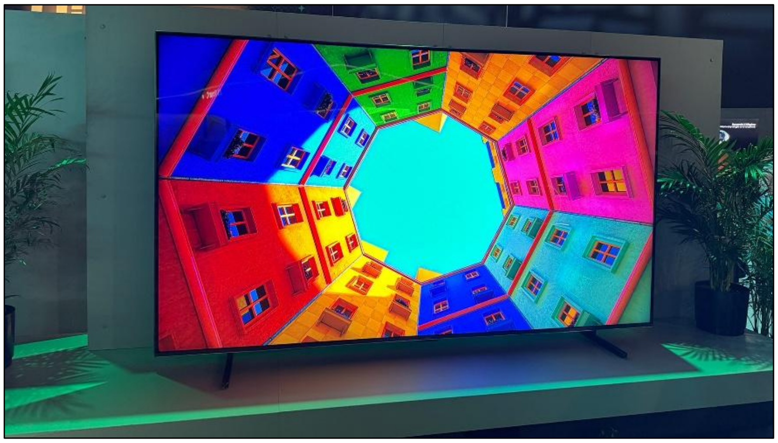

Figure 11: Hisense's RGB mini-LED TV

RGB Mini-LED backlights use arrays of very small Red, Green, and Blue LEDs positioned behind an LCD panel to serve as the illumination source, unlike standard Mini-LEDs which typically use a white backlight. This configuration allows all three colors to be displayed at once. Existing color filters on the LCD panel then separate the colors into subpixels. The Mini-LEDs are arranged in small zones to enable local dimming of individual colors rather than the entire backlight, a major advantage that delivers a wider color gamut and improved color accuracy across various brightness levels. However, these displays are generally less energy efficient than those using comparable white LED backlights because standard RGB LEDs inherently have lower luminous efficiency compared to modern white LEDs. The intricate, high degree of individual control required over the millions of small LEDs also adds to the overall system's power consumption.

1.1.1.11 Electronic Paper (ePaper)

Figure 12: Picture of a 75” electrophoretic ePaper display from E Ink

E-Paper (or electronic paper) is a class of reflective display technologies designed to mimic the appearance of ink on paper by moving tiny electrically charged particles. A key feature is that these displays only consume power when the image is changed (refreshed), which makes them ideal for battery- or solar-powered devices due to their extremely low total power consumption. However, e-paper is generally only suitable for static image content because it has a limited color depth and a long image refresh time, which can be around 30 seconds for color e-paper, preventing its use for video or fast-moving graphics.

Computer Monitors

PCL developed a preliminary estimate of 2024 global computer monitor sales, price ranges, screen sizes, and resolutions across major market categories to identify the highest-volume segments. The analysis was based on publicly available market data and multiple secondary sources, with aggregated insights from AI-based data extraction tools. These estimates were cross-checked against established market reports to verify total market size and segment proportions. The resulting estimates are presented in Table 11.

Table 11: Comparison of different monitor market segments

Segment	Estimated Annual Global Sales (Units)	Typical Price Range	Common Sizes (Diagonal)	Typical Resolutions
Consumer/Personal	70–80 million	\$100–\$350	21"–27"	1920×1080 (FHD*) 2560×1440 (QHD*)
Business/Enterprise	35–45 million	\$150–\$500	21"–27"	1920×1080 (FHD) 3840×2160 (4K)
Gaming	25–30 million	\$250–\$1,500	27"–34"	2560×1440 (QHD) 3840×2160 (4K) 3440×1440 (Ultrawide)
Professional/Creative	5–8 million	\$450–\$5,000	24"–34"	3840×2160 (4K) 5120×2880 (5K)

Note: *FHD = Full High Definition; QHD = Quad High Definition

The computer monitor market was valued at \$70.75 billion in 2024 according to The Business Research Company's Monitor Global Market Report. An approximate market value of \$71.65 billion can be derived from Table 11Table 9 by multiplying the midpoints of the estimated annual global sales and price ranges, yielding a result consistent with the published estimate.

Each category is characterized by different capabilities relevant to its intended users, detailed in the following sections.

Consumer/Personal

Figure 13: Picture of the HP 524SH from Newegg

Consumer and personal-use monitors are designed with affordability and general-purpose functionality in mind. These displays typically aim to meet the needs of everyday users by providing a balanced combination of screen quality and cost effectiveness. As a result, they often include only the most essential features. While perfectly adequate for browsing, streaming, and light productivity, they usually lack more advanced capabilities found in higher-tier categories. Features such as integrated keyboard, video, mouse (KVM) switches,[10] high refresh rates, or extensive ergonomic adjustments are uncommon in this segment, as manufacturers prioritize cost savings and broad market appeal.

Business/Enterprise

Figure 14: The Dell U4021QW computer monitor

Business and enterprise monitors are engineered for productivity, comfort, and long-term reliability in office environments. These displays often incorporate ergonomic stands with height, tilt, swivel, and pivot adjustments for workstation setups. To help reduce eye strain during long work hours, many enterprise models include blue-light-reduction modes and flicker-free backlighting. Built-in speakers are also commonly provided for conference calls or general office use. Increasingly, business monitors integrate USB-C docking capabilities which allow for video, power delivery, and peripheral connectivity through a single cable, as well as built-in KVM switches to support multi-computer workflows. These features make enterprise models ideal for hybrid offices, shared desks, and productivity-focused setups.

Gaming

Figure 15: This MSI gaming monitor has decorative lighting on the bottom of its bezel

Gaming monitors are optimized for fast, responsive, and visually smooth performance. Their defining characteristics include high refresh rates—typically ranging from 144Hz to 360Hz—paired with low response times to reduce motion blur and input lag. These displays also support variable refresh rate (VRR) technologies such as AMD FreeSync and NVIDIA G-SYNC, which help eliminate screen tearing and maintain smooth gameplay. In addition to performance enhancements, gaming monitors often incorporate decorative RGB lighting. They may also offer advanced tuning options, including overdrive modes to speed up pixel transitions and black-stabilizing features that brighten dark scenes for improved visibility in competitive games.

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[10] A KVM switch allows a user to control multiple source devices (e.g., computers, game consoles, media players) using one set of keyboard, monitor, and mouse.

Professional/Creative

Figure 16: The ASUS ProArt Display PA279CRV

Professional and creative-oriented monitors focus on delivering precise and reliable image quality for tasks such as photography, graphic design, video editing, and digital content creation. These displays prioritize color accuracy and offer wide color-gamut coverage, often supporting professional color spaces like Adobe RGB, DCI-P3, and Rec. 709—depending on the intended workflow. Many models come factory-calibrated with detailed calibration reports to ensure accurate color representation right out of the box. Creators rely on these monitors for consistent results across devices and media formats, making this category essential for work that demands high fidelity, uniformity, and dependable color performance.

Digital Signage Displays

High-level market segmentation of the digital signage display (DSD) market was informed by input from a marketing expert at a video wall display manufacturer. Estimates of 2024 global sales volume, screen size, and typical resolution for these categories were generated using publicly available data and AI-assisted data aggregation to provide an indicative overview of the DSD market landscape. These estimates were cross-checked against publicly available data from market reports and technical articles presenting performance metrics for different segments. The resulting information is presented in

Table 12.

Table 12: High-level DSD market segmentation and data

Segment	Estimated Annual Global Sales (Units)	Typical Price Range	Common Sizes	Typical Resolutions
Commercial Monitors and Digital Signs	15–18 million units	\$300–\$800	32"–98"	1920×1080 (FHD) 3840×2160 (4K)
Video Walls – DVLED	900,000–1.2 million m² (area)	\$3,000–\$13,000 per m²	Modular, any size	Custom resolutions
Video Walls – Tiled LCD	300,000–450,000 individual panels	\$800–\$3,000 per panel	46"–55" per panel	1920×1080 (FHD) 3840×2160 (4K)
Video Walls – Rear Projection	6,000–10,000 units	\$15,000–\$50,000	50"–80"	1920×1080 (FHD) 3840×2160 (4K)

Table 12 estimates a middle-range market size of $27.2 billion (calculated by taking the mid-point of each segment's estimated global sales in units or area). This roughly aligns with the 2024 market value assigned by different publicly available reports: IMARC Group valued the 2024 digital signage displays market at $28.5 billion, while Grand View Research estimated it at $28.83 billion. Given this information, the estimates in

Table 12 appear to fall within realistic values.

DSDs vary widely in form factor and application—ranging from standalone commercial monitors to large-scale video walls. Each segment is defined by a unique set of functional and technological characteristics.

These segments may also be divided into three categories according to where the display is placed:

- Indoor displays
    - The most common DSD display type, with brightness levels close to those common in televisions
    - May have Automatic Brightness Control (ABC) sensors
- Outdoor displays
    - High brightness for visibility under direct sunlight
    - Uses weatherproof enclosures to withstand the elements outdoors
    - Often have ABC sensors to adjust screen brightness levels throughout the day
- Semi-outdoor or “window” displays
    - Typically placed indoors and by windows, facing outside
    - High brightness for visibility under direct sunlight
    - Commonly used in storefront advertising, transportation hubs, and menu boards

Commercial Monitors

Figure 17: A touchscreen commercial monitor from LG

Commercial monitors are standalone displays designed for use in conference rooms, classrooms, and other collaboration-focused environments. Unlike consumer monitors, they are built to support group viewing, shared interaction, and multimedia presentations. These displays often serve as the central visual hub in meeting spaces, offering clear, robust image quality suitable for presentations and data visualization.

Many commercial monitors incorporate interactive touch capabilities and whiteboarding features, allowing teams or students to annotate content directly on screen. They may also include built-in speakers, webcams, and microphones to facilitate video conferencing. Products with these expanded collaborative features are frequently marketed as interactive whiteboards. Commercial monitors are generally designed for moderate duty cycles (commonly 8/5 or 16/6) rather than continuous 24/7 operation, as they are primarily intended for typical business or educational schedules.

Digital Signs

Figure 18: The LG 43UM340E, a digital sign

Digital signs refer to standalone commercial displays used across retail, hospitality, transportation hubs, and other public or customer-facing spaces. While they share some similarities with consumer televisions and monitors, digital signage displays are engineered for greater durability, higher uptime, and increased brightness. These models often support 16/7 or 24/7 operation and typically reach brightness levels of 400–700 cd/m² or higher to maintain visibility in brightly lit environments.

Many digital signs also feature Open Pluggable Specification (OPS) slots, which allow integrators to install dedicated computing modules directly into the display. Additional capabilities such as landscape/portrait orientation support, optional touch overlays, and remote management software make digital signs highly adaptable for commercial deployments. These features help ensure reliable performance and flexible installation for advertising, informational displays, and customer engagement.

Video Walls – DVLED

Figure 19: Samsung's Direct View LED The Wall

DVLED video walls consist of either preassembled all-in-one systems or modular display systems that can be combined to create displays of virtually any size or aspect ratio. Because DVLED uses self-emissive LED pixels (as explained in section 1.1.1.4: DIRECT VIEW LED (DVLED)), it is widely deployed in large-format visual applications. Most DVLED installations use real pixels, where each pixel contains its own red, green, and blue LED subpixels. Some lower-cost variants use virtual pixels, where subpixels are shared among adjacent pixels to reduce the total number of LEDs, lower energy consumption, and decrease cost while maintaining a perception of higher resolution. In marketing materials, real pixel pitch is typically defined by the distance between green subpixels, while virtual pixel pitch may be promoted as the distance between any two neighboring subpixels to give the appearance of finer resolution.

Modular DVLED systems are typically paired with LED controllers from specialized manufacturers such as NovaStar, Colorlight, Brompton, Barco, or Megapixel VR to manage image processing and synchronization. DVLED is available in both indoor and outdoor configurations and can achieve extremely high brightness levels, sometimes up to 10,000 cd/m², making it suitable for environments requiring strong visibility. Power consumption varies significantly depending on pixel pitch and brightness settings. Due to their scalability and visual impact, DVLED video walls are widely used in stadiums, digital out-of-home (DOOH) advertising, broadcast studios, virtual production stages, control rooms, airports, malls, and corporate lobbies.

1.1.1.12 Modularity

In traditional modular DVLED systems, the display is often constructed from cabinets, which are assemblies that typically include the following components:

- LED modules mounted on the front face
- Receiving card (control hub)
- Power supply unit(s)
- Hub/transfer board
- Flat cables connecting modules to receiving card
- Power cables
- The cabinet frame housing everything

Figure 20 illustrates typical cabinet architecture.

LED Cabinet

Steel Frame with LED Cabinet Mounted

Figure 20: Typical cabinet architecture, described in the Colorlit LED Installation Guide.

Note: See additional background information in the Colorlit LED screen cabinet guide.

Table 13 provides a few examples of typical DVLED configurations.

Table 13: DVLED configuration examples.

Application	Approximate size	Cabinets	Modules per cabinet
Conference room	138" (3.5m) diagonal	6	4
Corporate lobby	165" (4.2m) diagonal	12	4
Control room	6m wide × 2m tall	36	4
Broadcast studio backdrop	8m wide × 3m tall	72	4
Concert touring rig	12m wide × 6m tall	216	4
Large outdoor billboard	10m wide × 5m tall	54	9

Cabinet-based architectures dominate the commercial DVLED market, but a small subset of systems—particularly budget-oriented fine-pitch indoor displays—use cabinet-less or direct-mount designs. In these systems, LED modules are mounted directly to a shared mechanical frame that provides alignment, power distribution, and data connectivity, with no intermediate cabinet layer.

For efficiency policy purposes, cabinet-less systems could in principle be evaluated by measuring power at the DC input to the LED modules and applying a reference power supply efficiency factor to calculate equivalent AC power consumption. However, given their small market share and the additional test complexity involved, section 1.1.1.21: VIDEO WALLS – LCD TILES OR DVLED CABINETS recommends excluding cabinet-less systems from initial efficiency requirements and focusing on cabinet--based and all-in-one products, which represent the vast majority of installed DVLED area.

Video Walls – Tiled LCD

Figure 21: The VHR-R LCD video wall from Samsung

Tiled LCD video walls consist of multiple narrow-bezel LCD panels arranged to create a larger, unified display surface. These panels are designed with thin bezels to minimize the visible seams between adjacent screens. Based on bezel thickness, they may be classified as:

- **Ultra Narrow Bezel (UNB):** <5mm
- **Extreme Narrow Bezel (XNB):** <3mm
- **Razor Narrow Bezel (RNB):** <1mm

While tiled LCD video walls do not achieve the same seamless appearance as DVLED, they offer excellent image uniformity and higher resolutions at lower cost, making them popular for a variety of professional environments. Common applications include control rooms, boardrooms, corporate lobbies, museums, and digital art installations.

Tiled LCD video walls usually require external power and signal distribution systems, as well as control boxes that manage input routing and power delivery across multiple panels. These systems ensure that large, tiled installations can operate reliably and in synchronization, especially in mission-critical environments where uptime and consistency are essential.

Video Walls – Rear Projection

Figure 22: Rear-projection video wall from Facility Executive

Rear-projection video walls represent an older display technology that is still used in mission-critical environments such as industrial control rooms, utility monitoring stations, and some transportation operations centers. These systems typically rely on projection cubes with long-lasting light sources and redundant power supplies, offering exceptional reliability and long-term operation with minimal downtime. Although rear-projection video walls do not match the brightness, thinness, or color vibrancy of modern DVLED or tiled LCD systems, they have historically been valued for their stability and low maintenance requirements. They are now increasingly being replaced by newer technologies that offer higher brightness, better image quality, and more flexible installation options.

Key Concepts and Core Principles

This section describes the fundamental concepts and principles that inform the screen-average luminance-based approach to evaluating display energy efficiency. These elements establish the groundwork necessary for understanding the analyses and recommendations discussed later in this report.

Display Dimming Lines and Light Efficiency Limit Lines

Most display technologies require more power to increase the light source level. That is, power is an often-linear function of light source setting. However, power does not drop to zero if the light source is dimmed to zero luminance because some components use a fixed amount of power that is independent of luminance. The linear function is of the form:

Equation 2: Basic dimming line equation

$$Power = Slope * Luminance + Intercept$$

Where the Y-intercept represents power use at zero luminance (e.g., often 20 W or so for a basic LCD). Since power is also a function of screen area and native resolution, these are held constant for any dimming line plot. For example, a dimming line plot might show the relationship between power and luminance for several 55”, 4K TVs. Note that dimming line test points are obtained by manually adjusting the backlight (or light source setting) among minimum, default, and an intermediate level. For each setting, the test-clip-average power and screen-average luminance are measured and plotted. Figure 23 below shows three dimming lines for a 75” digital whiteboard LCD display for the three preset picture settings supported by this unit. This display does not support High Dynamic Range (HDR) content, so these measurements were made with traditional Standard Dynamic Range (SDR) test clips.

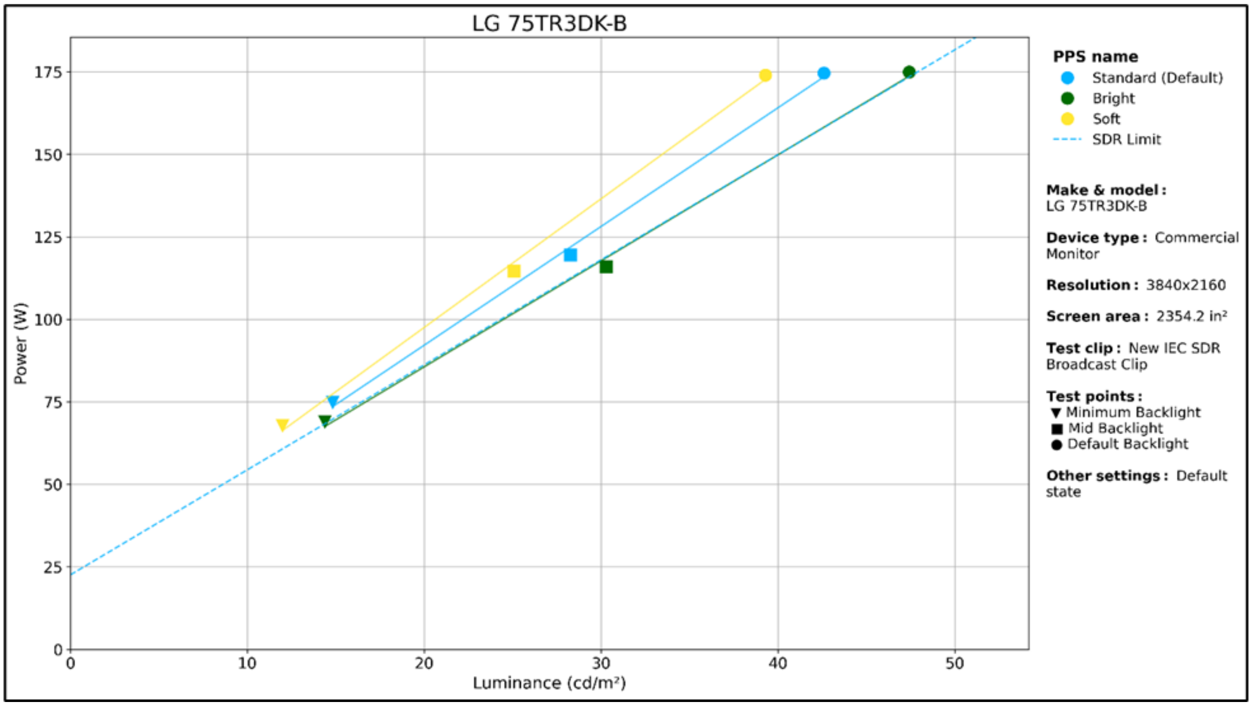

Figure 23: Introduction to dimming and limit lines

Note: The dotted blue SDR Limit line is an element of the 2024 proposed TV limits used here as a relative measure of efficiency; note that this is a hypothetical limit that is not in effect.

To develop the 2024 proposed TV SDR limit shown in the figure above, PCL used the approximately 1,000 or so unique models in the California Energy Commission's (CEC's) TV database to refine a limit structure that applies approximately equal pressure to TVs across all screen sizes and resolutions, normalized by several variables like brand, manufacturer, and technology type. In other words, the proposed limit equation puts about the same pressure on large and small LCDs regardless of resolution. It does apply more pressure to less efficient display types like basic LCDs. In that regard, the limits are formulated in a technology-agnostic way. The limits are structured so that a vast majority of displays pass. In this case, that means that the default backlight test point falls below the limit line. Label grade levels can be developed by reducing the scaling factor to define higher grading levels.

Conceptually, these limit lines were developed by identifying the average slope and intercept of comparable dimming lines (i.e., same area and resolution) and then multiplying the line by a scaling factor to increase the pass rate.

Equation 3: Basic equation for the Power Limit

$$Power\ Limit = Scaling\ Factor * (m * x + b)$$

Where *m* is conceptually the average dimming line slope and *b* is conceptually the average dimming line y-intercept for displays of a fixed screen area and native resolution (e.g., 75” 4K display bin). The actual limit line equation is more complex because both *m* and *b* are functions of screen area and native resolution.[11]

If the limit line was set to the average slope and intercept, about half the displays would pass. By increasing the scaling factor, a limit is achieved that has a TV pass rate of about 70%. These 2024 proposed TV limits are used as a benchmark to understand the relative efficiency of computer monitors and DSDs compared to TVs. As explained below, because they are designed for bright ambient light environments, computer monitors and DSDs tend to be set to output more light per watt than TVs so they generally score better against 2024 light efficiency metrics than TVs.

Note that the SDR TV limit line, like the SDR TV dimming lines on which it is based, has a greater than zero y-intercept. Without the y-intercept (i.e., the limit line passes through the (0,0) point), displays would achieve much lower scores for low luminance levels because the display power does not approach zero as luminance approaches zero. So, even a display with an efficient 10-watt y-intercept would fail at low luminance levels, for example, because it would have to achieve 0 watts to pass, and even small, efficient displays have a typical y-intercept that exceeds 10 watts.

Keep in mind that sloped dimming lines reflect power scaling as the light source level[12] is adjusted. As explained below, only some displays scale power when presenting dark or bright images.

Power Scaling in Response to Picture Level

While most displays scale power to backlight level – they have sloped dimming lines as determined by a series of tests at different manual backlight levels – basic LCDs do not scale power in response to content picture level (e.g., bright or dark frames in a video clip). The line plot of power while playing the 5-minute IEC broadcast test clip reflects a constant power level throughout the test even though luminance changes dramatically over time during the clip. In other words, basic LCDs scale power to luminance when the backlight is manually adjusted, but not frame-to-frame in response to frame-average picture level.[13] The figures below show the case for a basic LCD without local dimming.

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[11] See ERROR! REFERENCE SOURCE NOT FOUND. ERROR! REFERENCE SOURCE NOT FOUND. for an example of the full equation.

[12] For LCDs, the light source level is commonly called the backlight level.

[13] A black frame has an average picture level of 0%, and a solid white frame has an average picture level of 100%.

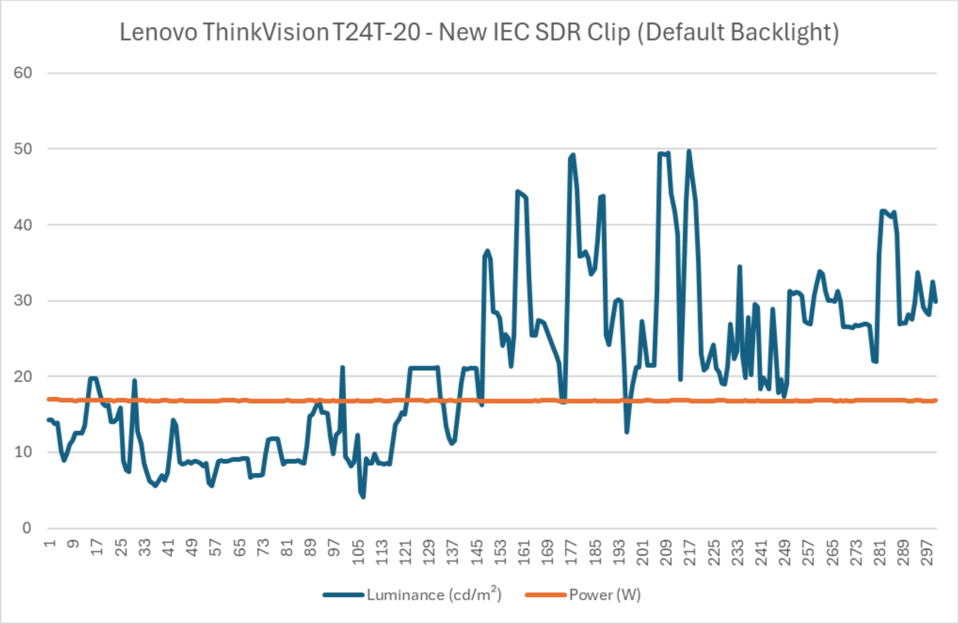

Figure 24: Power and luminance over time while testing the Lenovo ThinkVision T24T-20

Figure 24 shows power and luminance on the Lenovo ThinkVision T24T-20 computer monitor while playing the 5-minute international standard SDR broadcast test clip in its default preset picture setting (PPS) of “Warm.”

Dimming lines for the same display are shown below in Figure 25.Figure 25. Each point represents the average power and luminance from a full 5-minute test run like the one shown above.

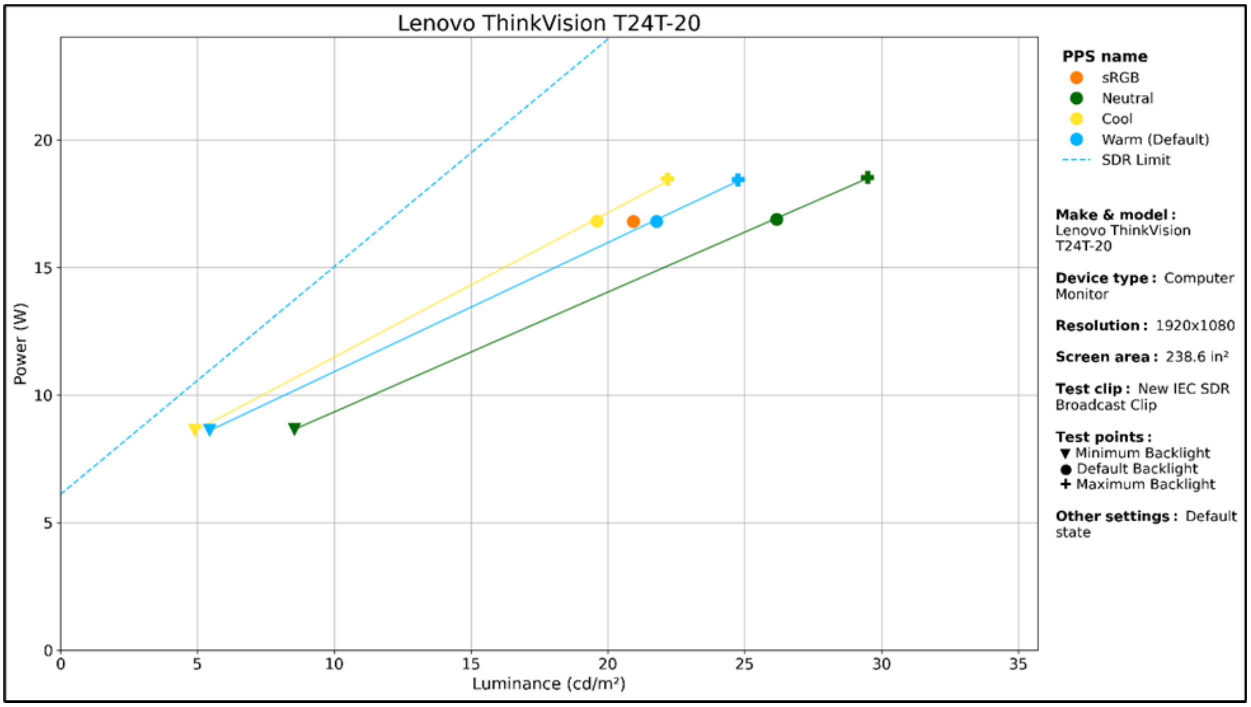

Figure 25: Dimming lines for the different PPSs of the Lenovo ThinkVision T24T-20

LCD Versus Emissive Technology

As detailed in section LIQUID CRYSTAL DISPLAYS (LCD), basic LCDs waste significant backlight energy because they block light coming from the light source to modulate regional light output rather than locally reducing the light source power and output. As a result, basic LCD efficiency scores can be manipulated through picture-setting changes (e.g., lifting midtones via gamma adjustments). By contrast, emissive displays and to an extent LCDs with local dimming inherently scale power to actual content, enabling light-efficiency metrics to provide a stronger incentive for software and component-level energy efficiency gains. If regulators apply too much pressure to basic LCDs, makers of these devices may respond by lowering gamma value, resulting in brighter images more tailored for brightly lit rooms. In other words, policy could negatively affect picture quality settings as opposed to driving energy efficiency improvements.

Emissive displays and LCDs with many local dimming zones scale power to average picture level, but the controls required to do so added a fixed power load. The result is a lower dimming line slope (more power scaling) along with a higher y-intercept (added fixed power load). This presents a policy challenge in that light efficiency limit lines are most useful when they run parallel to the display dimming lines near the limit line. That way there is no incentive to dim or brighten the grading point to achieve a better efficiency score. An OLED display with a high y-intercept and low slope has a strong incentive to have a bright enough light source setting (LSS) so that it falls under a dimming line developed based on the average slope and intercept of all displays (emissive and LCD).

Implications of Signal-to-Light Mapping

Driven by how the human vision system works, displays designed for bright ambient settings like outdoor displays or even computer monitors, which are generally designed for bright office environments are set so that the middle and dark parts of images are displayed at a higher luminance level than for, say, a TV designed for home theater use. To explain this concept, three terms are introduced to describe high, medium and low light output parts of any given image that is displayed:

- Highlights
- Midtones
- Shadow detail

Highlights represent visuals such as reflections of sunlight off a shiny object or direct headlights. Even the brightest displays cannot generate real-world luminance levels for these phenomena, so it is common to leave highlights set to the screen's maximum capability even in a dark theater setting.

Industry standard transfer functions (called gamma curves for SDR video) define how broadcast video signals are converted to light output levels. They control the mix of highlights, midtones, and shadow detail. In addition, these standard transfer functions can be tailored by display OEMs depending on the target ambient light level and other picture quality objectives. Sometimes these customizations are called "tone mapping." Here the broad term "signal-to-light mapping" is introduced as any means of mapping video signal level to light output level, which determines the proportion and light levels of highlights, midtones, and shadow detail achieved by a given display in a specific picture setting.

To put this concept into perspective, for a given highlight level, gamma curves designed for brighter ambient environments (e.g., sunlight or office lighting) result in much more average display light output as shown in the table and figure below, which describe common SDR Electro Optical Transfer Functions (EOTF) and the relative increase in screen-average light output for a given peak luminance level for each EOTF. Here, the light output effects of signal-to-light mappings that are unaltered gamma curves, which are types of SDR EOTFs, are explored.

Table 14: Percentage Increase in average luminance (area under curve) versus Gamma 2.4

Target Gamma	EOTF Description	Normalized Area (vs. Gamma 2.4)
2.4 (Reference)	Standard (Dim Room)	0.0%
2.2	Slightly Less Curved (Bright Room Monitor)	+6.3%
2.0	Less Curved (Typical Commercial/Retail)	+13.3%
1.8	Least Curved (Signage/Aggressive Brightness)	+21.4%

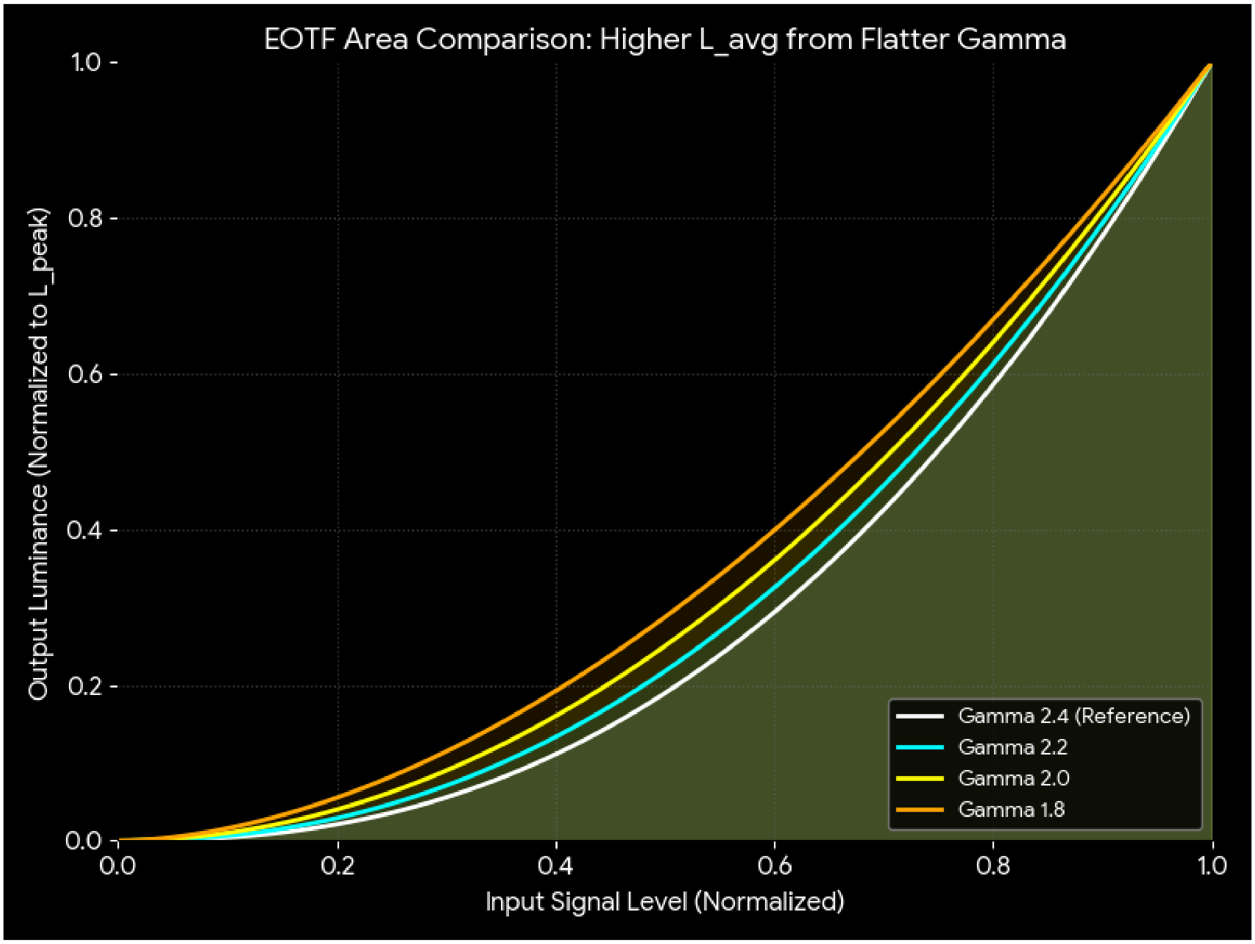

Figure 26: Gamma area comparison

Note: Screen-average light output is proportional to the area under the curve. This gamma 2.4 has the least light output of the curves shown.[14]

Figure 27: Indoor and outdoor displays

Note: Outdoor displays are often set to boost midtones and shadow detail to compete with direct sunlight; TVs are often set to reduce midtones and shadow detail for dark viewing environments.

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[14] Image generated by ChatGPT 5.1

Consider the hypothetical case of an emissive display that has three preset picture settings, one intended for sunlit rooms (gamma 2.0), one for bright indoor lighting (gamma 2.2), and the third for dark theater-style viewing (gamma 2.4). As before, assume that the small highlight areas are equally bright regardless of which of these three settings is chosen. In this context, emissive displays scale power to luminance at a subpixel level, so they emit light equally efficiently in all three settings discussed. Put another way, the dimming lines for all three settings have the same slope and intercept.

However, for basic LCDs, the backlight and therefore power is fixed, so all three settings would use equal power; however, the brightest setting (i.e., sunlight setting) would emit 13.3% more light than the theater setting at the same power level. All three settings would have the same y-intercept, but the slopes would differ by as much as 13.3% with the theater setting having the highest slope, which indicates the lowest light efficient level. While the area under the gamma curve represents the light output, the area above the gamma curve represents the light blocked by the liquid crystals relative to their open state for all subpixels.[15] Figure 28 illustrates a case in which different picture settings result in dramatically different dimming lines, as further discussed in section Limitations of this Approach.

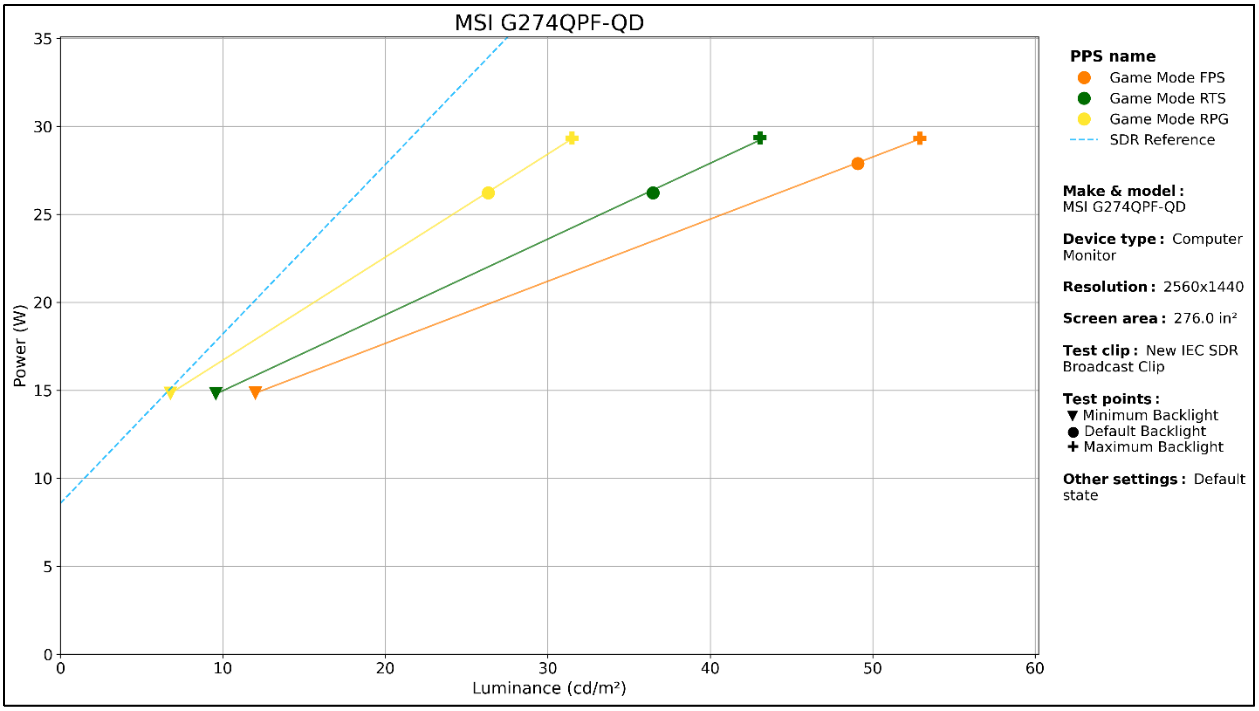

Figure 28: Dimming lines for the MSI G274QPF-QD

Because emissive displays and displays with a high level of local dimming use only as much power as needed to generate the light output across the screen area, power use remains proportional to the area under the gamma curve (the light output).

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[15] For a hypothetical case where there is an even distribution of signal levels across an image.

For an emissive display to improve its efficiency score, it must make a fundamental change in component-level energy efficiency (e.g., power supply, image processor, light source efficacy). However, a basic LCD can improve its efficiency score by changing its signal-to-light mapping, by lifting the midtones and shadow detail, which results in more light output for the same power. The unintended consequence of strict MEPS levels might be that LCD TV manufacturers set their default gamma curves to 2.0, raising the questions of whether consumers, advised by product reviewers, would change the gamma setting back to 2.4, defeating claimed savings and resurfacing questions about settings persistence.

One must also ask whether light output is an effective measure of amenity,[16] where efficiency is often defined as the level of amenity offered for a given amount of power use or energy consumption. An image rendered with gamma 1.8, with elevated midtones and shadow detail, certainly provides more amenity than a gamma 2.4 rendered image when displayed on an outdoor digital signage display. The gamma 1.8 image is clearly readable even in bright ambient light levels; however, the same gamma 1.8 image displayed in a home theater environment would look washed out compared to one rendered with a gamma 2.4 curve. So, while the gamma 2.4 image might involve significantly more power than the gamma 1.8 image at the same average luminance level, it provides more amenity in a theater setting. Screen-average luminance can be a poor proxy for amenity.

This is true for emissive displays as well as for basic LCDs, but light efficiency metrics do not yield unintended consequences with emissive displays. They provide incentives for meaningful component-level efficiency gains that would yield lower power levels regardless of picture settings. This is not the case for basic LCDs, in which case light efficiency metrics can be met by an array of measures, including:

- Lifting midtones and shadow detail (signal-to-light mapping)
- Global and local dynamic backlight dimming
- Component-level efficiency improvements

The first measure is the most concerning because it raises questions about settings persistence in the context of potentially sub-optimal settings that are unlikely to persist. Global and local dynamic backlight control can adversely affect picture quality, especially if set too aggressively. However, in general, reviewers recommend enabling these features because they generally improve contrast ratio. As a result, these features and the energy savings they offer are more likely to persist over time.

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[16] Here, amenity is referred to as a benefit that a display provides its users.

In summary:

- For displays without content-based power scaling/dynamic dimming:
    - Power is proportional peak brightness for 100% white pixels
    - The dimming line slope is higher because liquid crystal layer blocks light to control light output
    - Light-based efficiency metrics can be met by lifting midtones and shadow detail
    - A risk exists for unintended consequences
- For displays with granular content-based power scaling/dynamic dimming (e.g., emissive displays, LCDs with local dimming):
    - Power is proportional to screen-average luminance
    - The dimming line slope is generally lower because the local (or even subpixel) backlight level is adjusted to achieve most local light output adjustments; in the case of LCDs with local dimming, the liquid crystal layer has to perform only minor light output adjustments within small zones that are likely to have similar target light output levels
    - Light-based efficiency metrics generally cannot be met by lifting midtones and shadow detail
    - The risk of unintended consequences is minimal

Other implications of signal-to-light mapping are:

- Basic LCD outdoor displays generally have more light output per watt than indoor displays
- Basic LCD computer monitors generally have more light output per watt than TVs

For basic LCDs, “light efficiency” largely corresponds to the ambient light level that a preset picture setting has been designed to address.

How to Address the Signal-to-Light Problem

PCL’s initial thoughts about how to deal with the unique circumstances surrounding basic LCDs follow. For MEPS, setting limits that place only modest pressure on Active Mode power levels is recommended. PCL’s goal is to put the right Active Mode metrics in place without so much pressure that manufacturers respond in unproductive ways that harm picture quality without meaningfully improving energy efficiency. Supply chain actors like third-party operating systems and power supply component vendors would be monitored as they maneuver to establish a competitive advantage by enabling their customers—TV OEMs—to achieve better efficiency scores. Such differentiated software and hardware choices would reduce OEM risk of failing to meet MEPS and enable OEMs to score better in mandatory and aspirational labeling programs.

PCL tested three different low-cost LCD TVs with global dimming produced by the same OEM but representing all three major third-party operating systems (Google TV, Amazon Fire TV, and Roku TV). Significant variations in efficiency were observed across operating systems, as well as among the dynamic backlight control and picture settings they offer, all of which appeared to offer excellent picture quality. Based on this and other research, there is reasonable confidence that the light efficiency of volume LCDs can be significantly improved without negatively impacting picture quality

Figure 29: Comparison of the same TV with different operating systems

Note: The most efficient of these TVs was 20% more efficient against the light-based efficiency metric than the least efficient of the three. Picture quality demonstrated no detectable differences. The banding that is visible is a result of image capture with a digital camera; it is called the moiré effect.

Efficiency Driver Assessment

This section begins by introducing the definition of energy efficiency that this study adopts as a basis for energy efficiency driver assessment. The research questions, and the methodologies used to address them are described. Laboratory testing and analysis of existing public datasets are employed to identify the energy impacts of different factors. Finally, the results of this research for each display type and each research question are presented.

The dataset includes products from multiple manufacturers representing a range of display technologies and design approaches. References to specific manufacturers or models are included solely for analytical clarity and do not imply endorsement or evaluation by PCL or NEEA.

Energy Efficiency Determination

PCL started exploring the use of a camera photometer and associated light-based metrics in 2019. ENERGY STAR V9 for TVs (effective in 2022) represented the full implementation of these method and metrics. By 2023 the underlying TV test method was standardized as ANSI/CTA-2037-D and adopted by the U.S. Department of Energy as the federal standard. By 2024 several clarifications to this test method were added and PCL proposed several improvements to metrics. To assess for this report the relative Active Mode efficiency of the monitors and DSDs tested and their functions, these hypothetical[17] limits were used as a benchmark against which to compare. Specifically, the findings sections of this report uses the light efficiency part (Limit 1) of an approach that also includes a power cap (Limit 2).

In section POLICY RECOMMENDATIONS offers example metrics and limits based on PCL's 2024 work in that the equations and coefficients are the same. The way in which the limits are applied is different from the 2024 approach, which mirrored ANSI/CTA-2037-D. Additional detail is also provided on the regression methods used to develop the limits.

The sections that follow provide an overview of the basis for these 2024 limits to include a key concept review.

Dimming Line Framework

As mentioned in section KEY CONCEPTS AND CORE PRINCIPLES, the relationship between power and luminance for a display is called its "dimming line," the line that defines how much power the display will use at any given luminance, where luminance is the screen-average luminance averaged over the duration of one of the international standard broadcast test clips. A display that uses less power than its peers across a typical range of luminance levels is relatively more efficient.

Some display Preset Picture Settings (PPSs) present as more energy efficient than others. A single LCD can exhibit different dimming line slopes across PPSs, depending on how the signal is processed and translated to light output. For example, Figure 30 illustrates dimming lines for the different PPSs on a computer monitor tested, where the lower lines (DCI-P3 and Adobe) represent the most efficient PPSs

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[17] They are hypothetical in that no policy tool in effect uses them for Active Mode limits.

according to PCL's metric. In contrast, emissive displays typically show similar slopes and intercepts across PPSs, as illustrated in Figure 35 and discussed in section Benchmark Efficiency Metric Used in this Study.

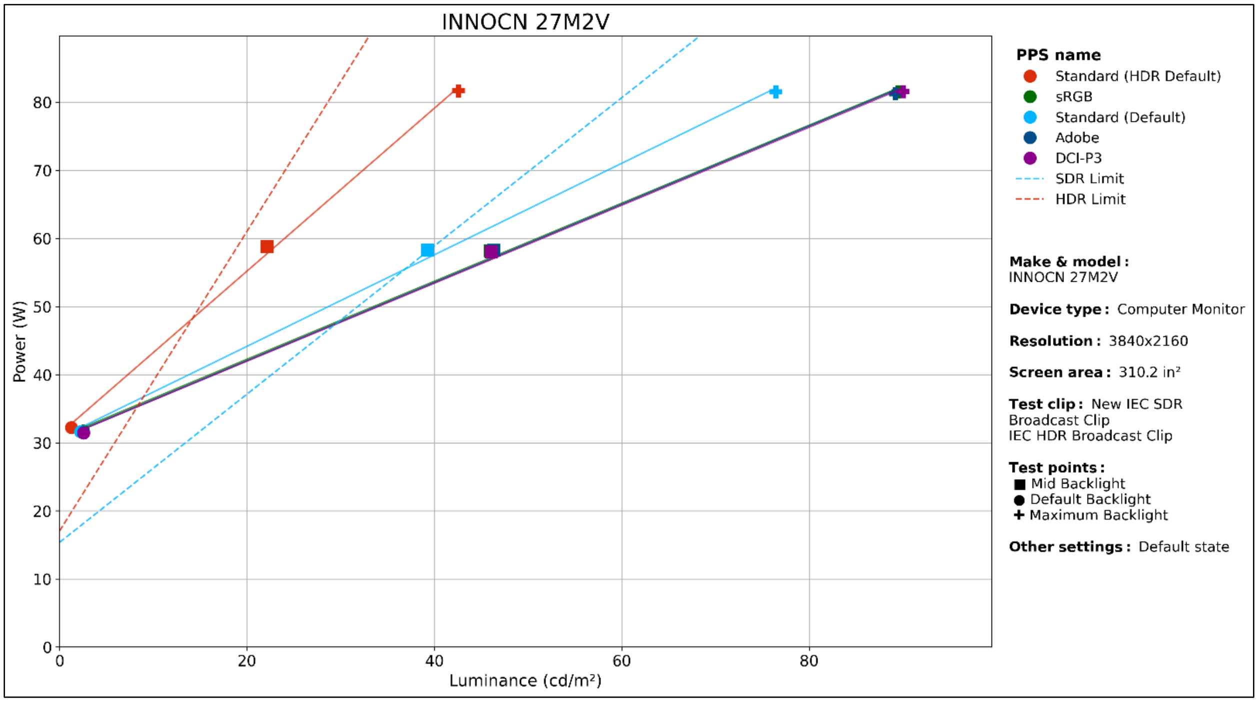

Figure 30: Dimming lines illustrating the relationship between screen-average luminance and power

Notes: The sRGB dimming line is behind the DCI-P3 dimming line as they both had very similar power and luminance readings.

The "Mid Backlight," "Default Backlight," and "Maximum Backlight" test points shown are achieved by adjusting the display's backlight level. For each test point, the backlight setting was held constant while PPSs were changed, so that any measured power differences observed across PPSs reflect signal processing rather than changes in the backlight setting.

In contrast to the proposed approach, the current international standard test method (IEC 62087-3, Edition 2) measures power while playing a broadcast test clip without an effective means to measure luminance. As a result, manufacturers can dim default settings to meet power limits, but users often raise brightness, thus defeating claimed savings.

The dimming line approach is not without risks. If misapplied, it could lead to low gamma images more suited to bright viewing environments or even washed-out images as manufacturers boost brightness in darker image areas to appear more efficient. These risks are analyzed in section Limitations of this Approach.

Benchmark Efficiency Metric Used in this Study

To enable relevant energy efficiency comparisons among models tested in this study across the full range of supported luminance levels, generally each display's dimming lines are plotted (one for each of the tested preset picture settings) against 2024 hypothetical TV power limits (Figure 31). Understanding how the slope and Y-intercept of a display dimming line compares to the slope and intercept of the relevant

2024 TV limit line can yield substantial learnings. **This section refers to limit lines as reference lines** as these lines are not proposed as regulatory limits but used solely as means of comparison across brands and models.

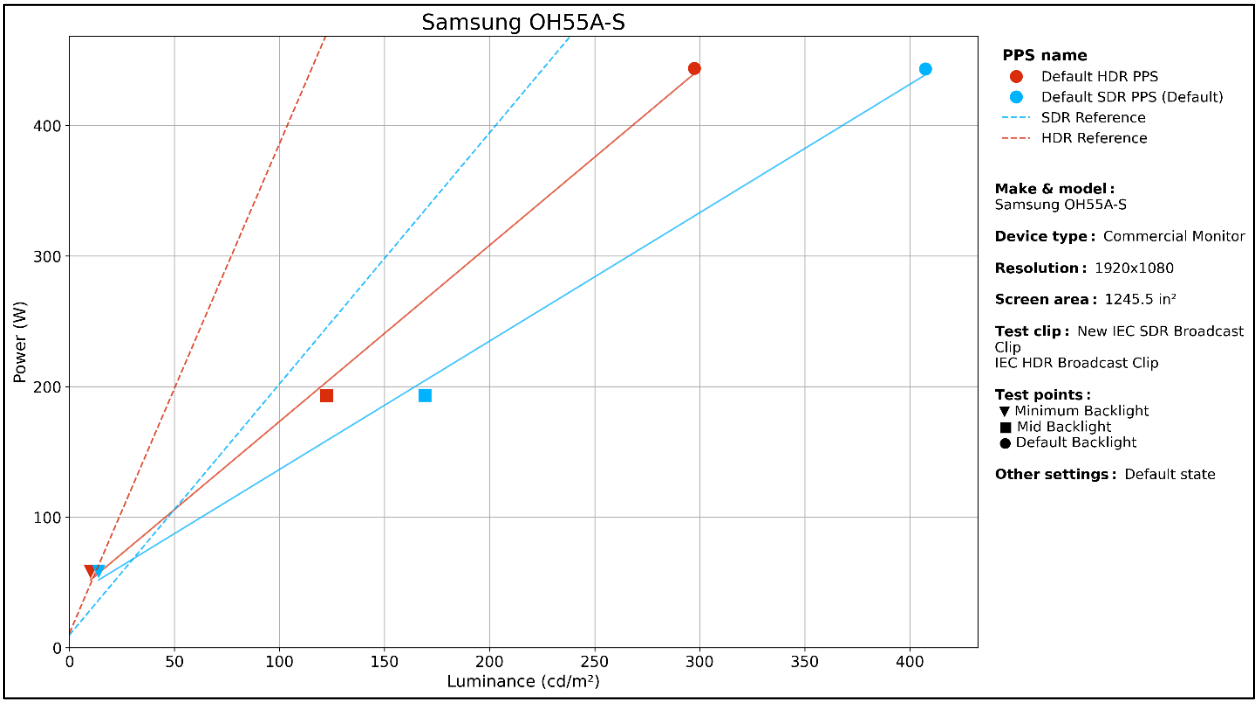

Figure 31: Power reference lines for SDR and HDR for the Samsung OH55A-S commercial monitor

This study quantifies the energy efficiency of each display dimming line with the Power/Reference metric, which is the measured power level divided by the power reference line at the measured screen-average luminance level during a test performed with the display set to its default light source setting (commonly known as backlight or luminance level in existing policy and test standards). Background on the TV limit formula, the efficiency equation, and discussion of energy savings are provided below.

2024 TV Power Reference Lines

In 2024, PCL developed hypothetical luminance-based TV power limit formulas as a starting point for stakeholder discussions about potential TV On Mode SDR and HDR power limits. PCL developed these levels based on analysis of television models in the California Energy Commission's database that span a range of panel technologies, sizes, and resolutions. These limits are modest and not yet adopted for policy use. While PCL developed luminance efficiency metrics (Limit 1) alongside power caps (Limit 2), this analysis focuses solely on Limit 1 (what is referred to as the reference line), as power caps do not support relative luminance-based efficiency comparisons.

PCL developed separate Limit 1 (or reference line) functions for SDR and HDR by averaging dimming lines within each screen area and native resolution category ("bin") and adjusting the slope and intercept to achieve the desired stringency for each bin. This approach helps visualize how far a display sits from a benchmark efficiency threshold across a wide range of luminance levels.[18]

Equation 4 and Table 15 below define Limit 1 or the reference line.

Equation 4: Reference Line (Limit 1)

$$\textbf{Reference Line} = \text{Scaling Factor} \times ((\text{a} + \text{b} \times \text{Screen Area} + \text{c} \times \text{Total Pixel Count}) \times \text{Luminance} + (\text{d} + \text{e} \times \text{Screen Area} + \text{f} \times \text{Total Pixel Count}))$$

Where:

- Luminance is obtained by measuring the screen-average luminance of a display throughout the run of the new IEC SDR dynamic broadcast clip (shown in Table 96)
- Screen Area refers to the viewable and logically addressable screen area (represented in square inches in this case)
- Total Pixel Count refers to the display's resolution, expressed as the total number of physical pixels across the screen

Other coefficients vary between SDR and HDR per Table 15 below.

Table 15: Reference Line coefficients

Coefficient	SDR	HDR
Scaling Factor	0.724673	0.817364
a	0.838099	1.472072
b	0.001413	0.002407
c	2.72E-08	5.7E-08
d	3.119322	3.486500
e	0.004866	0.004848
f	2E-06	1.91E-06

As mentioned earlier, Limit 1 is named to distinguish it from a potential Limit 2, which serves as a cap on power consumption. When using a power cap, displays cannot exceed a specified maximum power level, regardless of how much luminance they produce. While this study does not apply a Limit 2 in the comparison analysis, it is a possible regulatory tool that is used in PCL's example labeling scheme (1.1.1.39).

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[18] Limit 1 and luminance-based metrics in general have some limitations as they do not normalize for picture quality attributes (see 0 LIMITATIONS OF THIS APPROACH for more details).

Power/Reference

As explored in section KEY CONCEPTS AND CORE PRINCIPLES, many efficiency metrics can be used to assess the luminance-based efficiency of displays. One of these metrics was chosen for its ability to easily convey relative performance against the limit. The metric chosen is Power/Reference, which represents the efficiency of a display at its default light source setting (backlight level) with ABC disabled.

Equation 5: Power/Reference

$$\text{Power/Reference} = \frac{\text{Actual power at the grading point}}{\text{Limit 1 power at the grading point}}$$

Where:

- The grading point is the operating point defined by the screen-average luminance produced at the default light source setting with ABC disabled. Both the measured power (numerator) and the Limit 1 allowed power (denominator) are evaluated at this same luminance.

Power/Reference expresses measured power relative to the applicable limit at the measured luminance. In compliance terms, if measured power is 20% higher than Limit 1 power, then Power/Reference is 120%.

Figure 32 illustrates the performance of several 65” televisions with 4K resolution against Limit 1.

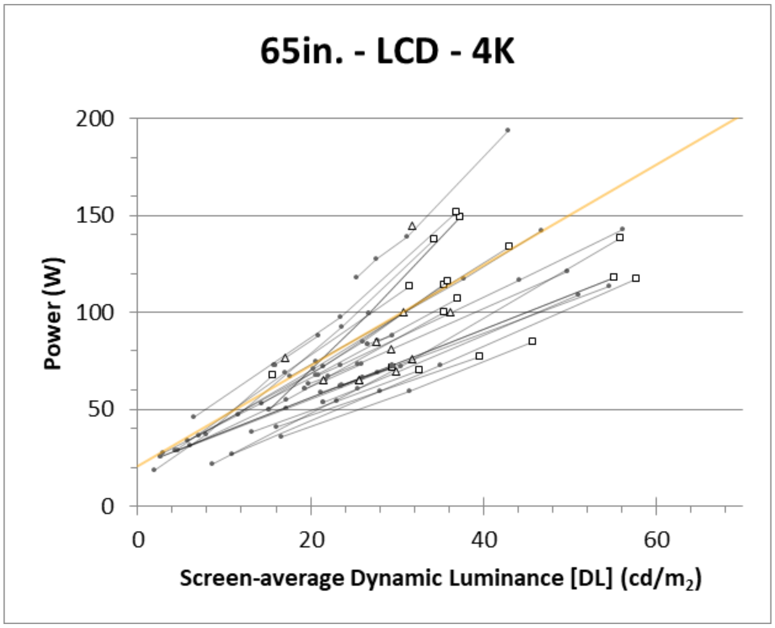

Figure 32: Television dimming lines plotted against the reference line (orange line)

Note: Per ANSI/CTA-2037-D the grading points in this plot are either default light source setting (ABC off, square points) or the average of all ABC points (ABC on, triangle points). If the grading point is on or below the limit line, then the TV complies. This example differs from PCL's approach in that ANSI/CTA-2037-D grades TVs at the average power and luminance of the ABC test points if ABC is enabled by default.

Limitations of this Approach

While this Power/Reference or Limit 1 metric is used as a proxy for energy efficiency throughout this report, it does not fully account for differences in picture quality attributes that can influence the relationship between power and luminance (e.g., contrast behavior and color settings/color gamut). While many such attributes exist (the impact of which is reviewed in sections COMPUTER MONITOR FINDINGS AND DISCUSSION and DIGITAL SIGNAGE DISPLAYS FINDINGS AND Discussion), this section highlights a particular attribute, signal-to-light mapping, which is introduced in the key concepts review (0).

As illustrated in Figure 33, the same display (in this case, the MSI G274QPF-QD) can exhibit varying "efficiency" levels across different PPSs when evaluated using this metric, highlighting the need to interpret results in the context of picture quality trade-offs. This phenomenon is observed across all panel technologies where subpixel-level light output is controlled by blocking light with LCD technology.

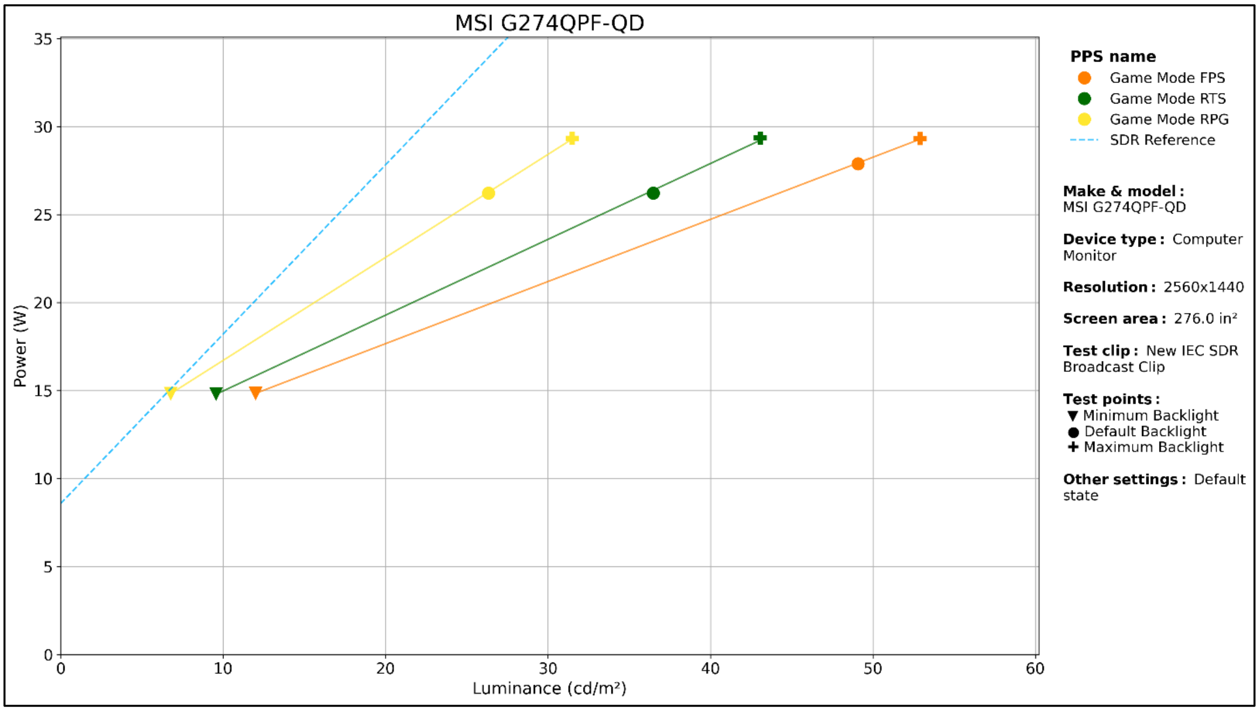

Figure 33: Different PPSs can have different Power/Reference values

To evaluate how picture quality affects the energy efficiency of each PPS, the same video frame using three different PPSs was captured. For each video frame capture, the camera pixel luminance values were plotted in descending order to analyze the distribution of brightness across the screen. As shown in Figure 34, the most efficient PPS by PCL's metric (Game Mode FPS) had raised mid-tones, shadow detail, and black levels, while the least efficient PPS (Game Mode RPG) had a larger proportion of darker pixels. This suggests that differences in signal-to-light mapping contribute to variations in energy efficiency across PPSs.[19]

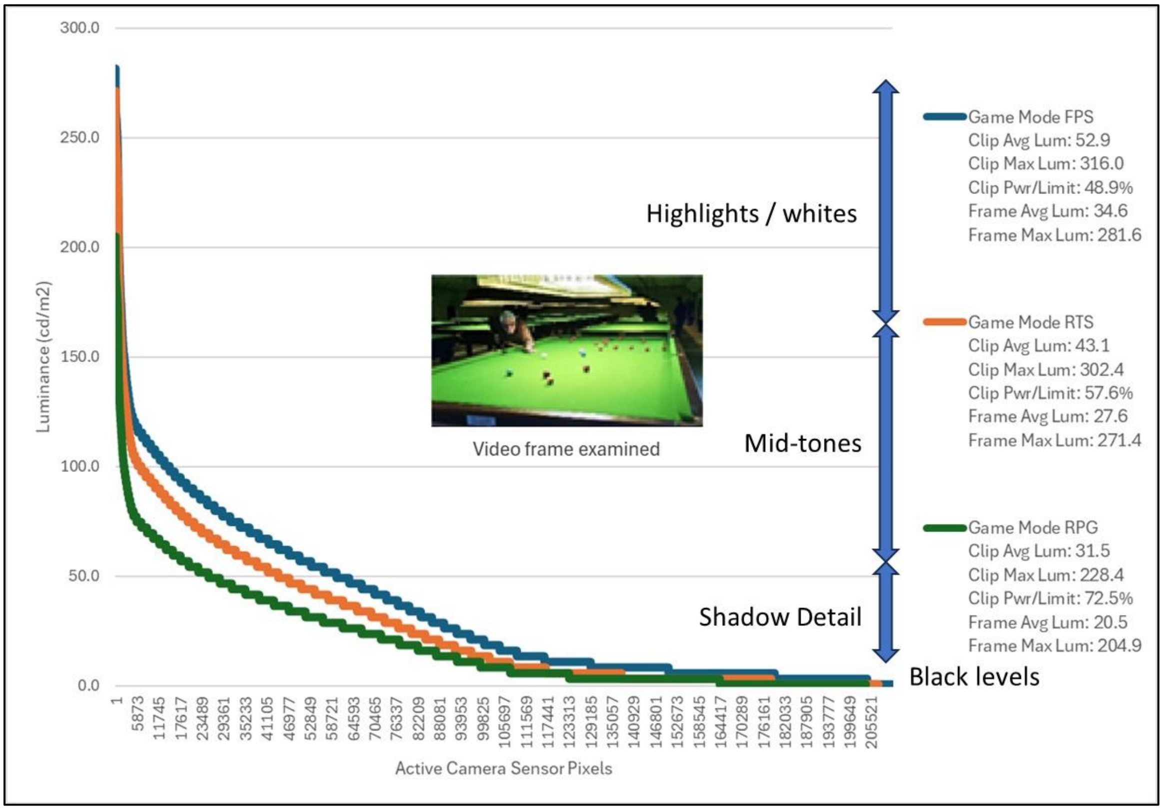

Figure 34: Luminance distribution of camera sensor pixels across PPSs

Basic LCDs with global dimming typically set the entire backlight's luminance level to support the brightest cluster of pixels in each video frame or series of frames and then block some or all that light across the rest of the pixels. Consequently, a PPS with high contrast (bright highlights but darker midtones and shadow detail) will result in low average luminance and high power for LCDs.

Metrics that rely on average screen luminance thus risk penalizing high-contrast modes in basic displays even if their visual quality is intentional and desirable. However, this behavior also reflects a limitation of low-cost global-dimming designs that waste energy by driving the full backlight for small bright areas—a trait that more advanced designs with local dimming or emissive technologies can avoid and which should, in principle, be penalized in efficiency metrics. An inherent trade-off therefore exists. Any metric based on measured screen-average luminance will unavoidably respond both to tone-mapping choices in high-contrast picture modes (undesirable) and to genuine light-output losses arising from low-cost global-dimming designs (desirable).

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[19] Signal-to-light mapping refers to both the transfer function, which translates the video signal into actual light output levels, and tone mapping, which adjusts the image so it fits within the capabilities of the display.

This penalty for rendering bright highlights and deep shadows in basic LCDs explains why HDR picture settings are typically less efficient (i.e., have steeper dimming lines) than SDR settings. Current policy treats this as justified by user amenity, applying less stringent efficiency limits to HDR modes. Although sufficient HDR power consumption data exists to support specific limit recommendations, extending this approach to other PPS (e.g., “Movie,” “Sport,” “Vivid”) would be impractical, as their names and signal-to-light mappings differ across manufacturers and cannot be standardized reliably.

Figure 35 shows a display from the same brand as the previous graph with same PPSs but with OLED instead of LCD technology. Emissive technologies like OLED do not need to block light since they produce the desired light level at each subpixel (of course, this precise fine-tuning over light emission comes at the cost of additional power overhead). So, an OLED display typically has PPS dimming lines that all fall on the same line regardless of the signal-to-light mapping applied.

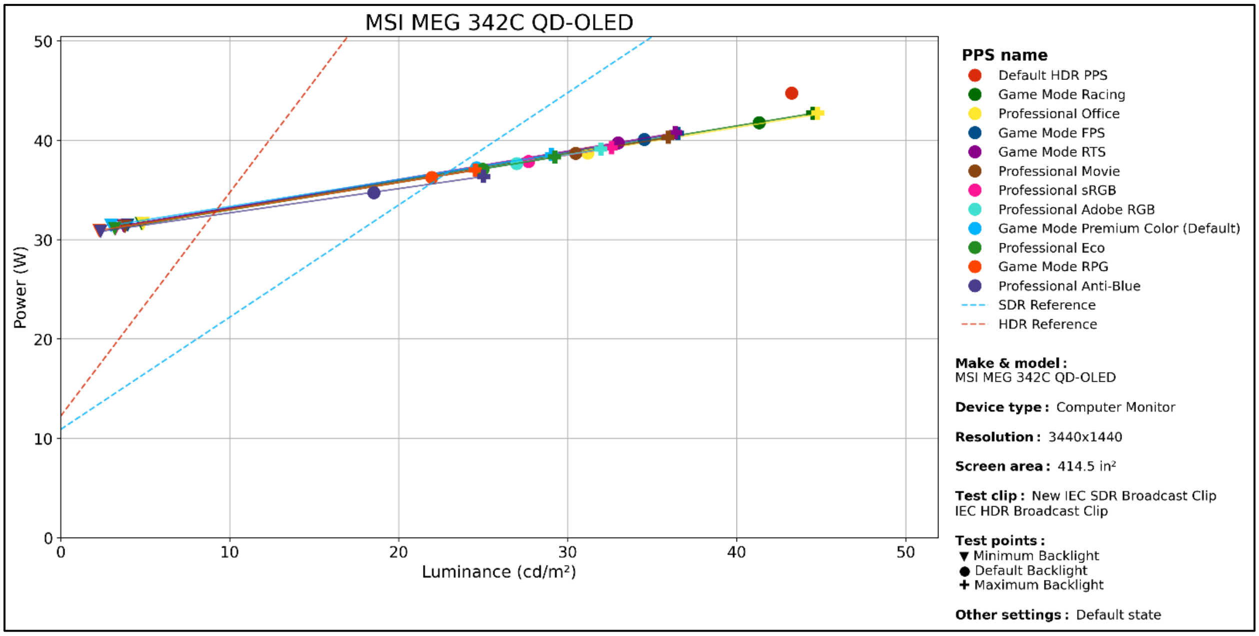

Figure 35: This MSI OLED monitor has similar energy efficiency across its different PPSs

As pictured in Figure 35, the efficiency differences between OLED PPSs are much smaller than for LCDs, showing that signal-to-light mapping has less influence on the relationship between power and luminance in emissive displays. Emissive displays only emit the light they need to display images. Light output is not controlled by blocking light with LCD technology.

The reference line equation does not normalize for several picture quality features that affect energy efficiency (e.g., contrast ratio, color gamut, local and global dimming; see test results in following sections). Signal-to-light mapping has been specifically highlighted because overly stringent limits for basic LCDs could encourage manufacturers to adjust mappings to score better while producing washed-out images with poor contrast. As basic LCDs occupy lower price points that advanced displays cannot reach, it would be inappropriate to impose limits they could meet only by degrading picture quality if no other technological alternatives are available at this price point.

It is difficult to account for signal-to-light mapping in an efficiency limit equation as it is hard to measure and translate into amenity. Without normalizing for it, one cannot tell whether a given display has a high dimming line slope because of signal-to-light mapping or because of other design decisions.

The picture quality of every display sold today has been optimized before product release to increase product marketability. The market offers a huge range of light efficiency levels, uncorrelated to price point within panel type size bins. Expensive displays are not necessarily more efficient, and cheap ones are not necessarily less efficient. The variation in efficiency largely reflects design choices such as signal-to-light mapping and dynamic backlight control, not manufacturing cost.

Furthermore, in past tests of basic LCDs, non-default PPSs were found that were much more efficient than the default setting and had the same or better picture quality to untrained eyes. This may indicate that default modes are often chosen for visual impact rather than for efficiency, and that meaningful energy savings could be achieved without degrading user experience. It also suggests that efficiency testing based solely on default settings may not reflect the best achievable performance.

The new camera-based test method effectively quantifies light output and power demand, but the interplay between luminance, perceived image quality, and efficiency should be treated carefully in policy development to ensure limits remain technically robust while taking into account viewing experience.

Research Methodology and Findings

This section presents the findings of PCL's efforts to determine the impact on energy efficiency of different features in computer monitors and DSDs.

Table 16 summarizes these research questions for developing effective policy recommendations. These research questions fall into two categories:

- What should be measured in policy
- The effects of different technologies, capabilities, and settings on energy efficiency/usage

Table 16 provides links to the relevant sections addressing each research question for both computer monitors and DSDs.

Table 16: Summary of research questions

Research Question	Computer Monitors	DSDs
Active Mode		
What to Measure		
Screen-Average versus Screen-Center Luminance	X	X
Dynamic Broadcast Clip versus Test Patterns	X	X
Automatic Brightness Control		X
Effect on Energy Efficiency		
Panel Technologies		
Panel Type	X	
Modular Panels		X
Local and Pixel-Level Dimming Setting	X	X
Global Dimming Setting	X	X
Image Processing		
Color Gamut Setting and Capability	X	X
Contrast Ratio Capability	X	X
Viewing Angle Capability	X	X
AI Image Processing Setting	X	
Performance		
Duty Cycle Capability	X	X
Refresh Rate Capability and Setting	X	
Variable Refresh Rate Capability and Setting	X	
Response Time Setting	X	
Other		
Touchscreen Capability and Setting	X	X
HDR Content Format	X	
USB Charging Capability and Setting	X	
Screen Curvature Capability and Setting	X	
KVM Switch Setting	X	
Operating System Capability and Setting		X
Outdoor Use Capability		X
Non-Active Mode		
What to Measure		
Which Non-Active Modes	X	X
Effect on Energy Usage		
Touchscreen Setting	X	
Quick Start and Deep Level Setting	X	
USB Charging Setting	X	
Decorative RGB Lighting Setting	X	

The section begins by proposing a means for quantifying Active Mode energy efficiency and explaining the limitations of this proposed scoring method. PCL's laboratory testing methodology is then introduced, which primarily builds on current TV energy efficiency testing methods (namely, the US federal test method, which incorporates by reference the ANSI/CTA-2037-D standard), while combining elements of existing monitor and DSD testing approaches (ENERGY STAR Displays 8.0, CEC Title 20, and the EU Ecodesign) for comparison. In addition, several picture quality tests are conducted—such as screen uniformity, contrast ratio, and color gamut—to assess whether these performance attributes meaningfully affect energy efficiency.

Next, the dataset analysis methodology is described, detailing the datasets utilized, any additional product information collected through supplementary research, and the regression analysis techniques used to identify and characterize energy drivers.

Finally, PCL's findings on which display features influence energy efficiency based on PCL's laboratory testing and dataset analysis results are presented. This report differentiates between the energy impact of a feature simply being available (**capability**) versus the impact of its **setting** (e.g., enabled/disabled, high/medium/low). Some features may increase baseline power consumption even when inactive, while others only affect energy use when enabled.

Table 17 summarizes PCL's findings about the energy efficiency impacts of different features. More in-depth explanations of each feature are available in the relevant findings section.

Table 17: Summary of different features' impacts on energy efficiency

Feature	Capability/Setting	Effect on Active Mode Energy Efficiency	Test method
Local and Global Dimming			
Local dimming	Setting	Active local dimming improves energy efficiency.	DYNAMIC BROADCAST Clip
Global dimming	Setting	Global dimming improves energy efficiency in optimized implementations.	DYNAMIC BROADCAST Clip
Image Processing			
Color gamut	Capability	Wide color gamut support decreases energy efficiency.	COLOR GAMUT
	Setting	Has no correlation with energy efficiency.	
Contrast ratio	Capability	High contrast ratios (as measured with a static pattern) decrease energy efficiency per PCL's metric.	CONTRAST RATIO
Viewing angles	Capability	Maintaining contrast ratio and color gamut at wide viewing angles does not affect energy efficiency.	VIEWING ANGLE
AI image processing	Setting	Enabling AI-powered features slightly increases power consumption in the implementation tested.	DYNAMIC BROADCAST CLIP
Content Format			
HDR	Setting	Playing HDR content is consistently less energy efficient than playing SDR content.	DYNAMIC BROADCAST CLIP
Performance			
Refresh rate	Capability	Supporting higher refresh rates correlates with lower energy efficiency.	DYNAMIC BROADCAST CLIP
	Setting	Using higher refresh rates increases power consumption and therefore decreases energy efficiency.	
Supported duty cycle[20]	Capability	Supported duty cycles do not correlate with energy efficiency.	DYNAMIC BROADCAST CLIP
Response time	Setting	Using a faster response time setting does not affect energy efficiency.	DYNAMIC BROADCAST CLIP

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[20] This refers to the active and inactive times for which a display system is rated.

Table 18 (cont'd): Summary of different features' impacts on energy efficiency

Feature	Capability/Setting	Effect on Active Mode Energy Efficiency	Test method
Hardware and Connectivity			
USB charging	Capability	Supporting USB charging has a very slight negative impact on energy efficiency.	Dynamic Broadcast Clip
	Setting	Enabling USB charging ports increases power consumption slightly.	
Touchscreen	Capability	There is a lack of sufficient data regarding the impact of touchscreen capability (without it being enabled) on energy efficiency.	Dynamic Broadcast Clip
	Setting	Enabling touchscreen increases power consumption.	
Screen curvature	Capability	Screen curvature negatively affects energy efficiency.	Dynamic Broadcast Clip
	Setting	Changing screen curvature on the same display has no correlation with energy efficiency.	
Support for outdoor use	Capability	Supporting outdoor use has no correlation with energy efficiency.	Dynamic Broadcast Clip
KVM switch	Setting	Enabling KVM switches does not impact energy efficiency.	Dynamic Broadcast Clip
Operating Systems			
Operating system	Capability	There is a lack of sufficient data on the impact of supporting an operating system on energy consumption.[21]	Dynamic Broadcast Clip
	Setting	Enabling the operating system slightly increases power consumption.[22]	Dynamic Broadcast Clip

Note: Legend for **Effect on Active Mode Energy Efficiency** column, relative to energy efficiency: Improves measure; slightly worsens measure; worsens measure; no impact or correlation; insufficient data.

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[21] This refers to a display supporting an operating system (e.g., Tizen, WebOS, Roku) rather than a pared-down options menu.

[22] Although disabling a display's operating system is generally not possible, one model tested (the LG 75TR3DK-B) offers such an option.

Features that do not impact energy efficiency will not be discussed further in section Policy Recommendations section unless PCL's recommendation regarding that feature differs from current policy approaches.

Methodology

Laboratory Testing

Testing was completed on 20 computer monitors and 9 DSDs to evaluate how various display settings and features influence energy efficiency, including those that may affect picture quality. This is a critical consideration given the risk of manufacturers meeting Active Mode limits by degrading visual performance.

Table 19 summarizes the test types, methods, objectives, equipment configurations, and research questions addressed. These tests were conducted on all displays tested. Additional details on PCL's overall methodology and sample plan are available in ANNEX A: METHODOLOGY and ANNEX B: SAMPLE PLAN. Specific models evaluated in this analysis are listed in ANNEX B: SAMPLE PLAN and are provided for transparency and reproducibility.

Table 19: Laboratory testing methodology summary

Test	Method and Objective	Equipment Under Test (EUT) Configuration
Active Mode		
Dynamic Broadcast Clip Test	Measures power and screen-average luminance while playing a broadcast content test clip to assess the relationship between power and luminance across various test conditions. Results are compared to a hypothetical power reference line developed by PCL for TVs to evaluate efficiency across product classes. This test is used throughout feature analysis to evaluate energy impact.	The EUT is configured according to the ANSI/CTA2037-D-based procedure described in BASIC ACTIVE MODE TEST CONFIGURATION. This is true for all Active Mode tests. Measurements are taken for each available PPS at different light source settings or ABC levels.
Screen-Center Test Pattern Test	Measures screen-center luminance using current policy test patterns (the three-bar video signal, Video Electronics Standards Association (VESA) L80, and box-and-outline patterns). The objective is to compare static test pattern to dynamic broadcast clip results and test the hypothesis that screen-center measurements poorly represent the dynamic, screen-average luminance perceived by a viewer.	EUT is set to its default PPS and default light source setting, with ABC off.
Uniformity Test	Measures both screen-center and screen-average luminance of a uniform gray pattern to assess whether screen-center luminance is a reliable proxy for viewers' actual experiences (screen-average luminance).	EUT is set to its default PPS and default light source setting, with ABC off.
Color Gamut Test	Measures the display's color gamut in its default setting to evaluate whether wider gamut coverage correlates with higher energy use.	EUT is set to its default PPS and default light source setting, with ABC off.
Contrast Ratio Test	Measures the contrast ratio of the display's default setting to explore its relationship with energy consumption.	EUT is set to its default PPS and default light source setting, with ABC off.
Viewing Angle Test	Assesses the extent to which contrast ratio and color gamut are maintained at various viewing angles in the default setting to evaluate their possible impacts on energy use.	EUT is set to its default PPS and default light source setting, with ABC off.

Table 20 (cont'd): Laboratory testing methodology summary

Non-Active Mode[23]		
For computer monitors	Measures power consumption in D3hot and D3cold states to reflect the Non-Active Mode energy consumption of modern monitor usage.	The EUT is configured according to the ANSI/CTA-2037-D-based procedure described in Sample Configuration
For DSDs	Measures Standby power per ANSI/CTA-2037-D and Off Mode power as defined by IEC 62087-3 Edition 3 committee draft.	

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[23] The testing approach differs between computer monitors and DSDs to better reflect the typical use cases of each display type.

Dataset Analysis

Dataset analysis was used to assess how key product features affect efficiency and to inform recommendations on product scope, test methods, and power adders. This approach enabled evaluation of a broader sample base than possible through laboratory testing. Regression analysis provided the main insights, identifying which features most strongly influence energy efficiency. The datasets were also used to examine feature prevalence and trends in Non-Active Mode power consumption

This analysis provides an initial basis for policy discussion. Although the regression results have low statistical confidence—reflecting weak model fit and uncertainty in feature effects—they draw on a much larger dataset than could be covered by testing. Specific power adders are proposed based on these findings (see section 1.1.1.41.2: ADDERS), but their adoption is not recommended without stakeholder review.

The dataset analysis addresses the research questions outlined in Table 21 below.

Table 21: Summary of research questions for dataset analysis

Research Question	Computer Monitors	DSDs
Active Mode		
What to Measure		
Screen-Average versus Screen-Center Luminance	X	X
Dynamic Broadcast Clip versus Test Patterns	X	X
Automatic Brightness Control		X
Effect on Energy Efficiency		
Panel Technologies		
Panel Type	X	
Modular Panels		X
Local and Pixel-Level Dimming Setting	X	X
Global Dimming Setting	X	X
Image Processing		
Color Gamut Setting and Capability	X	X
Contrast Ratio Capability	X	X
Viewing Angle Capability	X	X
AI Image Processing Setting	X	
Performance		
Duty Cycle Capability	X	X
Refresh Rate Capability and Setting	X	
Variable Refresh Rate Capability and Setting	X	
Response Time Setting	X	

Table 22 (cont'd): Summary of research questions for dataset analysis

Other		
Touchscreen Capability and Setting	X	X
HDR Content Format	X	
USB Charging Capability and Setting	X	
Screen Curvature Capability and Setting	X	
KVM Switch Setting	X	
Operating System Capability and Setting		X
Outdoor Use Capability		X
Non-Active Mode		
What to Measure		
Which Non-Active Modes	X	X
Effect on Energy Usage		
Touchscreen Setting	X	X
Quick Start and Deep Level Setting	X	
USB Charging Setting	X	
Decorative RGB Lighting Setting	X	

Note: Legend for **Computer Monitors** and **DSDs** columns: [applies]; [does not apply]

To this end, the following datasets were analyzed:

- California Energy Commission's Modernized Appliance Efficiency Database System (CEC MAEDbS) (March 2025)[24]
- ENERGY STAR Displays Version 8.0 Dataset (February 2020)[25]

Although the ENERGY STAR dataset is older, it includes several variables missing from the CEC MAEDbS dataset, making its resulting regression analysis an important point of review for this study.

When additional information for either dataset was needed, Google's Gemini Deep Research was used to perform initial data collection and then those results were validated with manual review of product documentation. For example, this tool was used to gather additional refresh rate data as the 2025 CEC MAEDbS dataset included maximum refresh data for only few models.

While access to the ENERGY STAR Certified Products list was available, this data was not used, as those displays are generally already present in the CEC MAEDbS dataset. Additionally, the European Product Registry for Energy Labelling (EPREL) could not be used, as the accessible dataset does not include luminance data from which energy efficiency could be estimated.

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[24] For CEC MAEDbS, display data was accessed by searching by Appliance Type. Computer monitor data can be accessed under the "Computers" category and "Computer Monitors" appliance type. DSD data can be found under the "Electronics" category and "Televisions and Signage Displays" appliance type.

[25] The ENERGY STAR 8.0 dataset is available on the Displays Specification Version 8.0 website. The same .XLS file stores computer monitor and DSD data.

To enable comparison of dataset results with the laboratory findings of this study, differences among the three test methods (PCL's research method, ENERGY STAR Displays, and CEC Title 20 for computer monitors) are presented in Table 23.

Table 23: Comparison between test methods

PCL Method for this Study		ENERGY STAR Displays 7.0 and 8.0	CEC Title 20 (Computer Monitors)
Pre-Testing Configuration	Connects EUT to the internet (if available), enables any Smart Standby features (if available; only on one sample). All other settings left in as-shipped configuration unless otherwise specified.	Uses as-shipped EUT configuration unless otherwise specified in test method. Warms up EUT for at least 20 minutes while displaying the IEC 62087:2011 dynamic broadcast-content signal.	Same as ENERGY STAR, except: • Product features and functions not specifically addressed by the test method shall be turned off or disconnected • Built-in speakers shall be muted or turned down to their lowest volume setting for Active Mode power measurements • Any feature unrelated to the display of images (USB hubs, webcams, speakers, LAN connections, SD card readers) shall be turned off
Active Mode Testing			
Luminance	Measures power and screen-average luminance while playing the new IEC 62087 broadcast test clip at default, minimum, and maximum light source settings.[26]	Measures luminance immediately after the warm-up period with ABC disabled using the three-bar video signal or VESA L80 if video signal cannot be displayed. Displays the test pattern for 10 minutes prior to measuring, unless luminance is stable to within 2% over a period of at least 60 seconds. Measures luminance in as-shipped and maximum levels (after setting brightness and contrast to their maximum values).	Same as ENERGY STAR
Power		Sets luminance using the three-bar pattern to at least 65% of the manufacturer-reported maximum luminance for DSDs, or as close as possible to 200 cd/m^2 for all other products. Measures power while displaying the IEC 62087:2011 dynamic broadcast test signal.	Same as ENERGY STAR

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[26] While this is PCL's main methodology, luminance was also measured according to the methods found in the ENERGY STAR Displays 8.0 and Ecodesign policies for comparison purposes.

Table 20 (cont'd): Comparison between test methods

Non-Active Mode Testing			
Standby	Measures D3hot and D3cold states in computer monitors.	Referred to as "Sleep" in this method. Sleep Mode test conducted with the EUT connected to the same host machine as during Active Mode tests. If possible, Sleep Mode is entered by putting the Host Machine to sleep. Other methods to enter Sleep Mode shall be measured. If there are different options for Sleep Mode behavior (e.g., Quick Start), those shall be measured as well. Measures Standby in DSDs per ANSI/CTA-2037-D. Measures D3hot and D3cold states in computer monitors.	Same as ENERGY STAR
Off	Not measured[27]	Measures Off Mode power per section 5.3.1 of IEC 62301:2011.	Same as ENERGY STAR

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[27] Off Mode power consumption was not measured as it is generally not supported. The ENERGY STAR dataset refers to what this report calls D3cold state as Off Mode. This is not the definition of Off Mode used here; instead, this report refers to the latest definition of Off Mode in IEC 62301.

The key regression outputs used for PCL's energy efficiency assessment are the explicit linear formulas to predict Power/Reference, listing the intercepts and coefficients for each setting or capability, to be applied per Equation 6 below.

Equation 6: How to predict dependent variables from regression analysis coefficients

$$Dependent\ Variable = Intercept + Coefficient\ Value * Independent\ Variable$$

Where:

- **Dependent Variable** is the expected Power/Reference value
- **Intercept** is the constant value to which coefficients are applied
- **Coefficient Value** is the effect a given feature is predicted to have on Power/Reference
- **Independent Value** indicates the presence or lack thereof of a given feature

Regression model performance was evaluated using the R^2 statistic, which indicates how well the model explains the variability in the target outcome. Higher R^2 values suggest a better fit.

Additional details on PCL's regression methodology are available in ANNEX A: METHODOLOGY.

Computer Monitor Findings and Discussion

This section presents PCL's findings regarding energy efficiency drivers in monitors via laboratory testing, dataset analysis, and secondary research.

PCL's laboratory testing attempted to isolate the impact of settings by turning the features on and off and comparing results within the same monitor. In each case, details are provided on the specific configurations tested.

Comparisons were performed across models with different capabilities and settings by seeing how they performed against the power reference line. This comparison was made using PCL's own test data and the dataset analysis approach described in section DATASET ANALYSIS. Although the previous section already presents PCL's dataset analysis findings, this section further discusses them.

Whenever relevant, test results and analysis are supplemented with secondary research for additional context.

The key research questions presented that are relevant to computer monitors are highlighted in

Table 24 below.

Table 24: Research questions for computer monitors

Research Question	Computer Monitors	DSDs
Active Mode		
What to Measure		
Screen-Average versus Screen-Center Luminance	X	X
Broadcast Clip versus Test Patterns	X	X
Automatic Brightness Control		X
Effect on Energy Efficiency		
Panel Technologies		
Panel Type	X	
Modular Panels		X
Local and Pixel-Level Dimming Setting	X	X
Global Dimming Setting	X	X
Image Processing		
Color Gamut Setting and Capability	X	X
Contrast Ratio Capability	X	X
Viewing Angle Capability	X	X
AI Image Processing Setting	X	
Performance		
Duty Cycle Capability	X	X
Refresh Rate Capability and Setting	X	
Variable Refresh Rate Capability and Setting	X	
Response Time Setting	X	
Other		
Touchscreen Capability and Setting	X	X
HDR Content Format	X	
USB Charging Capability and Setting	X	
Screen Curvature Capability and Setting	X	
KVM Switch Setting	X	
Operating System Capability and Setting		X
Outdoor Use Capability		X
Non-Active Mode		
What to Measure		
Which Non-Active Modes	X	X
Effect on Energy Usage		
Touchscreen Setting	X	
Quick Start and Deep Level Setting	X	
USB Charging Setting	X	
Decorative RGB Lighting Setting	X	

Note: Legend for **Computer Monitors** and **DSDs** columns: [applies]; [does not apply]

Since only one computer monitor in the laboratory sample had ABC functionality (the LG 42 OLED Flex), ABC performance in computer monitors was not assessed beyond developing dimming lines for that monitor. See ANNEX C: DIMMING LINES FOR ALL DISPLAYS Tested.

As before, this report distinguishes between the impact of a feature being available (referred to as its **capability**) and the impact of that feature being actively **enabled** or in use in the sections that follow.

1.1.1.13 Active Mode

1.1.1.13.1 What to Measure: Screen-Average versus Screen-Center Luminance

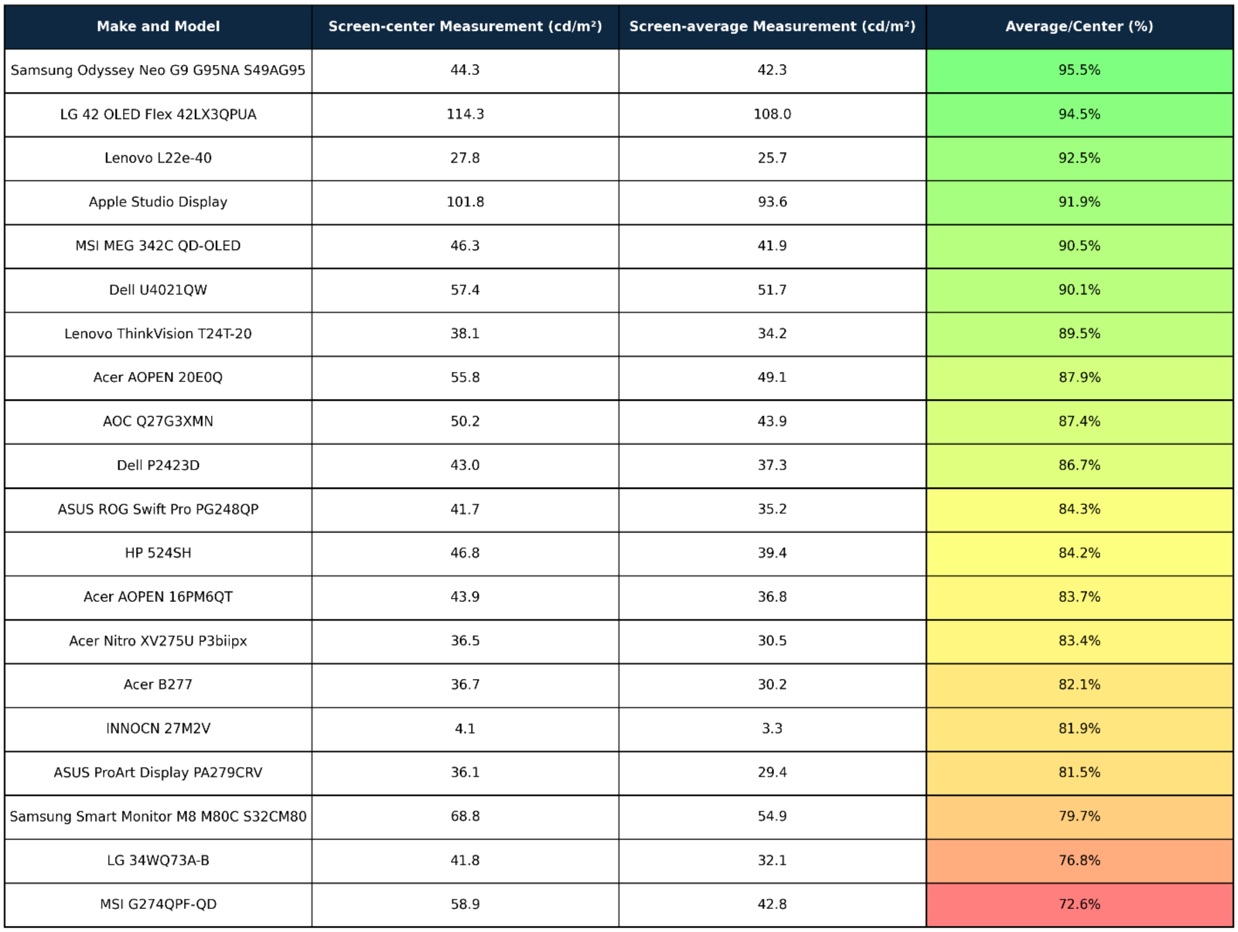
In many existing policies that do not use camera photometers to measure screen-average luminance, screen-center (also known as spot or peak) luminance readings are used. Power is measured separately, while playing broadcast content. A more detailed description of each measurement method is provided in the POWER AND LUMINANCE TESTING section of ANNEX A: METHODOLOGY.

The goal of this testing is to investigate whether screen-center luminance measurements are representative of screen-average measurements.

1.1.1.13.1.1 Test Results

Screen-center and screen-average luminance measurements of the same solid pattern (the gray pattern referenced in Table 96) were compared. This testing shows that the ratio of screen-center measurements to screen-average (full screen) measurements varies significantly across different models, as seen in Table 25.

Table 25: Screen-center versus screen-average measurements of the gray pattern



Make and Model	Screen-center Measurement (cd/m²)	Screen-average Measurement (cd/m²)	Average/Center (%)
Samsung Odyssey Neo G9 G95NA S49AG95	44.3	42.3	95.5%
LG 42 OLED Flex 42LX3QPUA	114.3	108.0	94.5%
Lenovo L22e-40	27.8	25.7	92.5%
Apple Studio Display	101.8	93.6	91.9%
MSI MEG 342C QD-OLED	46.3	41.9	90.5%
Dell U4021QW	57.4	51.7	90.1%
Lenovo ThinkVision T24T-20	38.1	34.2	89.5%
Acer AOPEN 20E0Q	55.8	49.1	87.9%
AOC Q27G3XMN	50.2	43.9	87.4%
Dell P2423D	43.0	37.3	86.7%
ASUS ROG Swift Pro PG248QP	41.7	35.2	84.3%
HP 524SH	46.8	39.4	84.2%
Acer AOPEN 16PM6QT	43.9	36.8	83.7%
Acer Nitro XV275U P3biipx	36.5	30.5	83.4%
Acer B277	36.7	30.2	82.1%
INNOCN 27M2V	4.1	3.3	81.9%
ASUS ProArt Display PA279CRV	36.1	29.4	81.5%
Samsung Smart Monitor M8 M80C S32CM80	68.8	54.9	79.7%
LG 34WQ73A-B	41.8	32.1	76.8%
MSI G274QPF-QD	58.9	42.8	72.6%

Figure 36 plots the screen-center versus screen-average luminance measurements.

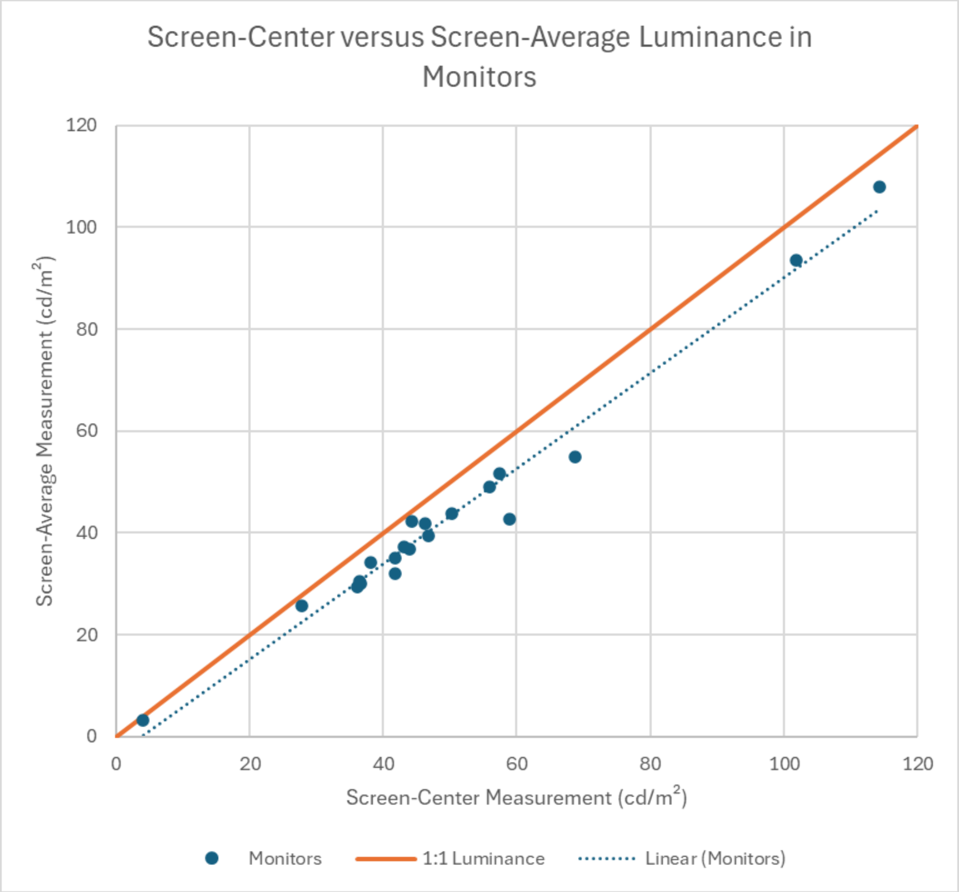


Figure 36: Screen-center versus screen-average measurements in monitors of grey pattern

The variation in screen-average to screen-center luminance ratio across displays shows that screen-center luminance is a poor predictor of the light output enjoyed by a viewer across the full screen.

Full screen measurement is therefore required to characterize luminance performance.

1.1.1.13.1.2 Dataset Findings

Since the datasets looked at do not have both screen-average and screen-center luminance data, further comparisons cannot be made with them.

1.1.1.13.2 What to Measure: Dynamic Broadcast Clip versus Test Patterns

Current energy efficiency policies often use test patterns and screen-center measurements to characterize luminance. These measurements do not represent full-screen luminance, and they do not reliably predict luminance during dynamic video content. For this reason, static pattern results are not a dependable basis for performance metrics intended to reflect in-use viewing conditions.

This testing aims to determine whether screen-center test pattern measurements can predict screen-average broadcast clip luminance.

1.1.1.13.2.1 Test Results

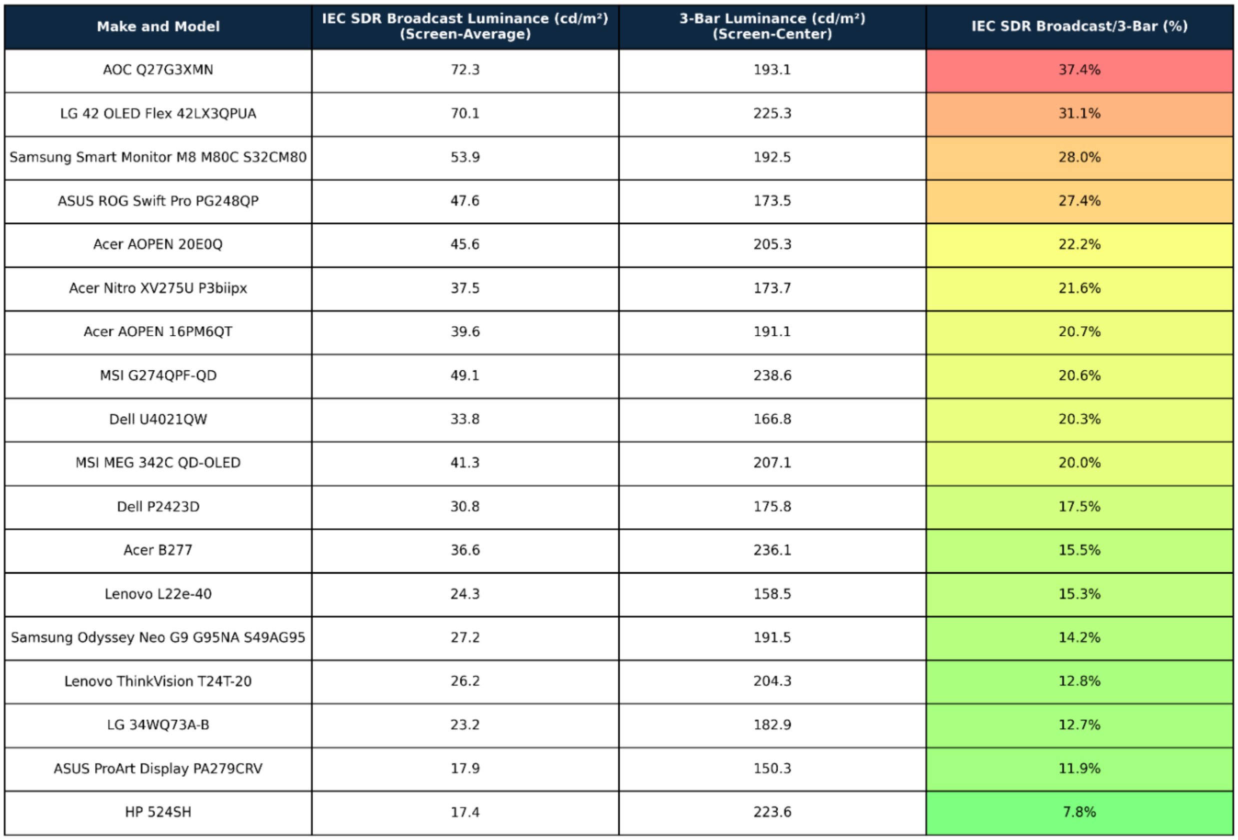
To evaluate whether static pattern measurements can reliably predict dynamic broadcast clip luminance, this test compared luminance ratios between the broadcast clip (measured over the screen area) and the following static test patterns (measured at screen center) currently used by monitor and DSD policies:

- Three-bar video signal (used in ENERGY STAR Displays 8.0 and CEC Title 20)
- Video Electronics Standards Association (VESA) FPDM2 L80 (used in ENERGY STAR Displays 8.0 and CEC Title 20 when the three-bar video cannot be played)
- L10-L80 box-and-outline patterns (used in Ecodesign and the EU Energy Label)

The results for the sample of computer monitors tested illustrate how different monitors exhibit highly variable ratios between static screen-center peak white pattern measurements and screen-average dynamic test clip measurements. It can be concluded that static patterns are inconsistent predictors of screen-average luminance, suggesting they may be unsuitable to support performance metrics.

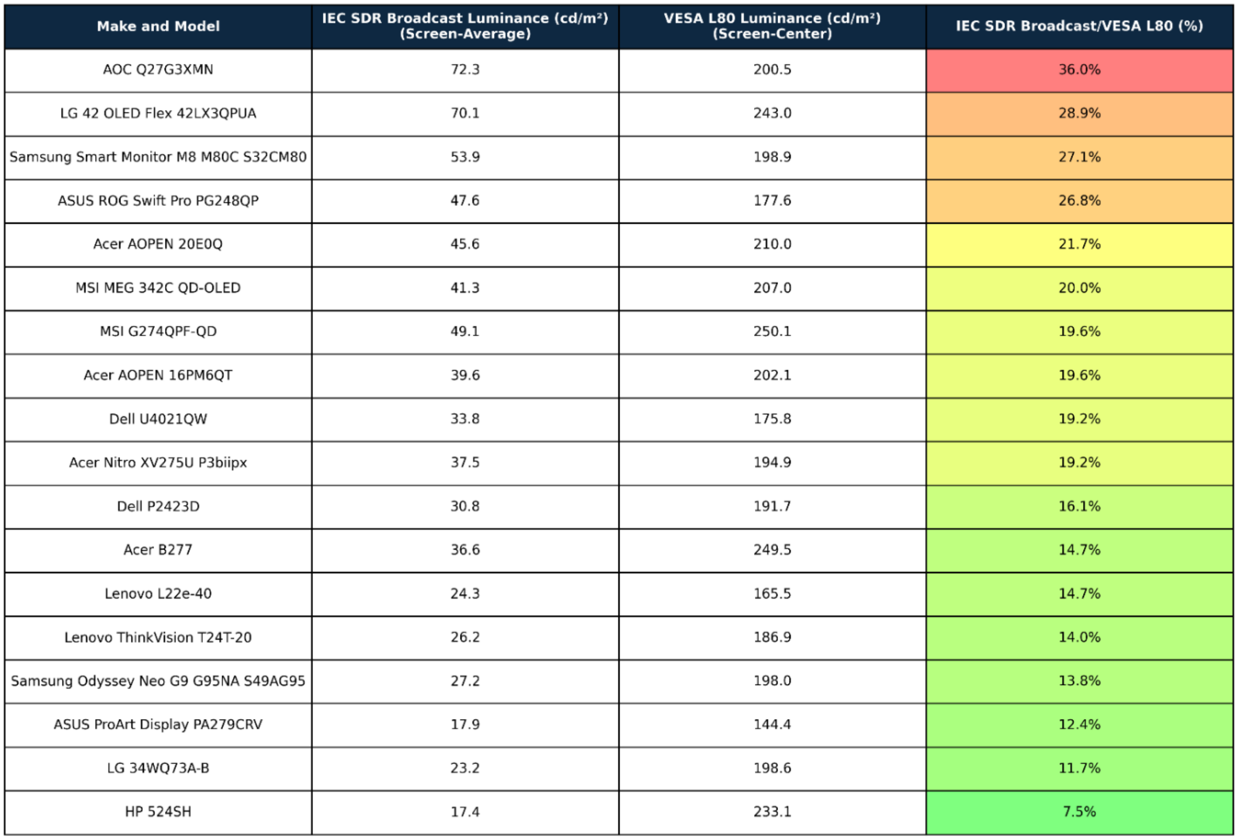
In the following tables, red and green only indicate high versus low values to highlight the difference in ratios of luminance between clips; they do not represent a value judgement about which ratios are better.

Table 26: Three-bar video signal and new IEC SDR dynamic broadcast clip comparison



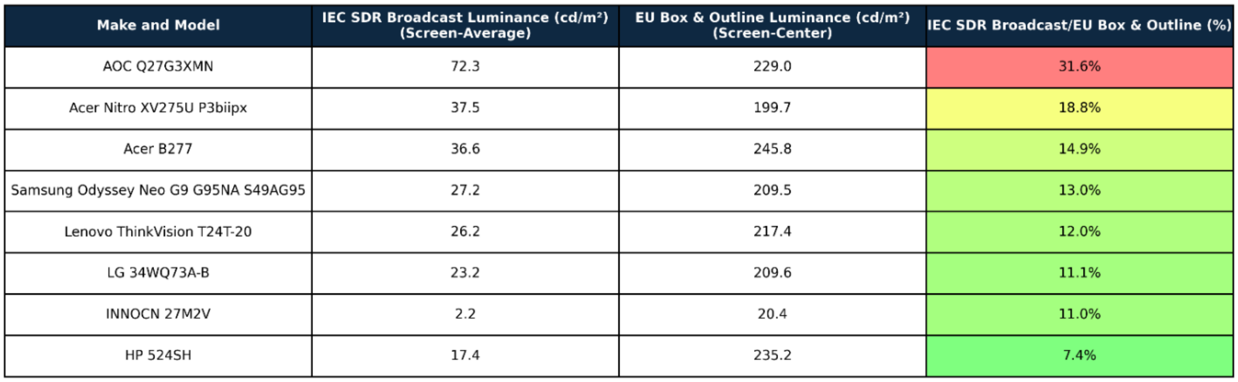
Make and Model	IEC SDR Broadcast Luminance (cd/m²) (Screen-Average)	3-Bar Luminance (cd/m²) (Screen-Center)	IEC SDR Broadcast/3-Bar (%)
AOC Q27G3XMN	72.3	193.1	37.4%
LG 42 OLED Flex 42LX3QPUA	70.1	225.3	31.1%
Samsung Smart Monitor M8 M80C S32CM80	53.9	192.5	28.0%
ASUS ROG Swift Pro PG248QP	47.6	173.5	27.4%
Acer AOPEN 20E0Q	45.6	205.3	22.2%
Acer Nitro XV275U P3biipx	37.5	173.7	21.6%
Acer AOPEN 16PM6QT	39.6	191.1	20.7%
MSI G274QPF-QD	49.1	238.6	20.6%
Dell U4021QW	33.8	166.8	20.3%
MSI MEG 342C QD-OLED	41.3	207.1	20.0%
Dell P2423D	30.8	175.8	17.5%
Acer B277	36.6	236.1	15.5%
Lenovo L22e-40	24.3	158.5	15.3%
Samsung Odyssey Neo G9 G95NA S49AG95	27.2	191.5	14.2%
Lenovo ThinkVision T24T-20	26.2	204.3	12.8%
LG 34WQ73A-B	23.2	182.9	12.7%
ASUS ProArt Display PA279CRV	17.9	150.3	11.9%
HP 524SH	17.4	223.6	7.8%

Table 27: VESA L80 pattern and IEC broadcast clip comparison



Make and Model	IEC SDR Broadcast Luminance (cd/m^2) (Screen-Average)	VESA L80 Luminance (cd/m^2) (Screen-Center)	IEC SDR Broadcast/VESA L80 (%)
AOC Q27G3XMN	72.3	200.5	36.0%
LG 42 OLED Flex 42LX3QPUA	70.1	243.0	28.9%
Samsung Smart Monitor M8 M80C S32CM80	53.9	198.9	27.1%
ASUS ROG Swift Pro PG248QP	47.6	177.6	26.8%
Acer AOPEN 20E0Q	45.6	210.0	21.7%
MSI MEG 342C QD-OLED	41.3	207.0	20.0%
MSI G274QPF-QD	49.1	250.1	19.6%
Acer AOPEN 16PM6QT	39.6	202.1	19.6%
Dell U4021QW	33.8	175.8	19.2%
Acer Nitro XV275U P3biipx	37.5	194.9	19.2%
Dell P2423D	30.8	191.7	16.1%
Acer B277	36.6	249.5	14.7%
Lenovo L22e-40	24.3	165.5	14.7%
Lenovo ThinkVision T24T-20	26.2	186.9	14.0%
Samsung Odyssey Neo G9 G95NA S49AG95	27.2	198.0	13.8%
ASUS ProArt Display PA279CRV	17.9	144.4	12.4%
LG 34WQ73A-B	23.2	198.6	11.7%
HP 524SH	17.4	233.1	7.5%

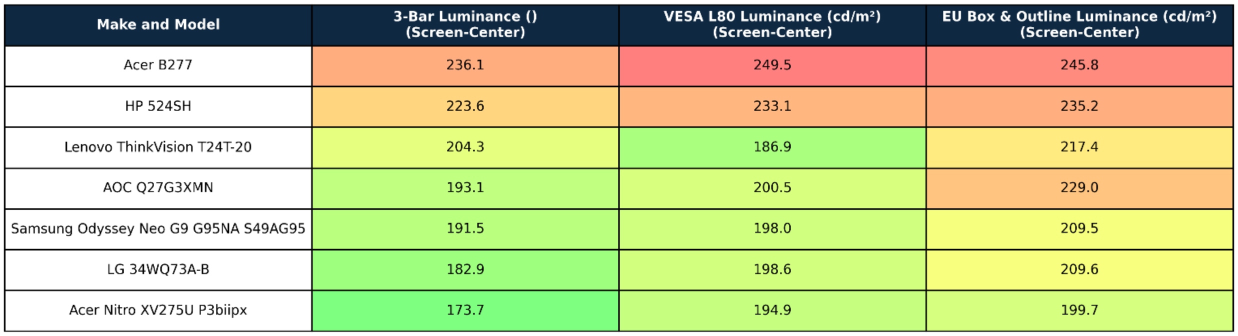
Table 28: Box-and-outline pattern and IEC broadcast clip comparison



Make and Model	IEC SDR Broadcast Luminance (cd/m^2) (Screen-Average)	EU Box & Outline Luminance (cd/m^2) (Screen-Center)	IEC SDR Broadcast/EU Box & Outline (%)
AOC Q27G3XMN	72.3	229.0	31.6%
Acer Nitro XV275U P3biipx	37.5	199.7	18.8%
Acer B277	36.6	245.8	14.9%
Samsung Odyssey Neo G9 G95NA S49AG95	27.2	209.5	13.0%
Lenovo ThinkVision T24T-20	26.2	217.4	12.0%
LG 34WQ73A-B	23.2	209.6	11.1%
INNOCN 27M2V	2.2	20.4	11.0%
HP 524SH	17.4	235.2	7.4%

Table 29 presents the screen-center luminance measurements for each test pattern, allowing direct comparison across patterns. In all cases, the measurement area is pure white, defined as an RGB value of (255, 255, 255).

Table 29: Comparison of screen-center luminance across the three test patterns



Make and Model	3-Bar Luminance () (Screen-Center)	VESA L80 Luminance (cd/m²) (Screen-Center)	EU Box & Outline Luminance (cd/m²) (Screen-Center)
Acer B277	236.1	249.5	245.8
HP 524SH	223.6	233.1	235.2
Lenovo ThinkVision T24T-20	204.3	186.9	217.4
AOC Q27G3XMN	193.1	200.5	229.0
Samsung Odyssey Neo G9 G95NA S49AG95	191.5	198.0	209.5
LG 34WQ73A-B	182.9	198.6	209.6
Acer Nitro XV275U P3biipx	173.7	194.9	199.7

Even when all test patterns have a white measurement area, they still produce inconsistent results across different displays.

Test patterns are often used in policy to confirm compliance with a minimum luminance level (as is the case for Ecodesign) based on tests conducted by Matsumoto et al. over a decade ago.[28] However, these tests were conducted with a 40% peak pattern (a pattern in which 40% of the center screen area is white; see Figure 37 for an example), which is not used by any of CEC Title 20, Ecodesign, or ENERGY STAR Displays 8.0. As a result, minimum luminance tests do not correlate with the available data.

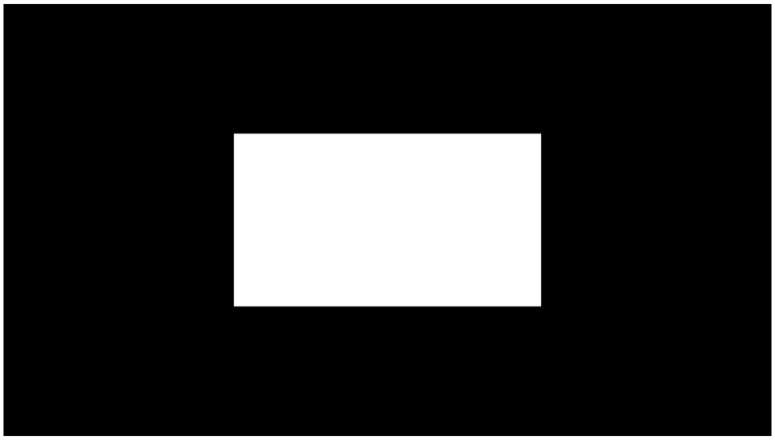


Figure 37: A 40% peak pattern, the VESA FPDM2 L40

Test patterns also present other issues. PCL observed in its testing that they can have temporal effects, with display luminance rising and sometimes dropping while playing the pattern. This makes it difficult to establish a standard measurement window after initially displaying the pattern. Even determining a stabilization in power can be complex, as certain displays show a periodicity in power regardless of the

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[28] Tatsuhiko Matsumoto, Satoru Kubota, Yuta Kubota, Kenta Imabayashi, Kazuyuki Kishimoto, Seiichi Goshi, Shigeki Imai, Youichi Igarashi, Shuichi Haga, and Takehiro Nakatsue, "Survey of Actual Viewing Conditions at Home and Appropriate Luminance of LCD-TV Screens," *Journal of the Society for Information Display* 19, no. 11 (2011).

content being played. Figure 38 shows a type of temporal effect that is commonly observed in computer monitors and other display types.

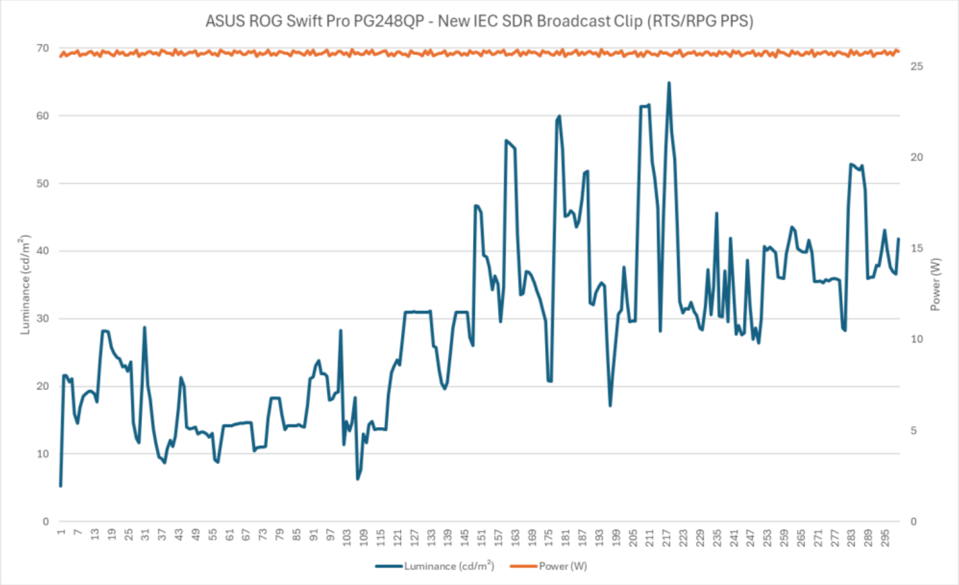


Figure 38: Power periodicity in the ASUS ROG Swift Pro Monitor

Using broadcast content instead allows for power and luminance to be measured and averaged over 300 seconds, making it harder for periodicity to affect results.

In cases where local dimming is enabled, the relationship between test patterns and screen-average dynamic luminance is even harder to characterize, because such displays can dim darker areas of the screen more effectively.

1.1.1.13.2.2 Dataset Findings

As stated in section 1.1.1.13.1.2: DATASET FINDINGS, further dataset comparisons cannot be made because the datasets reviewed do not include both screen-average broadcast clip luminance and screen-center luminance results.

1.1.1.13.3 Regression Analysis Results Overview

This section summarizes the computer monitor regression analysis results and highlights the limits of what can be inferred by datasets. The initial findings presented here serve as a foundation for deeper interpretation in the following sections, where these results are compared with PCL's laboratory testing to build a more confident understanding of the display features and capabilities that most significantly impact energy consumption.

As shown by PCL's regression analysis results, features and capabilities can only partially predict the energy efficiency of a display, making testing essential.

1.1.1.13.3.1 CEC MAEDbS Dataset

Figure 39 shows the linear regression results for computer monitors in the CEC MAEDbS dataset. As a reminder, a positive coefficient value means that the variable is predicted to increase Power/Reference (which indicates lower efficiency).

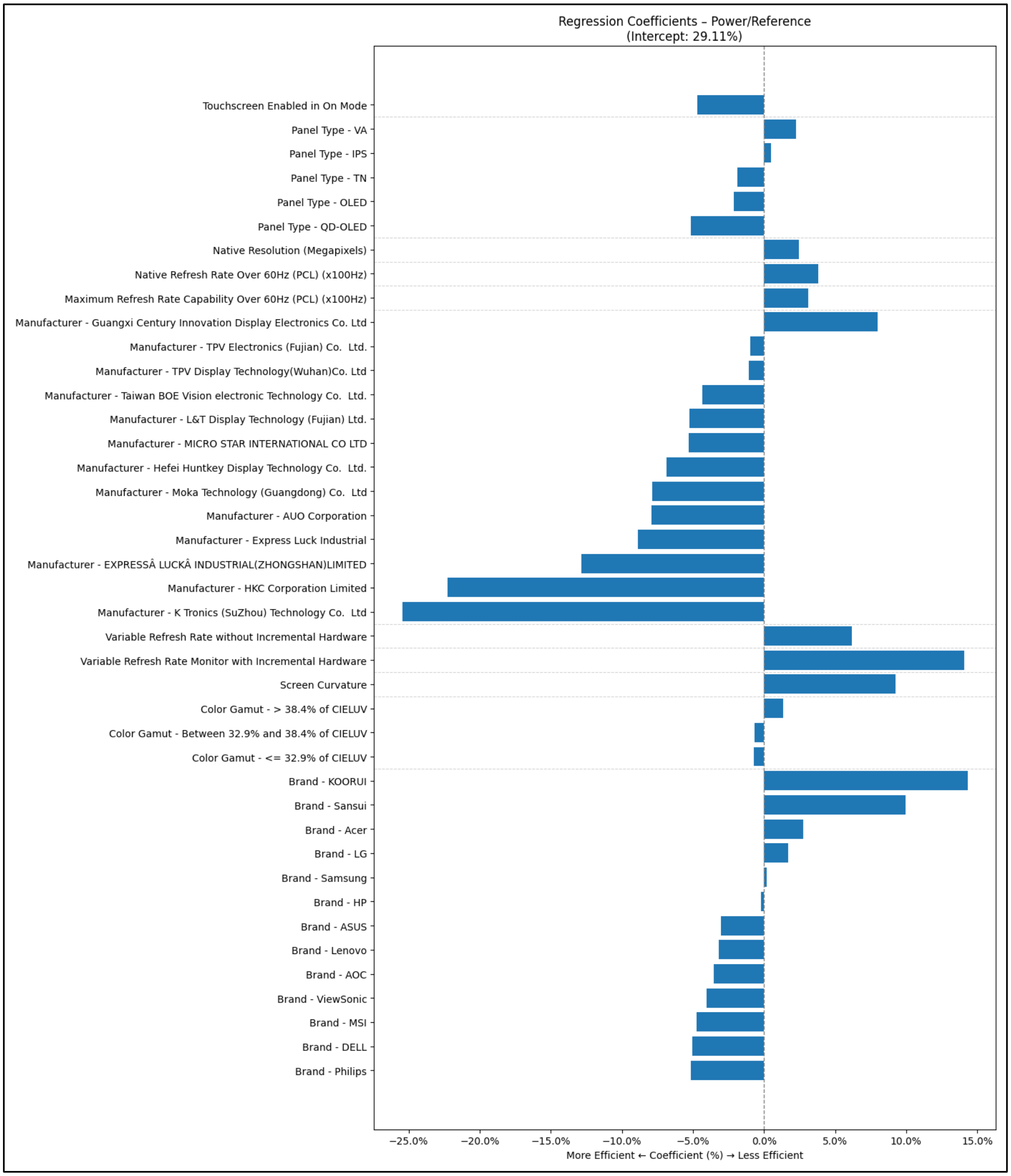


Figure 39: CEC MAEDbS regression results for computer monitors

The R^2 value for this regression model is 0.484, showing some predictive power for the energy impact of the individual features assessed.

Figure 40 plots actual versus predicted Power/ Reference values to visualize this. The predicted values are determined by the equation shown in section DATASET ANALYSIS.

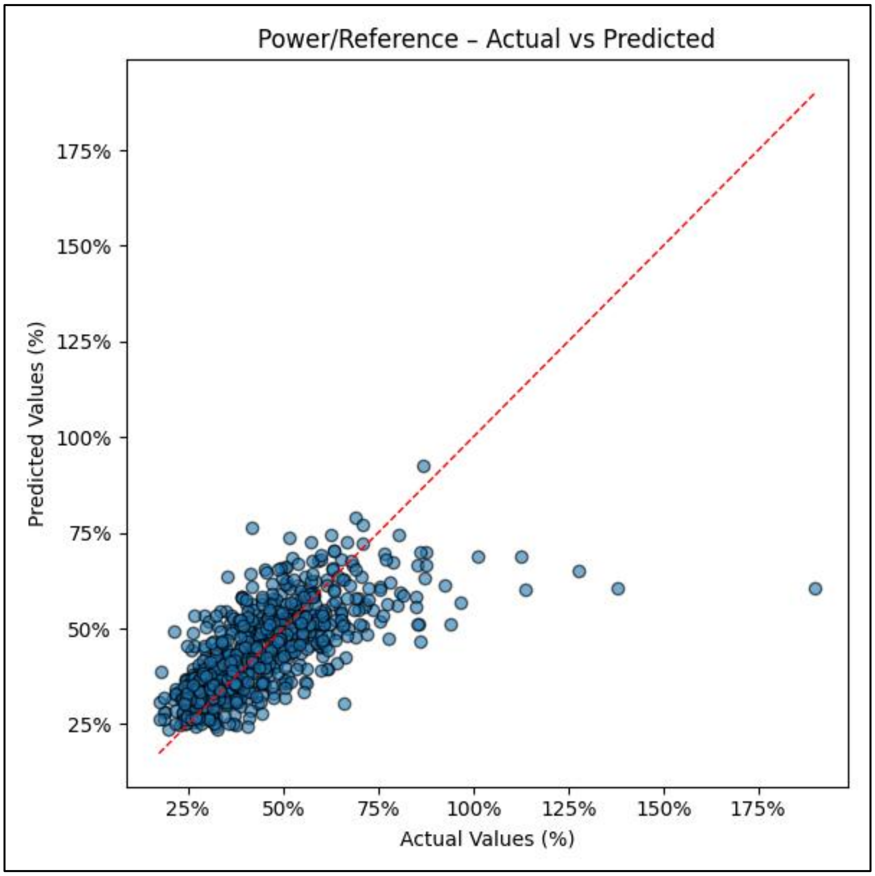


Figure 40: Actual versus predicted Power/Reference values in computer monitors for CEC MAEDbS

Note that some brands and manufacturers are represented by only a few models in these datasets. As a result, definitive conclusions cannot be drawn about their influence on energy efficiency. Table 30 and Table 31 show the number of monitors per manufacturer and brand in the CEC MAEDbS dataset.

Table 30: Monitor count per manufacturer in the 2025 CEC MAEDbS dataset

Manufacturer	Monitor Count
MICRO STAR INTERNATIONAL CO LTD	95
TPV Electronics (Fujian) Co. Ltd.	74
HKC Corporation Limited	45
L&T Display Technology (Fujian) Ltd.	33
TPV Display Technology (Wuhan)Co. Ltd	19
EXPRESS LUCK INDUSTRIAL (ZHONGSHAN) LIMITED	14
Moka Technology (Guangdong) Co. Ltd	13
AUO Corporation	5
Guangxi Century Innovation Display Electronics Co. Ltd	5
Hefei Huntkey Display Technology Co. Ltd.	4
Express Luck Industrial	3
K-Tronics (Suzhou) Technology Co. Ltd	2
Taiwan BOE Vision Electronic Technology Co. Ltd.	1

Table 31: Monitor count per brand in the 2025 CEC MAEDbS dataset

Brand	Monitor Count
LG	106
MSI	98
Samsung	83
Acer	71
ASUS	69
AOC	67
Dell	61
KOORUI	44
ViewSonic	44
Philips	35
Lenovo	32
HP	28
Sansui	15

1.1.1.13.3.2 ENERGY STAR Displays 8.0 Dataset

Figure 41 shows the regression results for computer monitors in the ENERGY STAR Displays 8.0 dataset.

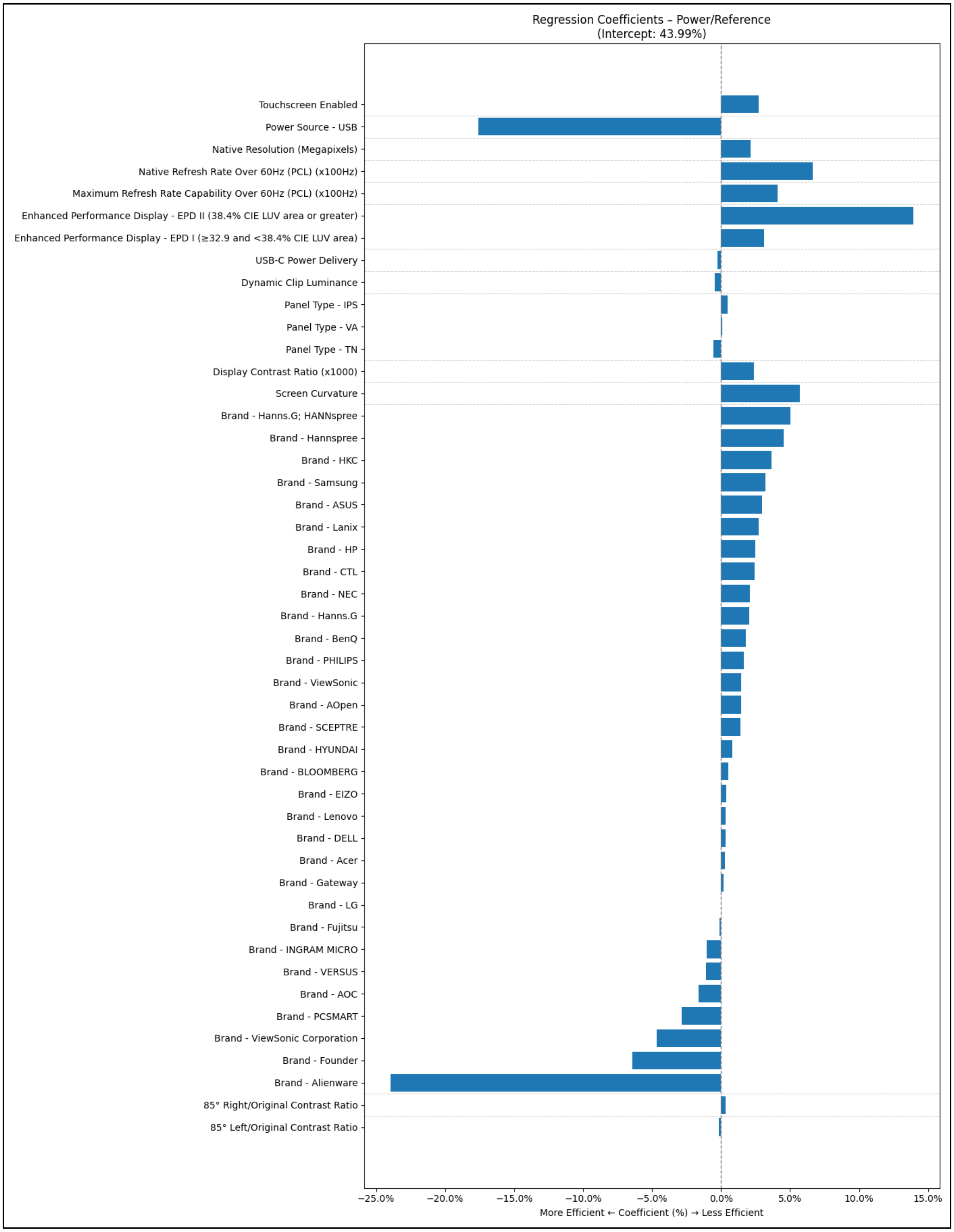


Figure 41: ENERGY STAR Displays 8.0 regression results for computer monitors

In this regression, an R^2 value of 0.6075 was achieved.

Figure 42 shows actual versus predicted values for this model.

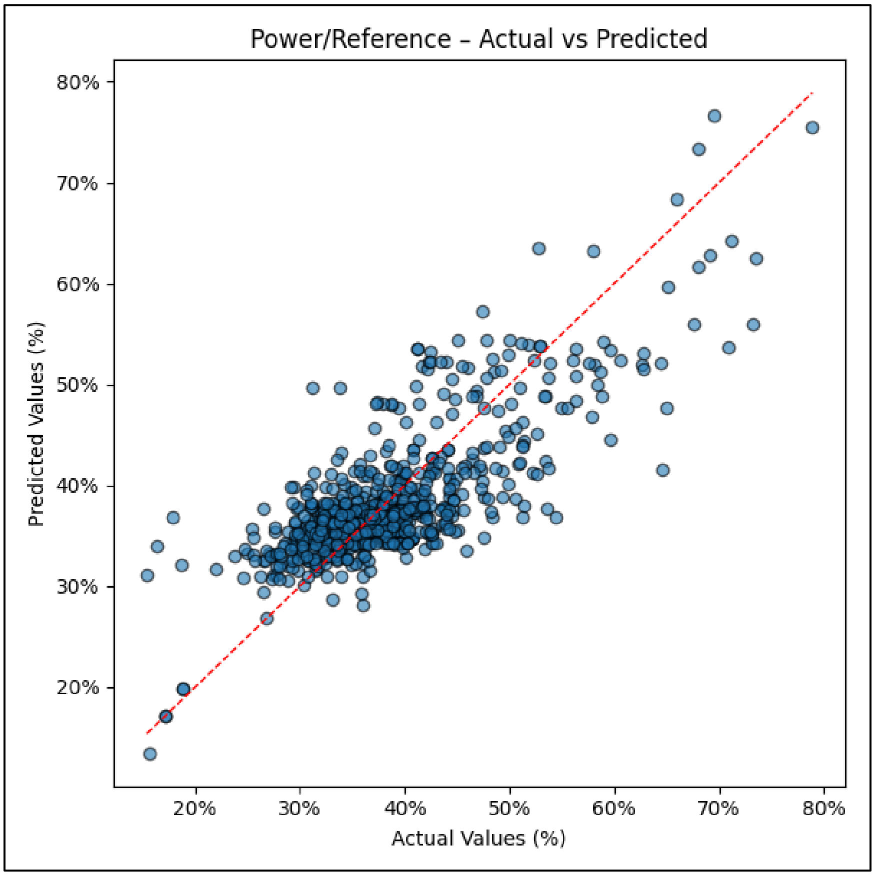


Figure 42: Actual versus predicted Power/Reference in computer monitors in ENERGY STAR Displays 8.0

Table 32 shows the number of monitors per brand in this dataset. 16 brands have fewer than 10 samples represented, and 7 of them only have a single sample. In these cases, one cannot be sure of these brands' impact on energy efficiency due to the limited data available.

Table 32: Monitor count per brand in the 2020 ENERGY STAR Displays 8.0 dataset

Brand	Monitor Count
HP	108
Acer	97
Dell	91
Philips	83
ViewSonic	82
Lenovo	79
LG	56
ASUS	47
AOC	21
BenQ	19
Samsung	18
EIZO	16
HANNS.G	15
Fujitsu	13
NEC	12
HYUNDAI	7
SCEPTRE	6
INGRAM MICRO	5
CTL	4
AOPEN	3
Lanix	3
BLOOMBERG	2
HANNspree	2
PCSMART	2
Alienware	1
Founder	1
Gateway	1
HANNS.G; HANNspree	1
HKC	1
VERSUS	1
ViewSonic Corporation	1

1.1.1.13.4 Panel Type

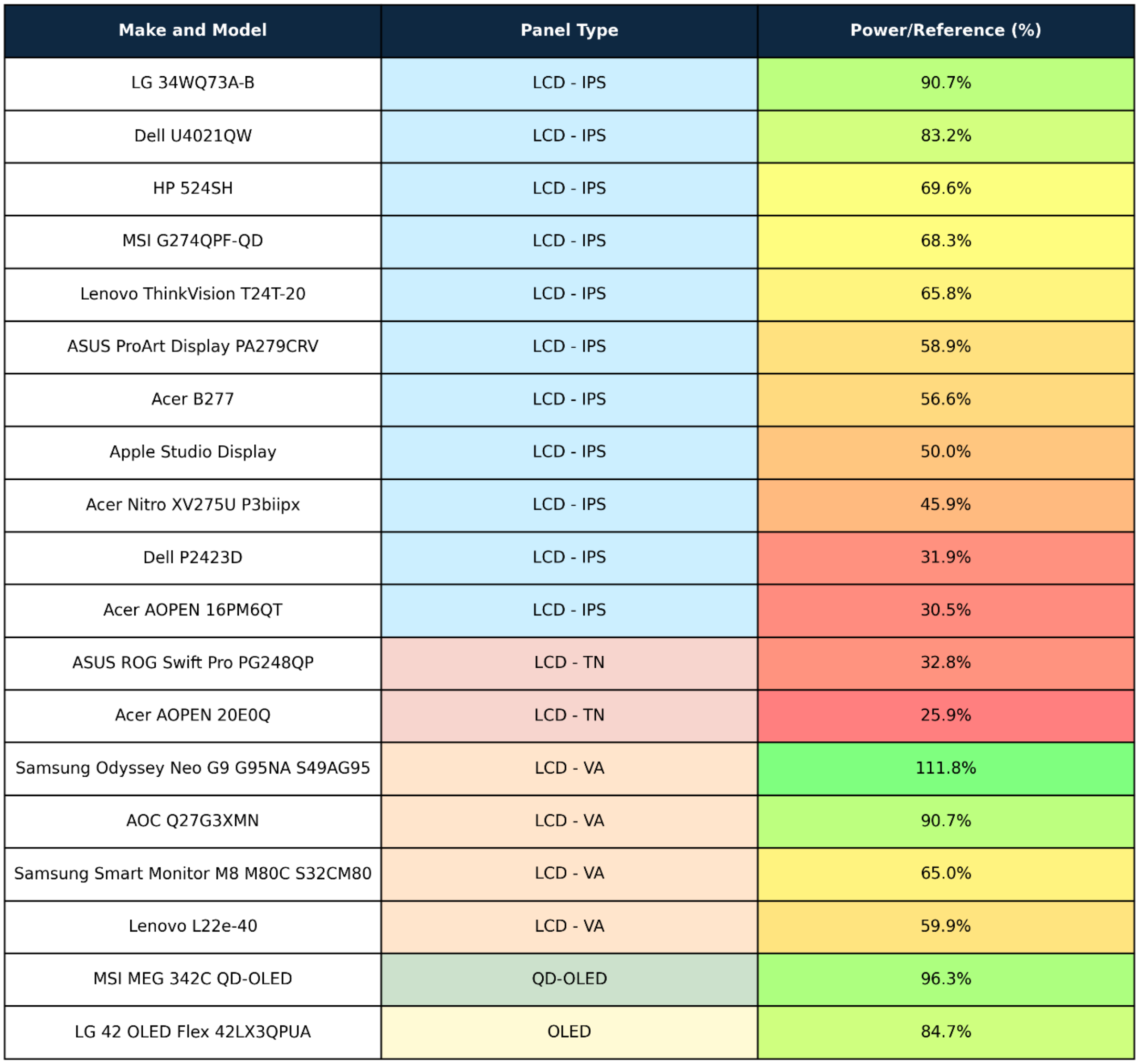
Our laboratory testing and dataset analysis examine the energy efficiency impact of different LCD panel subtypes (IPS, VA, TN). OLED was included as the only emissive technology examined in computer monitors, as DVLED displays are not commercially available in this product category.

The impact of edge-lit versus direct-lit backlight configurations was not assessed. Based on previous extensive analysis of television data, this distinction appears to have minimal effect on energy consumption. Furthermore, the datasets used for regression did not include this information about the backlight. Since backlight type is also not consistently reported by manufacturers, this data could not reliably be included in PCL's regression.

1.1.1.13.4.1 Test Results

For PCL's laboratory testing, the energy efficiency of the LCD subtypes identified in section Markets and Technologies (IPS, VA, and TN panels) was compared. The tables below show the performance against the power reference line (measured at each display's default PPS and light source setting) for each monitor and panel type tested.

Table 33: Power/Reference for different LCD panel types



Make and Model	Panel Type	Power/Reference (%)
LG 34WQ73A-B	LCD - IPS	90.7%
Dell U4021QW	LCD - IPS	83.2%
HP 524SH	LCD - IPS	69.6%
MSI G274QPF-QD	LCD - IPS	68.3%
Lenovo ThinkVision T24T-20	LCD - IPS	65.8%
ASUS ProArt Display PA279CRV	LCD - IPS	58.9%
Acer B277	LCD - IPS	56.6%
Apple Studio Display	LCD - IPS	50.0%
Acer Nitro XV275U P3biipx	LCD - IPS	45.9%
Dell P2423D	LCD - IPS	31.9%
Acer AOPEN 16PM6QT	LCD - IPS	30.5%
ASUS ROG Swift Pro PG248QP	LCD - TN	32.8%
Acer AOPEN 20E0Q	LCD - TN	25.9%
Samsung Odyssey Neo G9 G95NA S49AG95	LCD - VA	111.8%
AOC Q27G3XMN	LCD - VA	90.7%
Samsung Smart Monitor M8 M80C S32CM80	LCD - VA	65.0%
Lenovo L22e-40	LCD - VA	59.9%
MSI MEG 342C QD-OLED	QD-OLED	96.3%
LG 42 OLED Flex 42LX3QPUA	OLED	84.7%

Table 34: Average Power/Reference per panel type

Panel Type	Average Power/Reference (%)
LCD- IPS	56%
LCD- VA	81.8%
LCD- TN	29.3%
QD-OLED	96.3%
OLED	84.7%

From PCL's limited sampling, TN panels appear to have the best energy efficiency. This makes sense since these panels often struggle with high black levels, leading to dark areas appearing brighter (emitting more luminance) than they should. VA panels perform considerably worse than IPS panels although they have similarly good contrast ratios. PCL's two OLED-based monitors have higher Power/Reference values than might be expected from emissive technology; however, the sample size is too small in this case to draw any conclusions.

1.1.1.13.4.2 Dataset Findings

The energy efficiency impact was compared across different panel types in the 2025 CEC MAEDbS dataset. This dataset includes the LCD panel subtypes tested, as well as OLEDs and QD-OLEDs.

Figure 43 shows the regression coefficient of each panel type. Because the target metric is Power/Reference, positive coefficient values indicate higher Power/Reference (lower efficiency), while negative coefficients indicate lower Power/Reference (higher energy efficiency).

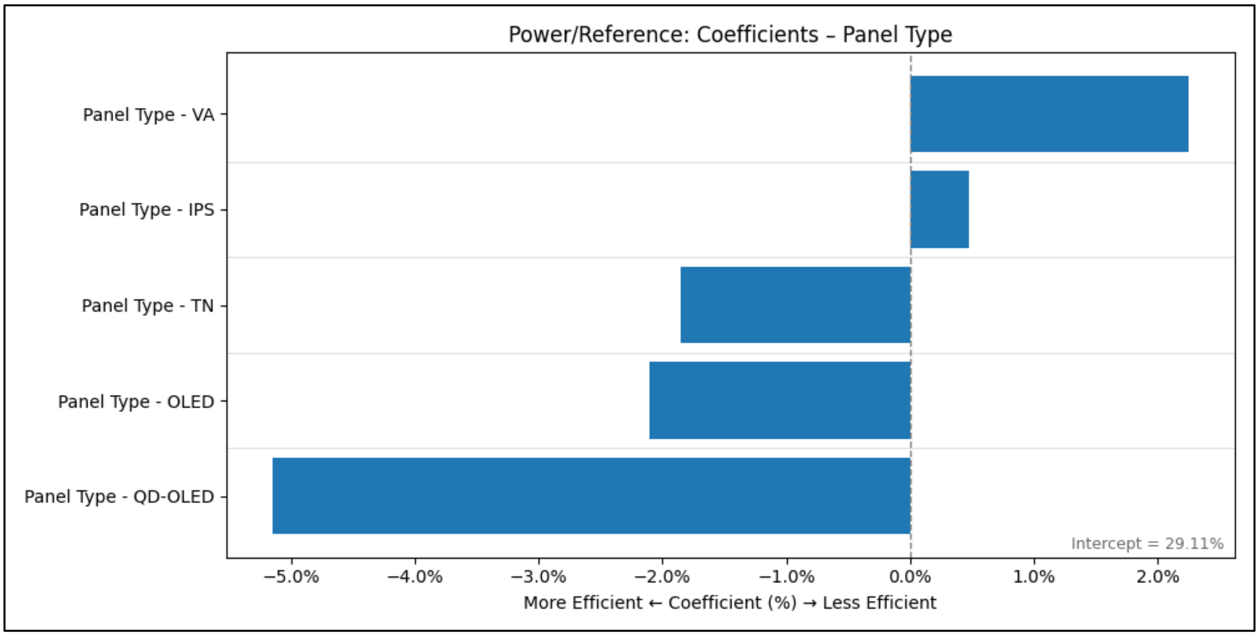


Figure 43: Impact of panel type in energy efficiency on the CEC MAEDbS dataset

Among LCD panels, VA panels performed the worst in the regression analysis, and TN panels performed the best. When including emissive panels, QD-OLED panels performed the best across all panel types.

OLED and QD-OLED displays are likely to have a higher fixed power overhead (baseline) due to the circuitry needed to control individually lit pixels. However, past PCL testing has shown that these panels often outperform LCDs at higher luminance levels because power scales more effectively with image light level in emissive displays. Their dimming lines have higher Y-intercepts but have flatter slopes than LCD panels as OLED panels have pixel-level control over light emission, and do not need to block light using liquid crystal technology to dim dark areas of the screen. Figure 44 illustrates this.

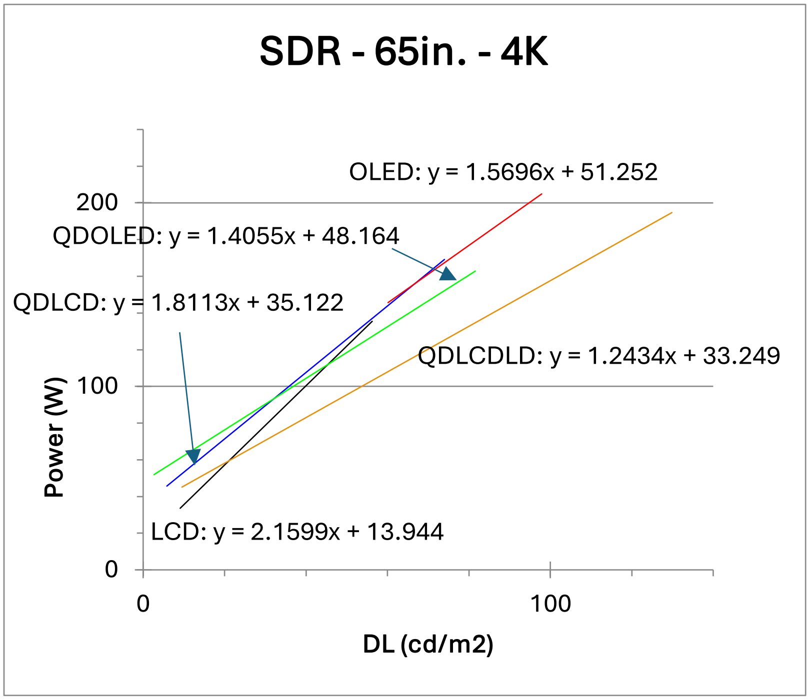


Figure 44: Dimming lines for 65” 4K TVs with different panel types

Notes*:* The graph above is based on PCL analysis of the CEC MAEDbS dataset of televisions tested using the US federal test method (ANSI/CTA-2037-D).

Each dimming line is named based on the TV’s panel type (LCD versus OLED), whether it has Quantum Dot technology (QD), and the kind of dynamic dimming used (LD for local dimming and GD for global dimming).

While OLED panels (red line) have a higher Y-intercept, their slope is flatter than that of plain LCD panels (black line).

The 2020 ENERGY STAR Displays 8.0 dataset contains a wider variety of LCD panel technologies represented than the 2025 CEC MAEDbS dataset, including proprietary technologies such as Advanced Super Dimension Switch (ADS). Since ADS and Azimuthal Anchoring Switch (AAS) are both subtypes of IPS, both were reclassified as IPS for PCL’s regression analysis.

Both datasets also include panels labeled as simply TFT, which is an overarching LCD technology that includes subtypes like IPS, VA and TN. Since the actual panel subtypes of panels labeled as TFT are unknown, those models were removed from PCL's regression.

Figure 45 shows the coefficient of each panel type on this dataset.

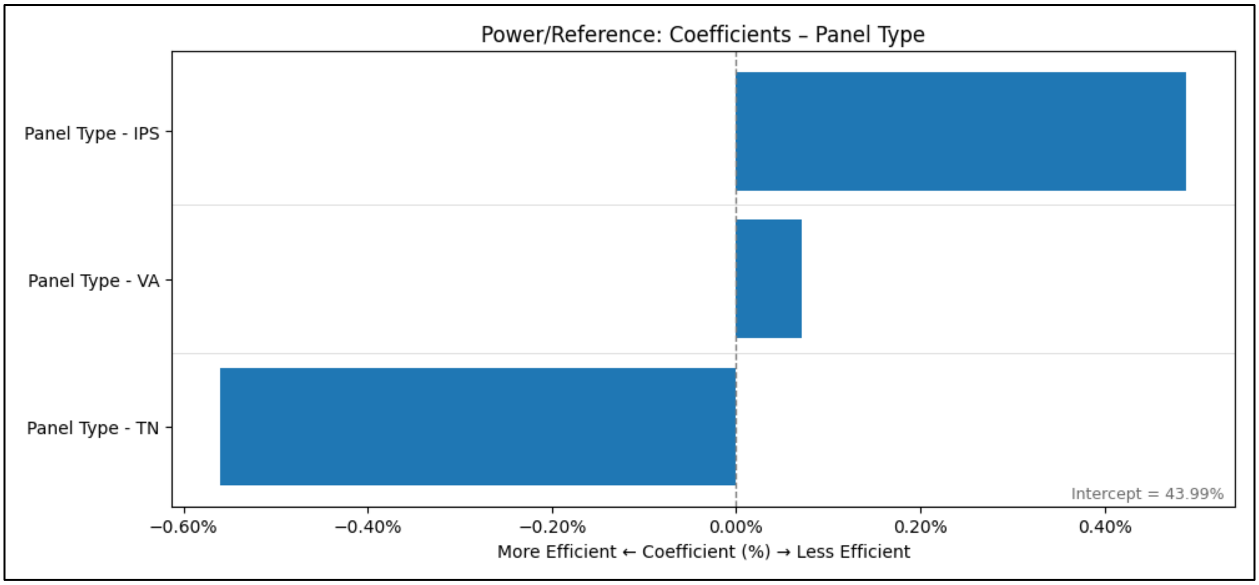


Figure 45: Impact of panel type in energy efficiency on the ENERGY STAR Displays 8.0 dataset

In this dataset, IPS panels performed worse than VA panels. TN scored the best per PCL's efficiency metric.

While PCL's policy recommendations do not call for factoring panel type into the determination of Active Mode energy efficiency, these findings help contextualize the energy performance of various display technologies.

1.1.1.13.5 Local Dimming Setting

Local dimming is a feature used in some LCD displays that improves contrast by dimming the parts of the backlight behind darker areas of the image. It can also save energy as it scales backlight power with image luminance at the zone level.

1.1.1.13.5.1 Test Results

Among the LCD computer monitors tested, five of them supported local dimming. In all cases, the shipped setting was either with local dimming disabled by default or set to an intermediate level (e.g., Medium or Auto), rather than its highest setting, as seen on Table 35.

Table 35: Status of Local Dimming on the computer monitors that support it

Make	Model	Local Dimming Available	Local Dimming On by Default
Acer	Nitro XV275U P3biipx	Yes	Yes ("Average")
AOC	Q27G3XMN	Yes	No
ASUS	ProArt Display PA279CRV	Yes	Yes ("Medium")
INNOCN	27M2V	Yes	No
Samsung	Odyssey Neo G9 G95NA S49AG95	Yes	Yes ("Auto")

This indicates that local dimming is not consistently configured for maximum energy savings out of the box. This may reflect trade-offs as local dimming can negatively affect picture quality by introducing reduced detail in darker areas and blooming around bright objects.

The graphs below illustrate the energy efficiency benefits of local dimming for two cases: a monitor for which local dimming was off by default (the INNOCN 27M2V, Figure 46) and a monitor for which it was set to auto (the Samsung Neo G9, Figure 47).

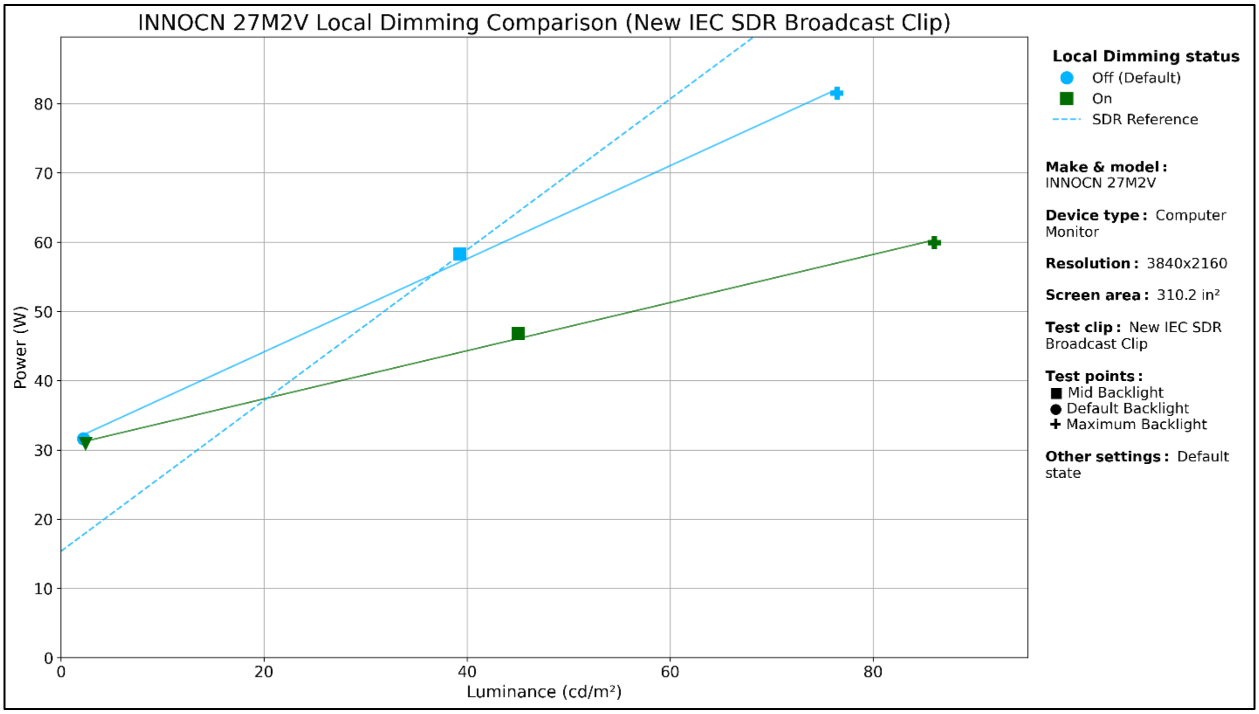


Figure 46: INNOCN 27M2V local dimming comparison

Note: Local dimming is off by default in the INNOCN 27M2V, yet it significantly improves energy efficiency.

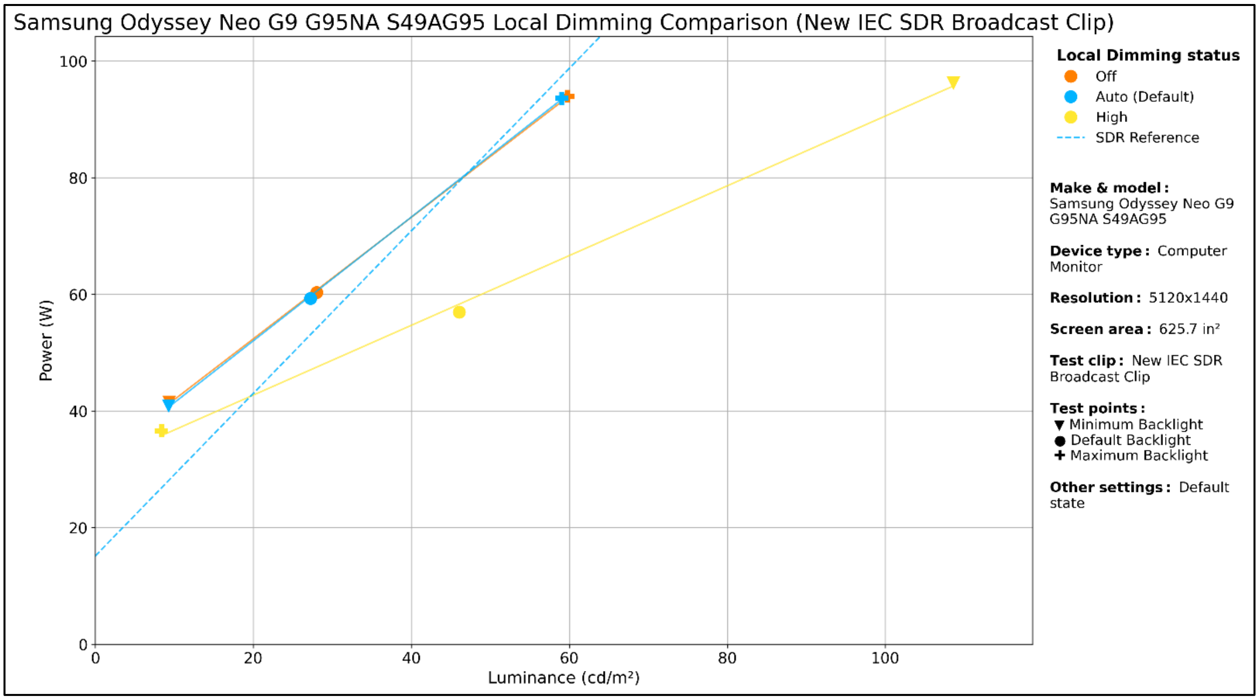


Figure 47: Samsung Odyssey Neo G9 local dimming comparison

Note: Local dimming set to Auto does not seem to activate the feature for this test clip in the Samsung Odyssey Neo G9

As shown in Figure 48 below, setting local dimming to high causes power to scale with screen-average luminance throughout the test run.

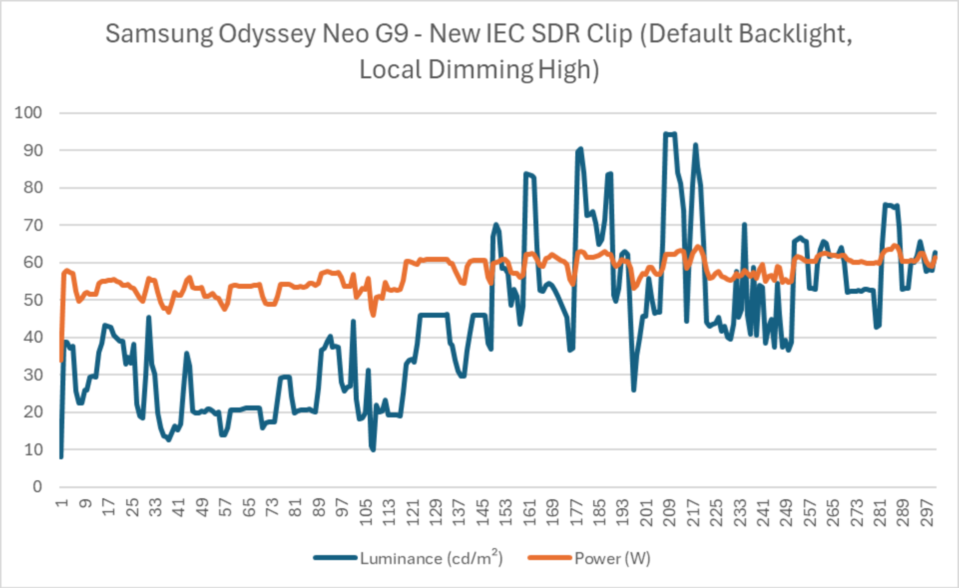


Figure 48: Power and luminance over time in the Samsung Odyssey Neo G9 (Local Dimming High)

This scaling does not occur when local dimming is off (Figure 49).

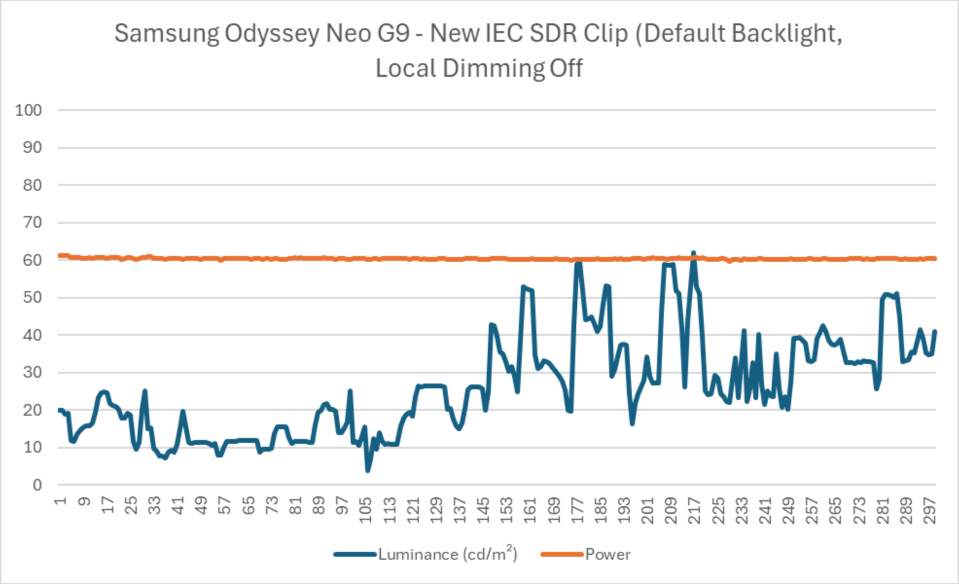


Figure 49: Power and luminance over time in the Samsung Odyssey Neo G9 (Local Dimming Off)

Display policies based on screen-average dynamic luminance could incentivize monitors to be shipped with local dimming optimized as default to save energy.

1.1.1.13.5.2 Dataset Findings

Based on the additional data collected to complete product feature fields with Gemini Deep Research, only 10 out of 753 and 4 out of 1,014 models (prior to filtering the data) were identified as having local dimming capabilities in the 2025 CEC MAEDbS and 2020 ENERGY STAR Displays 8.0 datasets, respectively.

Because local dimming was often disabled by default in the laboratory samples, and display configuration during dataset testing is unknown, the impact of local dimming cannot confidently be analyzed with this data.

1.1.1.13.6 Global Dimming Setting

Like local dimming, global dimming dynamically adjusts the backlight output in response to the brightness of the content being played. However, rather than adjusting multiple dimming zones, the backlight is controlled via a single dimming zone across the full screen.

1.1.1.13.6.1 Test Results

Global dimming is generally not advertised as a discrete feature. It was identified by reviewing time-series plots of power and luminance during broadcast clip test runs.

Global dimming should cause power to scale with the maximum luminance in a frame, since this represents the highest brightness level the backlight must support. Many global dimming algorithms include thresholds. For example, the backlight may not react to isolated bright pixels and may require a sufficient concentration of bright pixels before increasing the backlight output.

Figure 50 shows an example of a monitor without global dimming. In this case, power stays flat regardless of screen luminance.

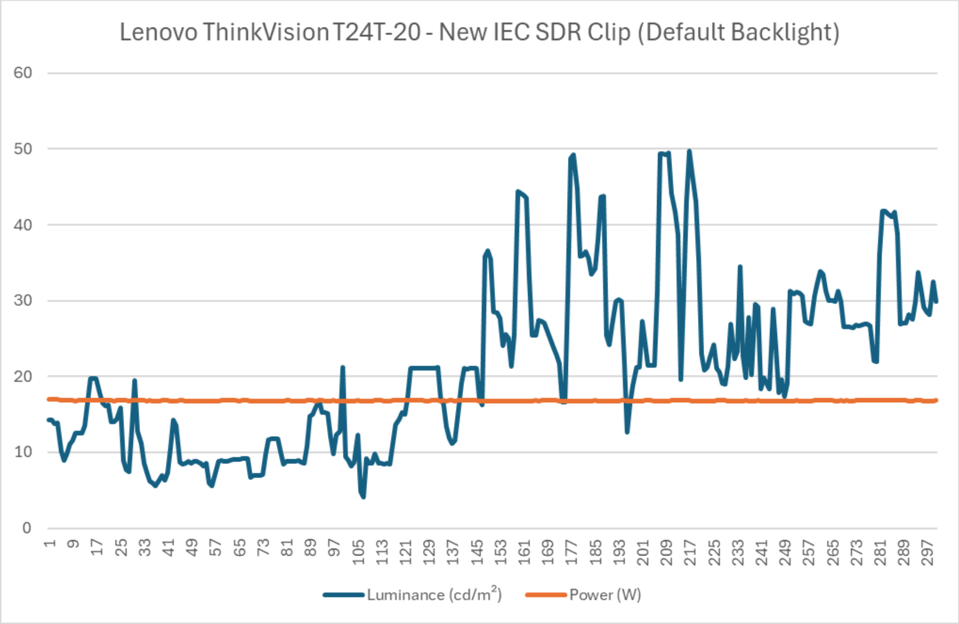


Figure 50: Power and luminance while testing the Lenovo ThinkVision T24T-20

Global Dimming is marketed in computer monitors under various names, (e.g., Variable Backlight and Dynamic Contrast) based on secondary research. Several candidate settings were tested based on reviews of manufacturer websites and user forums. Table 36 summarizes which settings in PCL's sample list constitute global dimming.

Table 36: Potential global dimming settings and test results

Make and Model	Feature Name	Default Setting	Acted as Global Dimming?
ASUS ROG Swift Pro PG248QP	Variable Backlight	Off	No
LG 34WQ73A-B	N/A	N/A	Yes
Acer AOPEN 16PM6QT	ACM (Adaptive Contrast Management)	Off	No
HP 524SH	Dynamic Contrast	Off	No
Lenovo ThinkVision T24T-20	Dynamic Contrast	Off	No

As Table 36 shows, none of the settings expected to function as global dimming acted as such. Only one monitor exhibited global dimming behavior, and no user setting was found to enable or disable it.

Figure 51 shows how power scales with luminance increases in the LG 34WQ73A-B. However, this scaling is minimal and does not occur with all luminance increases.

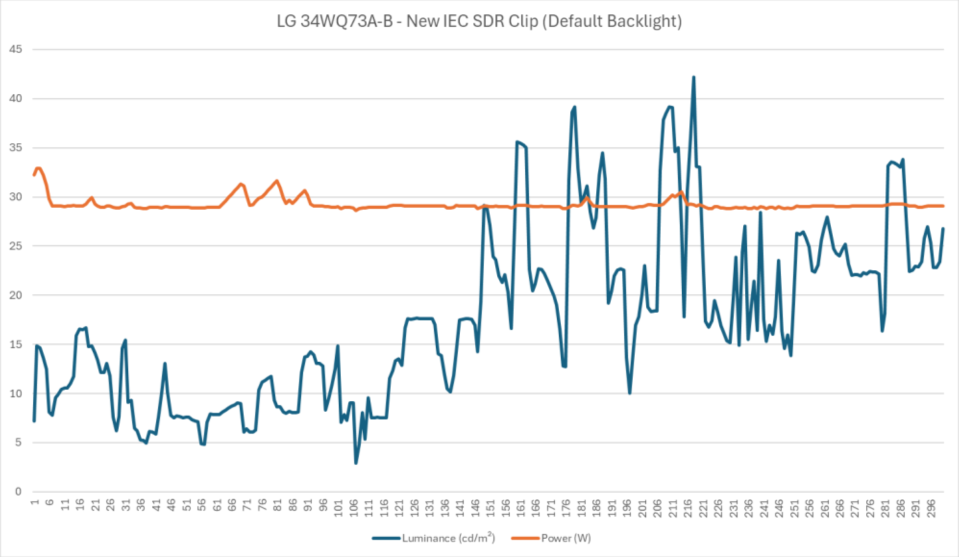


Figure 51: Dynamic backlight dimming in the LG 34WQ73A-B

In the absence of global dimming, power would be expected to remain closer to the highest observed level of 32.9 W throughout the full test clip. Instead, the average power for this test was 29.2 W.

This example shows a less responsive implementation of global dimming. More pronounced global dimming behavior is shown in the DSD findings section 1.1.1.15.7: GLOBAL DIMMING SETTING.

Global dimming should not be confused with periodic variations in power that do not correlate with luminance. Figure 52 shows this phenomenon in the ASUS ROG Swift Pro monitor.

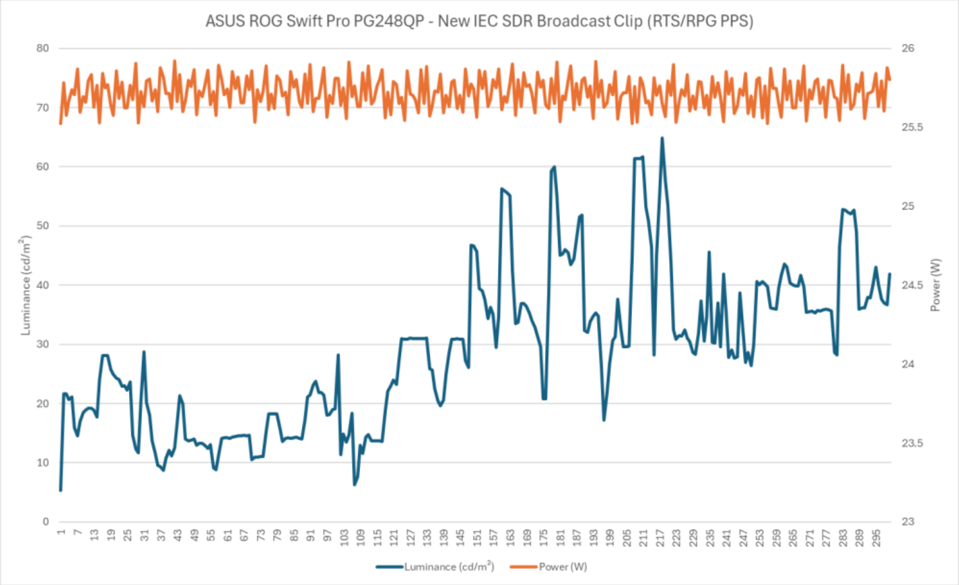


Figure 52: Power periodicity in the ASUS ROG Swift Pro Monitor

Note: The scale of this plot was adjusted to better illustrate the periodicity of power.

1.1.1.13.6.2 Dataset Findings

The datasets consulted did not record whether global dimming was used during testing. Because global dimming is rarely advertised and is difficult to classify without reviewing a plot of power and luminance over time (to see if these values scale with each other), the dataset evidence was not sufficient to assess global dimming impacts beyond the laboratory testing.

1.1.1.13.7 Color Gamut Setting and Capability

Color gamut refers to the range of colors a display can produce, typically measured as a percentage of a standard color space (e.g., sRGB, Adobe RGB, DCI-P3). A wider color gamut allows for richer, more vibrant colors, making it an important feature for professional, creative, and high-end gaming monitors.

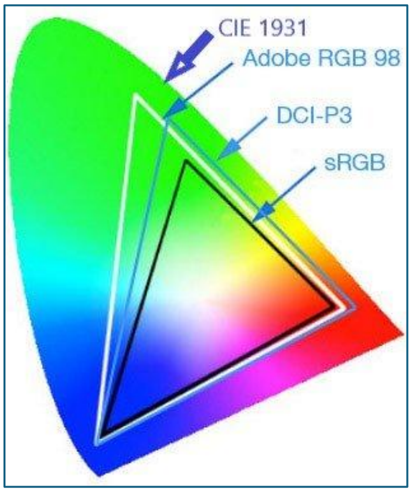


Figure 53: Common display color spaces shown inside the CIE 1931 color space

Display hardware ultimately defines the maximum achievable color gamut, but picture settings can influence the color gamut a display produces in practice. Because the setting that reveals a panel's full color gamut **capability** is not always clear, cross-display comparisons are reported for the Default PPS only, to ensure consistency.

Where supported, the impact of selecting different color space presets within the same monitor was also reviewed. In this context, color gamut **setting** refers to presets intended to emulate a specific color space (e.g., Adobe RGB, sRGB, DCI-P3).

Changes in measured color gamut across PPSs cannot be isolated from changes in signal-to-light mapping (see section LIMITATIONS OF THIS APPROACH). While color gamut area can be quantified, signal-to-light mapping cannot yet be quantified within this work.

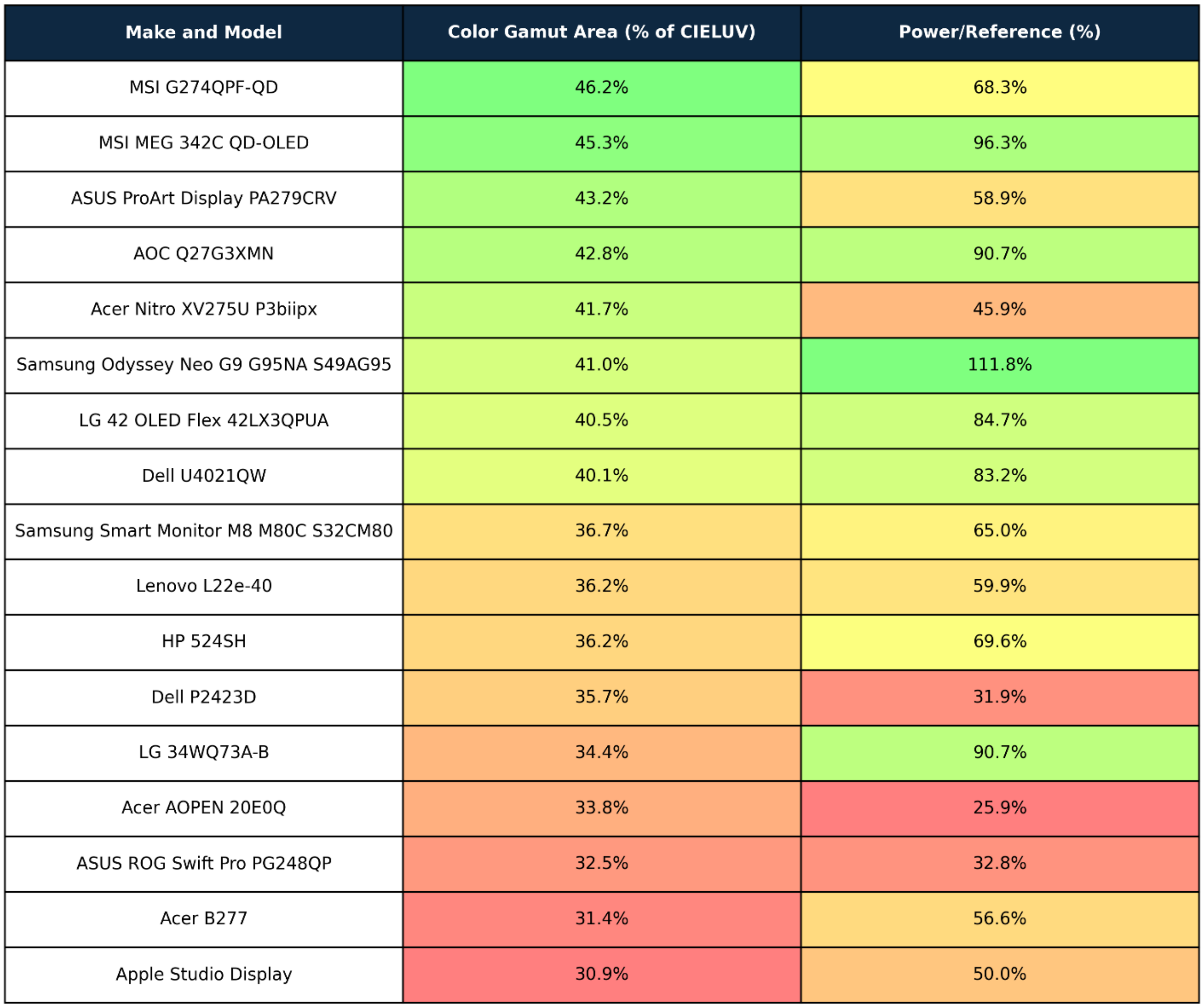
Finally, the Helmholtz–Kohlrausch (H-K) effect should be considered. More saturated colors can appear brighter to viewers even when measured luminance does not increase. In practice, supporting a wider color gamut could enable some users to reduce display brightness while maintaining perceived brightness, potentially saving power. However, the dataset analysis later in this section associates wider color gamut capability with lower energy efficiency at a given luminance.

1.1.1.13.7.1 Test Results

To compare color gamut **capability** across displays, it was expressed as a percentage coverage of the CIELUV color space and measured using the IEC 62977-2-1 window pattern, as described in the previous Color Gamut test method section. The laboratory sample size was not sufficient for regression analysis so only correlations are reported in this section.

When comparing computer monitors with different color gamut coverage, it was found that higher-gamut displays have lower energy efficiency overall, with some exceptions. Table 37 shows the color gamut area coverages of each display along with their Power/Reference value. Figure 54 plots the relationship between both values, showing a low-confidence correlation with an R^2 value of 0.27.

Table 37: Color gamut area versus Power/Reference in computer monitors



Make and Model	Color Gamut Area (% of CIELUV)	Power/Reference (%)
MSI G274QPF-QD	46.2%	68.3%
MSI MEG 342C QD-OLED	45.3%	96.3%
ASUS ProArt Display PA279CRV	43.2%	58.9%
AOC Q27G3XMN	42.8%	90.7%
Acer Nitro XV275U P3biipx	41.7%	45.9%
Samsung Odyssey Neo G9 G95NA S49AG95	41.0%	111.8%
LG 42 OLED Flex 42LX3QPUA	40.5%	84.7%
Dell U4021QW	40.1%	83.2%
Samsung Smart Monitor M8 M80C S32CM80	36.7%	65.0%
Lenovo L22e-40	36.2%	59.9%
HP 524SH	36.2%	69.6%
Dell P2423D	35.7%	31.9%
LG 34WQ73A-B	34.4%	90.7%
Acer AOPEN 20E0Q	33.8%	25.9%
ASUS ROG Swift Pro PG248QP	32.5%	32.8%
Acer B277	31.4%	56.6%
Apple Studio Display	30.9%	50.0%

Note: In this table, the red-to-green gradient indicates magnitude of color gamut coverage. Higher color gamut coverage (red) is generally considered better color performance, but (with a few exceptions) it tended to be associated with poorer energy efficiency in this sample. However, this trend is relatively weak, as illustrated in Figure 54.

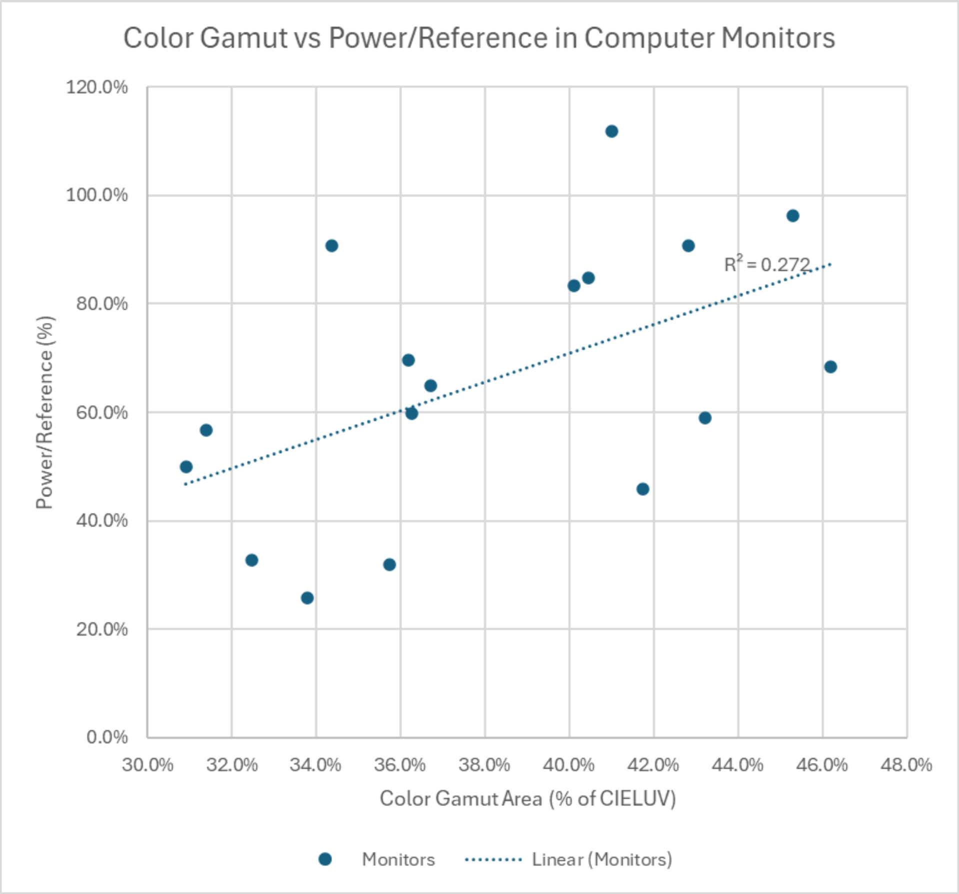


Figure 54: The relationship between color gamut and performance against the reference

These findings suggest that supporting a wider color gamut may be associated with a poorer efficiency performance relative to the reference line. However, given the small sample size and the resultant lack of regression analysis, other variables are likely affecting these results and the relationship should be treated as indicative only.

It was also examined whether different color space **settings** within the same monitor affect energy efficiency. Several displays—particularly those designed for image and video editing—offer preset modes corresponding to specific color spaces such as sRGB, Adobe RGB, and DCI-P3, each with varying color gamut coverage.

To explore this, the ASUS ProArt Display was analyzed, which includes presets for common color spaces and is factory-calibrated to ensure accurate color reproduction in each mode.

The results on Table 38 show no clear correlation between the color gamut coverage of a PPS and its energy efficiency relative to the reference line.

Table 38: Power/Reference versus color gamut area in PPSs of the ASUS ProArt Display monitor

Preset Picture Setting	Color Gamut Area (% of CIELUV)	Power/Reference (%)
Rec. 2020	43.6%	67.2%
Native	43.2%	58.9%
DICOM	43.0%	75.0%
DCI-P3	38.0%	73.9%
Adobe RGB	35.0%	58.5%
Rec. 709	30.9%	65.8%
sRGB	30.5%	64.6%

Similar testing performed with the Apple Studio Display also showed no correlation between color gamut **setting** and its energy efficiency.

This testing is limited as changes in color gamut area cannot be isolated from changes in signal-to-light mapping, which section Limitations of this Approach proves can affect this report's energy efficiency metric. However, an initial review of the data shows changes in color gamut **setting** within the same display do not seem to significantly affect energy efficiency, unlike the display's overall color gamut **capability**.

1.1.1.13.7.2 Dataset Findings

The 2025 CEC MAEDbS records color gamut **capability** by classifying displays according to a range of CIELUV coverage, as seen in Figure 55.

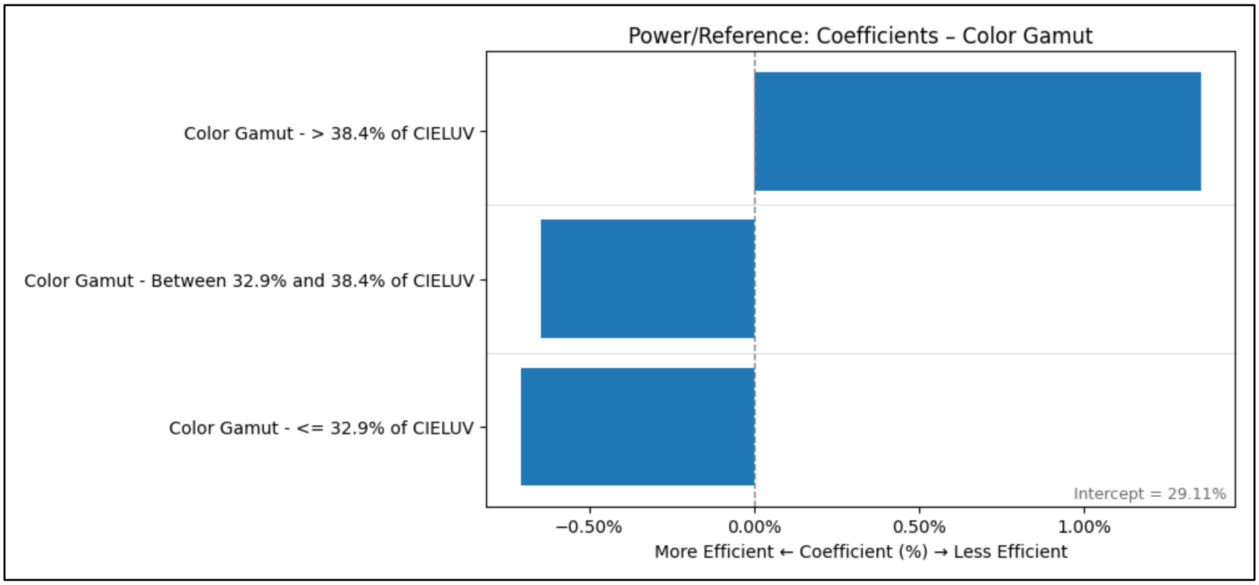


Figure 55: Impact of color gamut on energy efficiency in the CEC MAEDbS dataset

Note: This graph sorts these results by the coefficients' magnitude, rather than by the color gamut range.

This analysis suggests that very high color gamut coverage (greater than 38.4% of CIELUV) is associated with reduced energy efficiency. The estimated effect is very small. The relationship (between color gamut and Power/Reference) is also not linear and is likely influenced by other variables not represented in the regression. For example, the lowest color gamut group of displays (<= 32.9%) appears less efficient than the medium group (between 32.9% and 38.4%).

The 2020 ENERGY STAR Displays 8.0 dataset includes a field for color gamut area percentage, but entries are not in a consistent format. This field was therefore not standardized for the analysis. Instead, the Enhanced Performance Display category was used. This metric classifies displays into two levels (EPD I and EPD II) based on their color gamut coverage, as seen in Figure 56.[29]

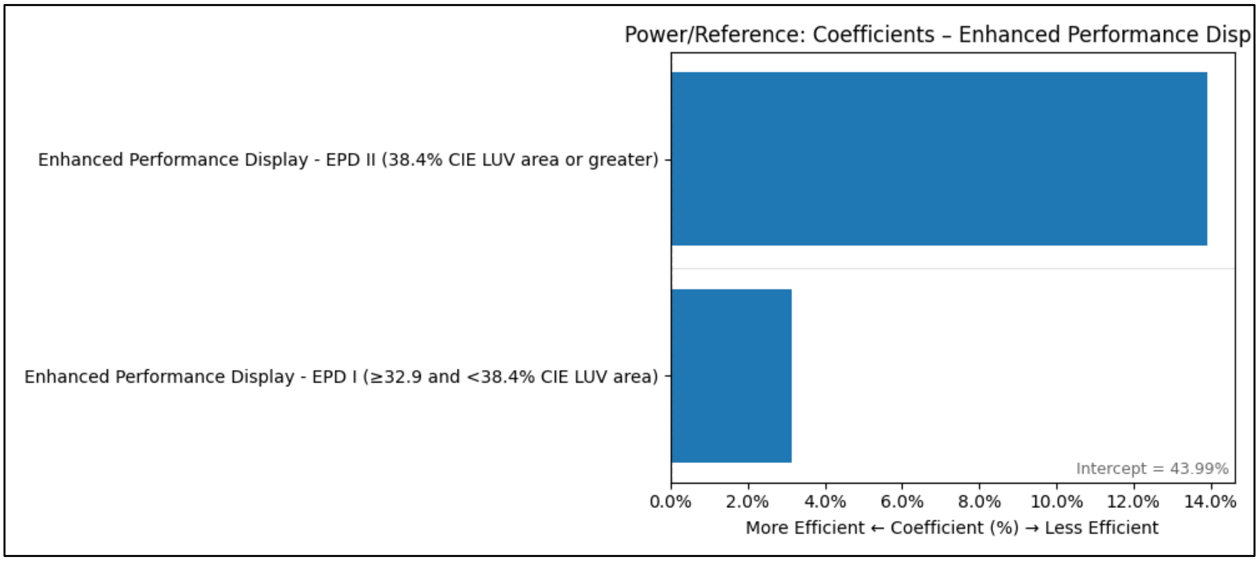


Figure 56: Impact of color gamut on energy efficiency in the ENERGY STAR Displays 8.0 dataset

This analysis suggests a larger association between color gamut and energy efficiency. However, the ENERGY STAR dataset includes display models older than those in the 2025 CEC dataset, so direct comparison should be made with caution.[30]

1.1.1.13.8 Contrast Ratio Capability

Contrast ratio, as tested, refers to the difference between the brightest white and the darkest black a display can produce while approximating dynamic content per the method described in CONTRAST RATIO. It

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[29] ENERGY STAR Displays 8.0 designates Enhanced Performance Displays as meeting all the following:
(i) Contrast ratio ≥ 60:1 at 85° horizontal (flat screens) or 83° (curved screens);
(ii) Native resolution ≥ 2.3 megapixels;
(iii) Color gamut ≥ 32.9% of CIELUV.

[30] The ENERGY STAR 8.0 dataset primarily comprises models from 2012–2018 (plus one 2000 model), while this analysis of the CEC dataset is limited to models from 2023–2025.

is typically represented as X:1, meaning the brightest white is X times brighter than the darkest black. A higher contrast ratio generally improves image depth and detail, especially in darker scenes.

1.1.1.13.8.1 Test Results

The contrast ratio measurements in this section were performed using the PR-655 SpectraScan.[31]

A negative relationship between contrast ratio and energy efficiency (as contrast ratio increases, energy efficiency decreases) was observed in the laboratory sample, as shown in Table 39.

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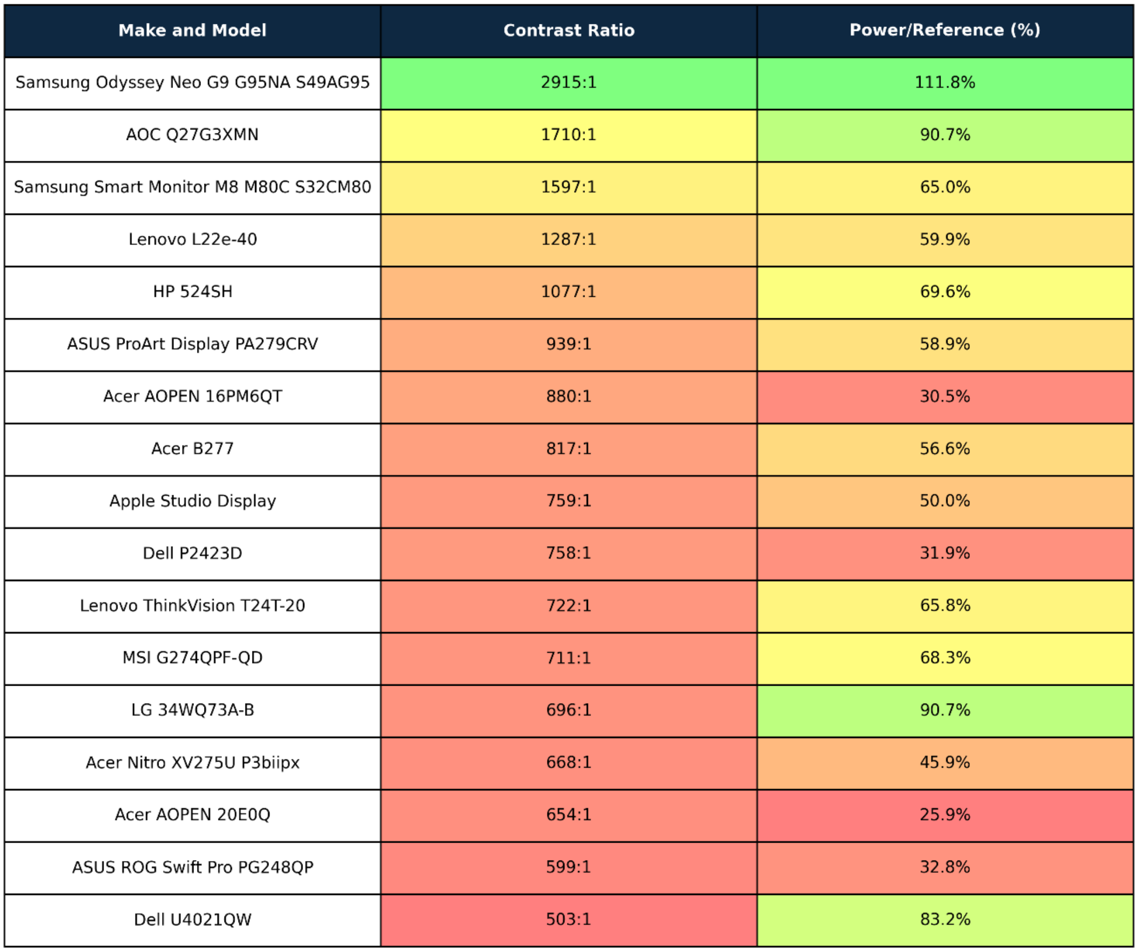
[31] Although the PR-655 has reduced accuracy below 0.68 cd/m², this was sufficient for comparison testing as this laboratory testing was not used to quantify the impact of contrast ratio on energy efficiency (this was done with regression analysis of existing datasets instead).
Some of PCL's contrast ratio results were cross-referenced with those in RTINGS and they were comparable. In the case of the Samsung Odyssey Neo G9, RTINGS identified a result of 2866:1 contrast ratio (with local dimming off), while this testing identified 2915:1. For the ASUS ProArt Display, this research's result was 939:1 while RTINGS' was 920:1.

Table 39: Contrast ratio comparison across computer monitors



Make and Model	Contrast Ratio	Power/Reference (%)
Samsung Odyssey Neo G9 G95NA S49AG95	2915:1	111.8%
AOC Q27G3XMN	1710:1	90.7%
Samsung Smart Monitor M8 M80C S32CM80	1597:1	65.0%
Lenovo L22e-40	1287:1	59.9%
HP 524SH	1077:1	69.6%
ASUS ProArt Display PA279CRV	939:1	58.9%
Acer AOPEN 16PM6QT	880:1	30.5%
Acer B277	817:1	56.6%
Apple Studio Display	759:1	50.0%
Dell P2423D	758:1	31.9%
Lenovo ThinkVision T24T-20	722:1	65.8%
MSI G274QPF-QD	711:1	68.3%
LG 34WQ73A-B	696:1	90.7%
Acer Nitro XV275U P3biipx	668:1	45.9%
Acer AOPEN 20E0Q	654:1	25.9%
ASUS ROG Swift Pro PG248QP	599:1	32.8%
Dell U4021QW	503:1	83.2%

Notes*:* Red (higher) contrast ratio is better performance.

OLED displays were excluded from this testing because their contrast ratio is theoretically very high (perfect/infinite) and could not be reliably measured using normal photometers. OLED displays are also excluded from Figure 57 below.

In the laboratory sample, higher contrast ratio computer monitors tended to be associated with lower energy efficiency relative to the reference line. This may reflect trade-offs in some LCD designs in which achieving deeper blacks can reduce light output efficiency in the darker areas where local dimming is not active (due to more light from the backlight being blocked in dark areas). Figure 57 shows a linear trendline through the data with a slope of 0.0002 and an R^2 value of 0.37.

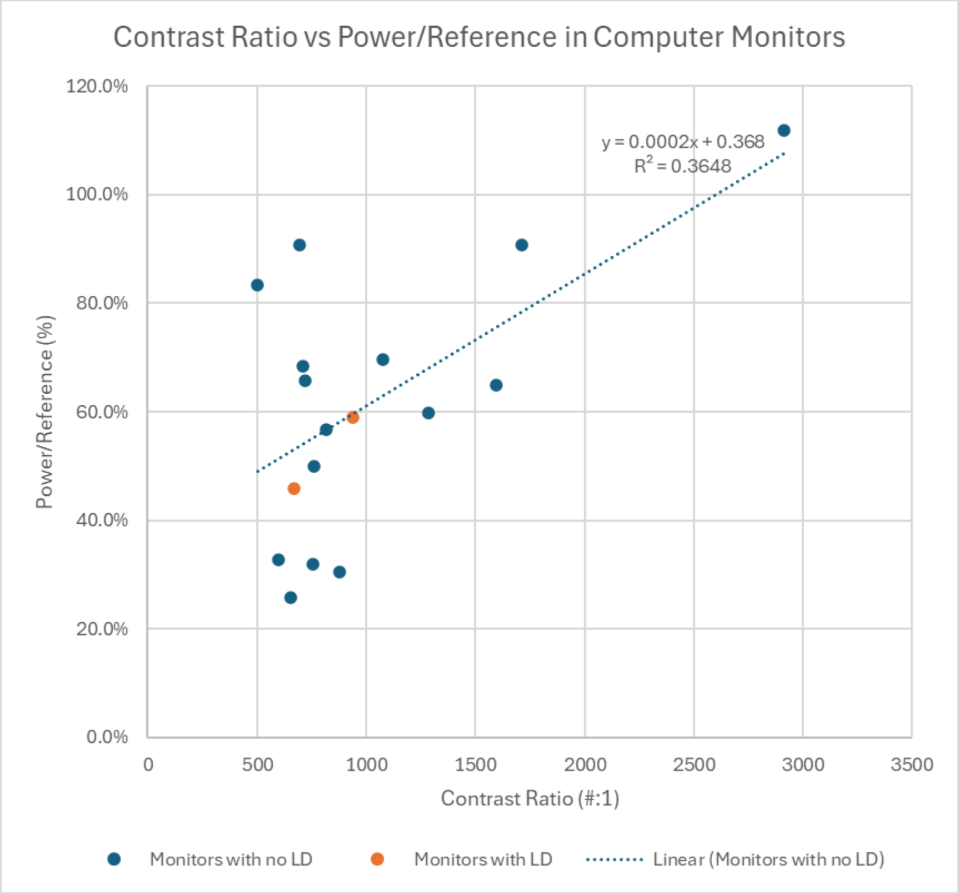


Figure 57: Contrast ratio versus Power/Reference in computer monitors

Computer monitors labeled as “Monitors with LD” in this plot are those that exhibited active local dimming during the broadcast clip test, as determined by reviewing power and luminance over the duration of the clip. Although three computer monitors in the dataset had a local dimming setting enabled by default, local dimming behavior was observed during the dynamic test clip in only two of them.[32]

Given the small sample size and different technologies and features in each monitor, this simple correlation alone should not be treated as a generalizable relationship between contrast ratio and Power/Reference.

1.1.1.13.8.2 Dataset Findings

The 2025 CEC MAEDbS dataset does not have contrast ratio information for computer monitors. While contrast ratio information for many computer monitors is available online, it is difficult to draw meaningful

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[32] In the case of the Samsung Odyssey Neo G9, which had the highest contrast ratio among monitors tested, it does not appear that the Local Dimming default setting (“Auto”) was activated by the test clip, as RTINGS measured contrast ratio at 14,843:1 for this display when local dimming was enabled. RTINGS used the Konica Minolta LS-100 for their readings.

comparisons since the method for measuring contrast ratio is not standardized in the industry. Some manufacturers use sequential contrast ratio measurements (full white screen compared with full black screen). This can produce much higher contrast ratio values than the method used in this study (see section CONTRAST RATIO in ANNEX A: METHODOLOGY). For this reason, comparisons based on manufacturer-claimed contrast ratio values are not considered reliable for policy analysis.

The 2020 ENERGY STAR Displays 8.0 dataset indicates that each 1,000-point increase in contrast ratio is associated with a 2.37% increase in Power/Reference. Consistent with the laboratory testing results, this suggests that power adders may be needed to avoid disincentivizing higher contrast ratio performance.

1.1.1.13.9 Viewing Angle Capability

Viewing angle describes how well a display maintains image quality when viewed from different angles. It is an important factor in professional and consumer displays, particularly for applications where multiple viewers or off-center viewing is common. Viewing angle performance can be assessed through several metrics such as brightness loss, color shift, contrast ratio decrease, and color gamut coverage loss.

1.1.1.13.9.1 Test Results

This study analyzes how contrast ratio and color gamut coverage changed at 45° and 85° viewing angles.

Contrast ratio viewing angle was analyzed in part because it is used in current policy, with ENERGY STAR Displays 8.0 for displays having a contrast ratio requirement at 85° from the perpendicular. Additionally, contrast ratio viewing angle as a metric can signal both brightness loss in bright areas and black level rise in dark areas. Color gamut viewing angle measurements were performed to see if the impact to energy efficiency observed in color gamut coverage was exacerbated by the display's ability to maintain its color gamut at wide viewing angles.

As shown in Figure 58 and Figure 59 below, no clear correlation was found between contrast ratio viewing angle or color gamut viewing angle and a display's energy efficiency. All relationships plotted have low R^2 values.

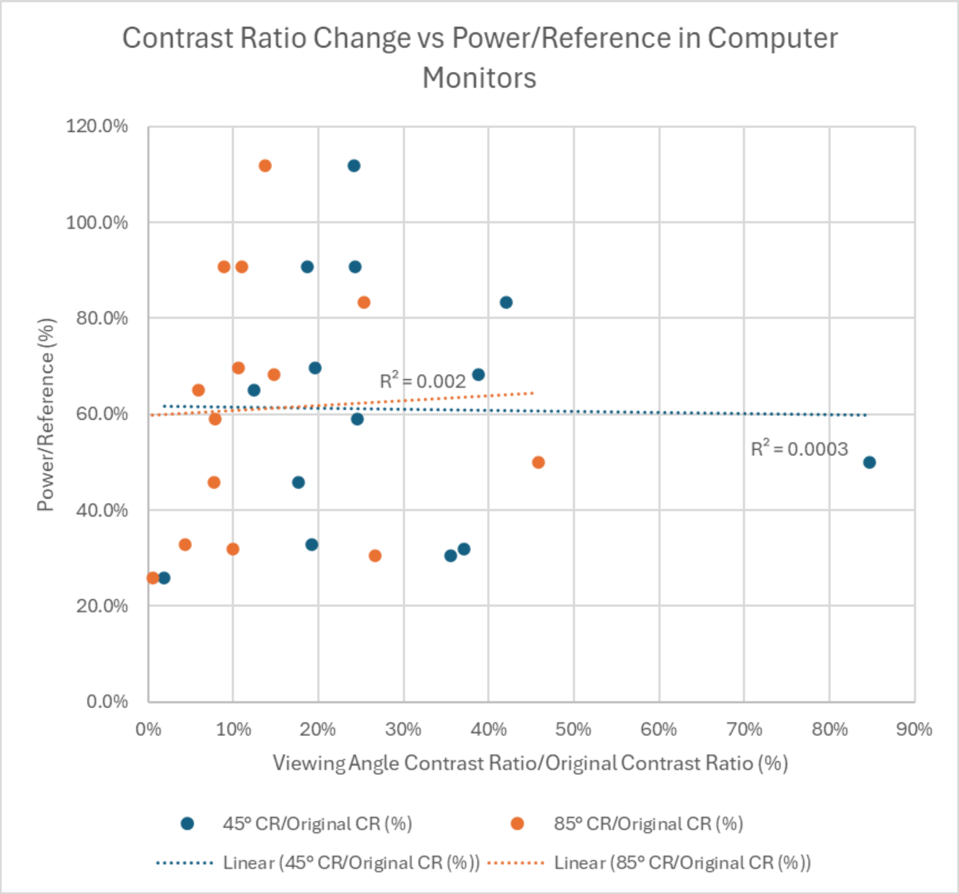


Figure 58: Contrast ratio viewing angle comparison at 45° and 85°

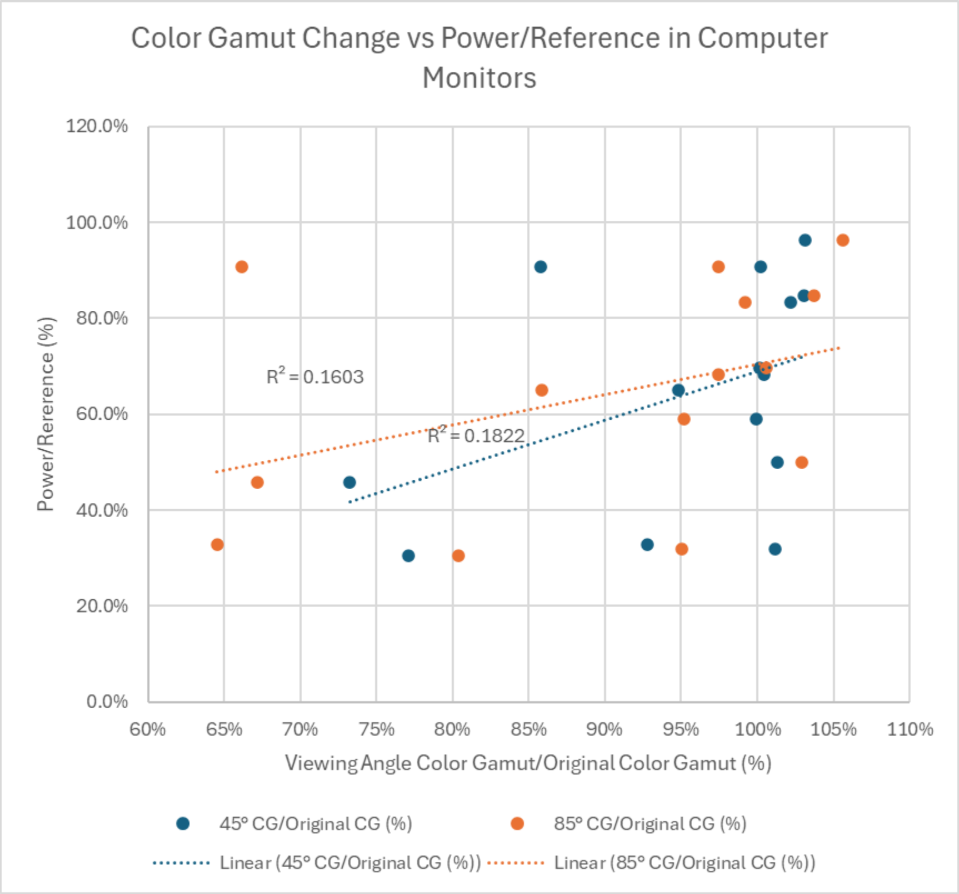


Figure 59: Color gamut viewing angle comparison at 45° and 85°

Although these results suggest limited association between viewing angle and energy efficiency, this comparison does not normalize for other variables that may affect energy efficiency.

1.1.1.13.9.2 Dataset Findings

The 2020 ENERGY STAR Displays 8.0 dataset has contrast ratio viewing angle measurements taken at 85° from the perpendicular on both the left and right sides of the monitor. There is no data for color gamut viewing angles on this dataset.

This dataset shows that contrast ratio viewing angle likely has no real effect on energy efficiency, as Table 40 shows.

Table 40: Impact of viewing angle on the ENERGY STAR Displays 8.0 dataset

Feature	Coefficient Value
85° Left/Original Contrast Ratio	-0.14%
85° Right/Original Contrast Ratio	+0.31%

For example, if a computer monitor preserves 60% of its contrast ratio at an 85° right angle, its Power/Reference value would only increase by 0.19%. Given the small effect size, the fact that Power/Reference can decrease as more contrast ratio is preserved, and the inconsistent direction of the coefficients (left versus right), viewing angle is not recommended for special treatment in display policy.

The CEC dataset has no viewing angle data, so it could not be analyzed in this case.

1.1.1.13.10AI Image Processing Setting

AI-powered display features use real-time processing to optimize brightness, contrast, sharpness, and other image parameters based on content. Industry reporting indicates that artificial intelligence features are increasingly being integrated into displays to enhance graphics and user experience. AI-powered features are more common in premium computer monitors and unavailable in budget and entry-level models.

AI-powered display features that apply changes to picture settings may include:

- **AI-based image and color adjustments:** Adjusting brightness, contrast, local dimming, and color based on the content being played
- **AI upscaling:** improving the appearance of lower-resolution content
- **Content detection and PPS selection:** Switching between PPSs based on detected content (e.g., selecting a Sports PPS when a sports game is being viewed)

1.1.1.13.10.1 Test Results

Among the computer monitors tested, the LG 42 OLED Flex was the only model with an AI-powered image enhancement feature. While this model also had a similar feature for enhancing sound, since PCL's test method has no way to quantify the amenity of sound (in the same way luminance is quantified as an amenity), its energy efficiency impact could not be assessed.

As shown in the graph below, enabling this feature increased power consumption, but the impact was not significant (power increased by less than a watt for any given luminance).

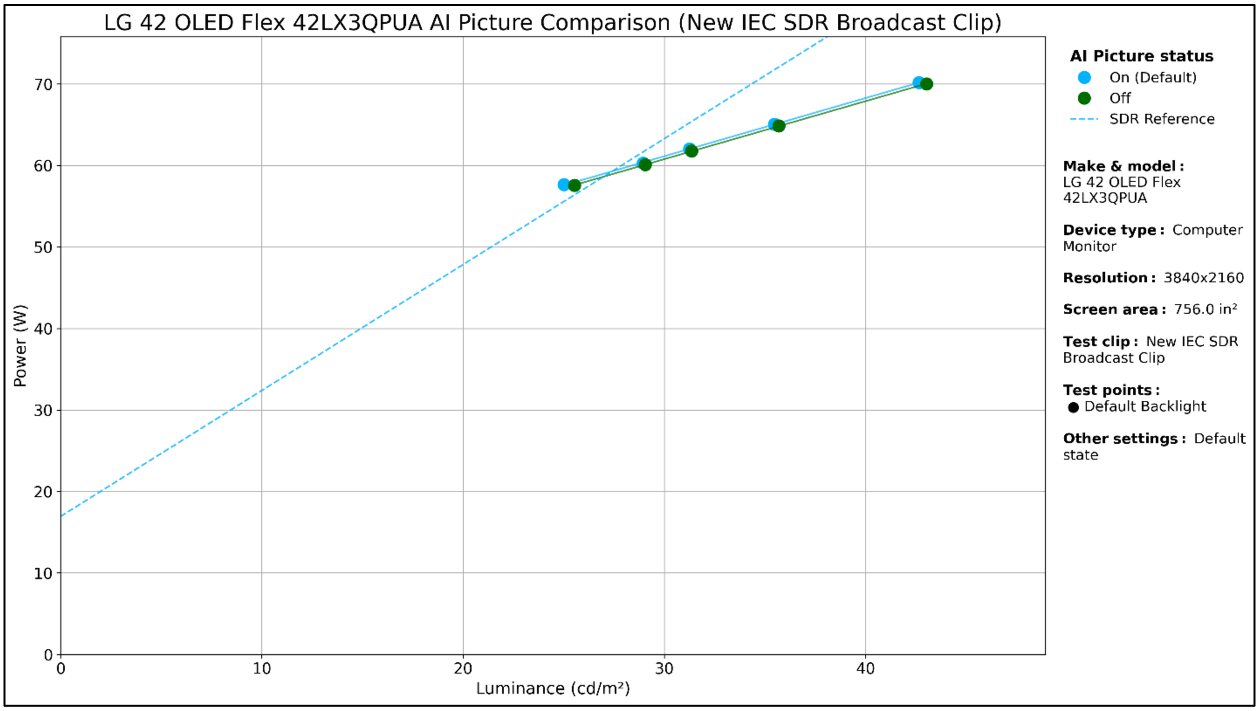


Figure 60: AI Picture setting comparison in the LG 42 OLED Flex

1.1.1.13.10.2 Dataset Findings

As AI-powered features are relatively new, neither dataset records whether similar features were present or enabled during testing. The datasets therefore cannot be used to assess the energy impact of AI image processing settings.

1.1.1.13.11 Duty Cycle Capability

Some computer monitors, especially those intended for security and surveillance applications, are rated for 24/7 usage. Although no monitors with this rating were tested, section 1.1.1.15.11: DUTY CYCLE presents findings from testing DSDs with 24/7 usage ratings. In that testing, a correlation between support for more intensive duty cycles and increased power consumption was not observed.

1.1.1.13.12 Refresh Rate Capability and Setting

Refresh rate refers to how many times per second a screen updates its image, measured in hertz (Hz). Higher refresh rates provide smoother motion, which is important for gaming applications.

Both fast refresh rates and short response times are necessary for smooth, blur-free motion. A fast refresh rate requires a reasonably short response time to be visually effective. If the pixel response time is slow, at high refresh rates the display will be unable keep up with the frequent refreshes, leading to motion blur or ghosting. For policy purposes, refresh rate is investigated to determine whether it is a performance feature that can increase energy use when enabled.

1.1.1.13.12.1 Test Results

Both the energy impact of the maximum refresh rate a monitor can support (but is not necessarily using) and its actual refresh rate setting were reviewed.

Native (or default) and maximum refresh rates for each of the computer monitors tested are on Table 41 below.

Table 41: Refresh rates for all computer monitors tested

Make	Model	Native Refresh Rate	Maximum Refresh Rate
ASUS	ROG Swift Pro PG248QP	60	540
Samsung	Odyssey Neo G9 G95NA S49AG95	60	240
AOC	Q27G3XMN	60	180
MSI	MEG 342C QD-OLED	60	175
MSI	G274QPF-QD	60	170
Acer	B277	60	170
Acer	Nitro XV275U P3biipx	60	160
INNOCN	27M2V	60	160
LG	42 OLED Flex 42LX3QPUA	120	120
HP	524SH	60	100
Acer	AOPEN 20E0Q	60	75
Lenovo	L22e-40	60	75
Acer	AOPEN 16PM6QT	30	60
Dell	P2423D	60	60
Lenovo	ThinkVision T24T-20	60	60
Apple	Studio Display	60	60
ASUS	ProArt Display PA279CRV	60	60
Samsung	Smart Monitor M8 M80C S32CM80	60	60
LG	34WQ73A-B	60	60
Dell	U4021QW	60	60

Note: Red here indicates more functionality relative to the other samples, as higher refresh rates are desired for gaming applications.

Power/Reference was plotted against maximum refresh rate capability to explore whether higher refresh rate capability has an influence on a monitor's energy efficiency, regardless of whether the maximum refresh rate is being used. For this comparison, all test points were taken at each monitor's native refresh rate (not at its maximum refresh rate). Apart from two computer monitors (with native refresh rates of 120Hz and 30Hz), all samples tested had native refresh rates of 60Hz.

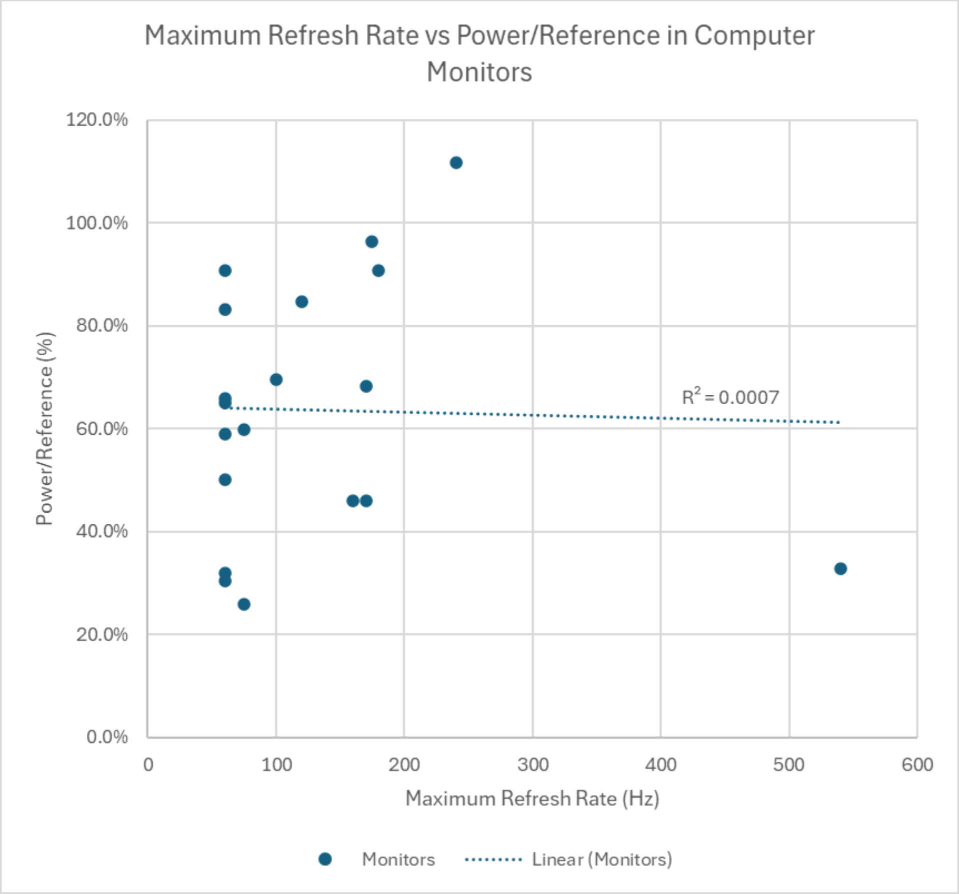


Figure 61: Maximum refresh rate versus Power/Reference

In this limited laboratory testing sample, no relationship was observed between maximum refresh rate **capability** and Power/Reference (while taking measurements at native refresh rate). This should not be interpreted as capability having no impact on energy use, because the test did not hold other display characteristics constant and did not measure power at maximum refresh rate. Dataset analysis indicates that supporting higher native and maximum refresh rate capability is associated with higher Power/Reference values.

To assess how refresh rate **settings** affect energy use within the same display, power and luminance were measured at several refresh-rate configurations. A mainstream gaming monitor with a maximum refresh rate of 144Hz (the AOC Q27G3XMN) and a high-end competitive gaming monitor (the ASUS ROG Swift Pro PG248QP) with a maximum refresh rate of 540Hz, currently among the highest available in the market, were tested.

To ensure that each monitor received enough frames per second (FPS) to fully utilize its refresh rate capability (so that every refresh cycle displayed a new frame), measurements were taken while rendering the loading screen of the Broforce video game, which the test system could run at over 2,500 FPS. Power and luminance were recorded over a one-minute period for each refresh-rate setting.

For the AOC Q27G3XMN monitor with a maximum refresh rate of 144Hz, power consumption increased progressively with higher refresh-rate settings (Figure 62).

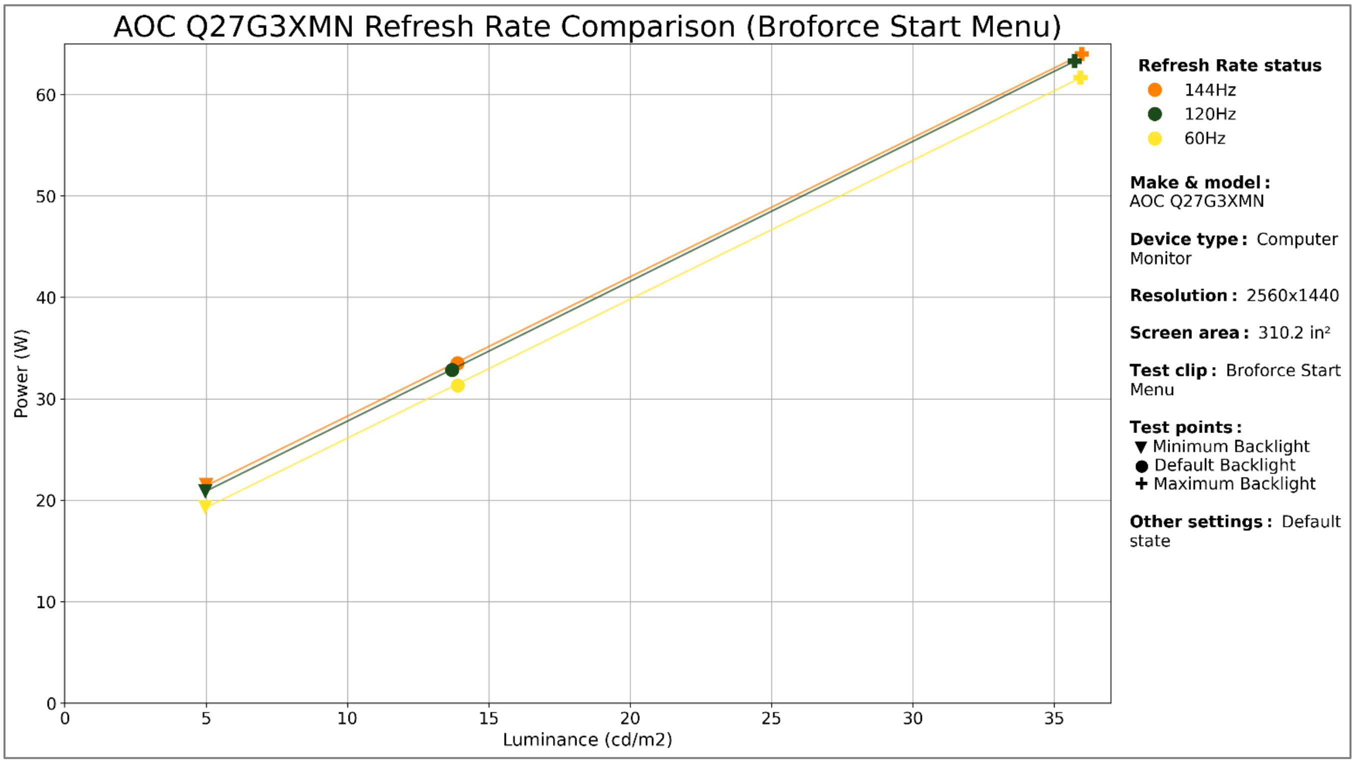


Figure 62: AOC Q27G3XMN refresh rate settings

In comparison, the monitor with a maximum refresh rate of 540 Hz (ASUS ROG Swift Pro PG248QP) exhibited an even steeper rise in power consumption at each successive refresh-rate setting (Figure 63).

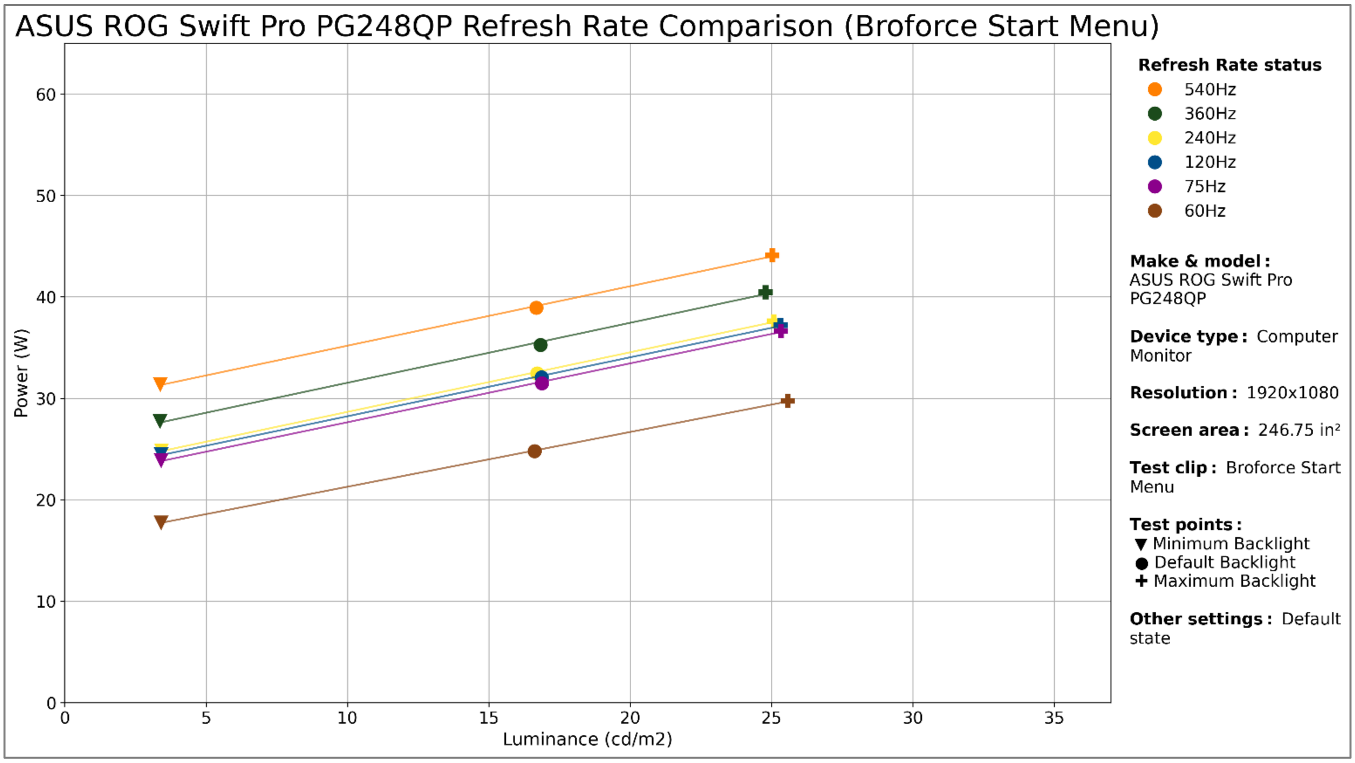


Figure 63: ASUS ROG Swift Pro PG248QP refresh rate settings

The non-linearity in power usage increases with refresh rate (above) shows that the activation of hardware assistance used in monitor refresh rate technology can increase energy consumption.

1.1.1.13.12.2 Dataset Findings

Both the 2025 CEC MAEDbS and 2020 ENERGY STAR Displays 8.0 datasets show a correlation between higher native and maximum refresh rate **capabilities** and reduced energy efficiency, as shown in Table 42.

Table 42: Refresh rate's impact on Power/Reference in CEC MAEDbS and ENERGY STAR Displays 8.0

Dataset	Feature	Coefficient Value
CEC MAEDbS	Native Refresh Rate over 60Hz (x100Hz)	+3.13%
	Maximum Refresh Rate over 60Hz (x100Hz)	+3.81%
ENERGY STAR Displays 8.0	Native Refresh Rate over 60Hz (x100Hz)	+6.65%
	Maximum Refresh Rate over 60Hz (x100Hz)	+4.09%

Higher refresh rate **settings** lead to increased energy consumption, as does having a higher refresh rate **capability**. Given that high refresh rates are a key feature for certain market segments (particularly gaming), display policies can account for this by including appropriate power adders.

1.1.1.13.13 Variable Refresh Rate Capability and Setting

Variable refresh rate (VRR) is a display technology that dynamically adjusts a monitor's refresh rate to match the frame rate of the content being rendered. By synchronizing the display with the graphics card's output, VRR reduces screen tearing, stuttering, and input lag, resulting in a smoother visual experience — particularly important for gaming. Common implementations include NVIDIA G-SYNC and AMD FreeSync, both of which coordinate refresh rates with the GPU to maintain consistent visual performance.

VRR can be implemented with or without additional incremental hardware. CEC Title 20 cites as examples of incremental hardware a dedicated processor that receives frames from the host computer's graphics card and a dedicated memory to temporarily store these frames. This hardware is not required to enable basic VRR functionality, but it can enable lower latency, finer control over frame timing, and improved visual stability compared to implementations that rely on monitor scalers or timing controllers (TCON), which are standard components inside most computer monitors.

1.1.1.13.13.1 Test Results

The impact of enabling VRR was tested using NVIDIA's G-SYNC Pendulum Demo as a test clip to simulate screen tearing, thereby activating this feature to observe its impact on power consumption. As seen in Table 43 and Table 44, turning VRR on and off did not impact luminance or power; therefore, it did not affect energy efficiency.

Table 43: FreeSync comparison in the AOC Q27G3XMN monitor

FreeSync Status	Luminance (cd/m²)	Power (W)
On	39.5	31.5
Off	39.6	31.5

Table 44: FreeSync comparison in the Acer Nitro monitor

FreeSync Status	Luminance (cd/m²)	Power (W)
Off	26.0	20.2
On	26.0	20.2

1.1.1.13.13.2 Dataset Findings

The 2025 CEC MAEDbS dataset identifies computer monitors with VRR capabilities as "gaming monitors." These may have incremental hardware. This dataset was used to analyze the energy impact of supporting VRR **capability**.

As shown in Table 45, models with VRR functionality tend to exhibit higher Power/Reference values, particularly where incremental hardware is present. This suggests that additional computing components contribute to increased energy demand.

Table 45: Impact of VRR capability on energy efficiency in CEC MAEDbS

Feature	Coefficient Value
VRR capability with Incremental Hardware	+14.07%
VRR capability without Incremental Hardware	+6.18%

While these results indicate an apparent association between VRR capability and higher power consumption, the analysis does not control for other product characteristics not reflected in the dataset that could influence energy performance. The observed correlation may therefore reflect broader design attributes typical of gaming monitors rather than the VRR feature itself. From a policy perspective, if VRR capability remains mainly confined to gaming and other specialized monitors with their own distinct regulatory limits, no need may exist for an additional allowance. However, for situations in which such capability extends to a broader range of products, a functional allowance could be considered to recognize performance benefits.

1.1.1.13.14 Response Time Setting

Response time refers to how quickly a pixel transitions from one color to another, impacting motion clarity and the extent of ghosting effects in motion (Figure 64).

Figure 64: The dark trails that the moving logo leaves behind are an example of ghosting from RTINGS

In this analysis, response time is treated only as a user-adjustable setting, not as an intrinsic hardware capability. Response time performance is closely linked to panel technology. TN panels generally achieve the fastest transitions among LCD types, followed by IPS and VA panels, while OLED displays exhibit even faster response times than TN.

1.1.1.13.14.1 Test Results

RTINGS, an independent testing and review platform specializing in display performance, measures response times at various refresh rates by calculating the milliseconds required for a screen to transition between different levels of grey. In the case of the Samsung Smart Monitor M8 (Figure 65), the average response time was approximately 19 ms at 60 Hz, which is both its native and maximum refresh rate. This monitor and the HP 524SH were selected because both include a discrete user-adjustable response time setting that allowed direct comparison of power consumption between configurations.

The energy efficiency policies reviewed (ANNEX J: OVERVIEW OF CURRENT DISPLAY POLICIES) do not provide specific guidance on response time settings and do not offer allowances linked to response time performance. PCL's limited testing across these two models suggests that adjusting response-time settings has a negligible impact on energy use, as shown in the figure below. Accordingly, response time performance does not appear to warrant any functional allowances, and no changes to current test configurations appear necessary.

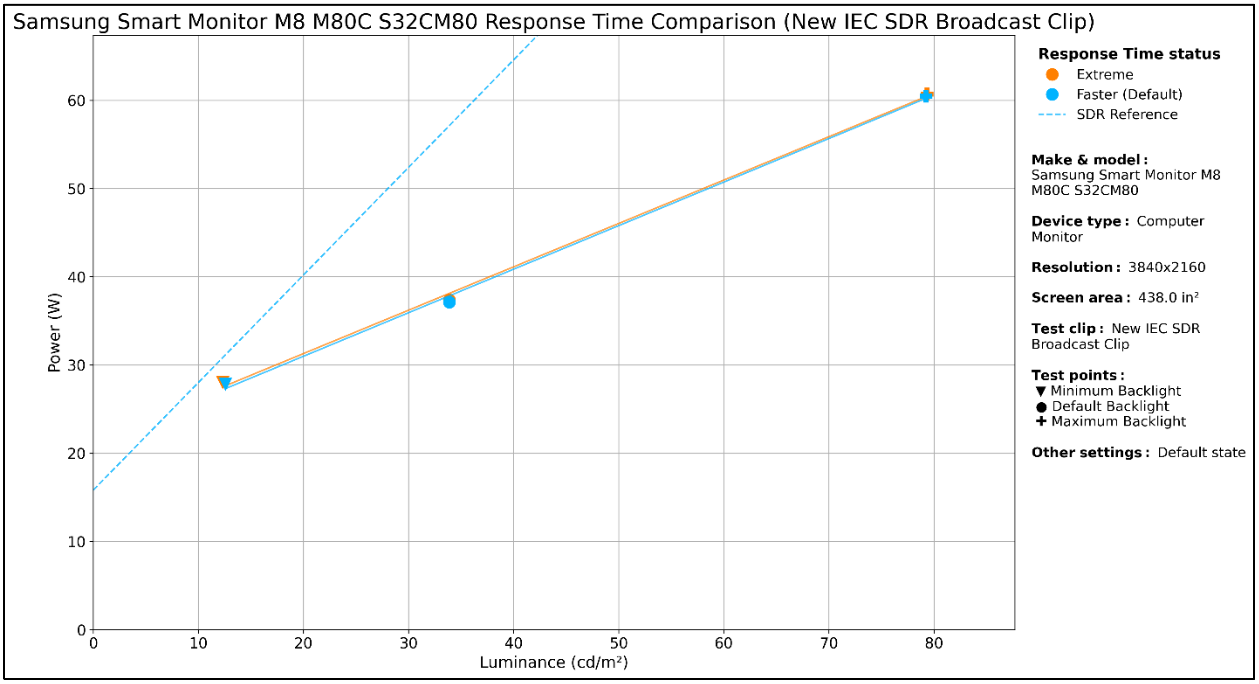


Figure 65: Response time setting comparison in the Samsung Smart Monitor M8

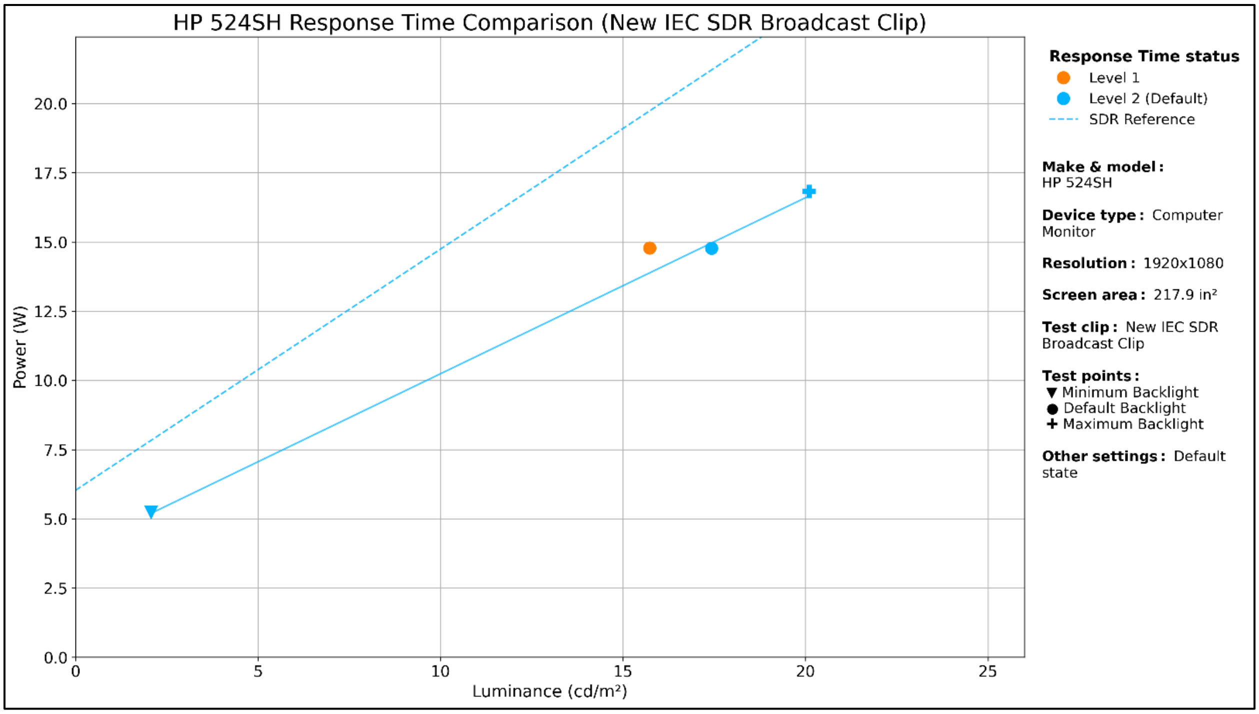


Figure 66: Response time setting comparison in the HP 524SH

1.1.1.13.14.2 Dataset Findings

As neither dataset included comparisons among different response time settings, no additional analysis was completed based on this data.

1.1.1.13.15 Touchscreen Capability and Setting

Touchscreen **capability** may influence display energy efficiency in two ways: 1) through the additional hardware and optical layers required for touch capability, and 2) through any power overhead specifically when the touch feature is enabled and operating. The current laboratory testing sample and dataset evidence are not sufficient to quantify this effect reliably. However, industry insights suggest that certain touchscreen technologies introduce additional optical layers—such as cover glass or touch sensors—that reduce light transmission by blocking a portion of the display's emitted light, requiring higher backlight output to maintain the same on-screen luminance and thereby increasing energy consumption while reducing overall efficiency.

According to display industry expert Marques Girardelli, different touchscreen technologies affect luminance as follows:

- **Infrared (IR):** Typically results in a luminance reduction of about 10%. The IR components are positioned around the panel and don't directly block light, but a cover glass layer is usually added, which causes the drop (e.g., from 500 to 450 cd/m^2).
- **Projected Capacitive (PCAP):** Adds an additional 10% luminance reduction on top of a cover glass, totaling about 20% reduction (e.g., from 500 to 400 cd/m^2).

One example is the Planar Simplicity P Series, which uses PCAP technology. Its brightness drops from 500 cd/m^2 in the non-touchscreen edition to 400 cd/m^2 in the touchscreen edition, showing the typical 20% reduction.

This section assesses whether **enabling or disabling** touchscreen on the same display affects its measured power demand.

1.1.1.13.15.1 Test Results

PCL's tests suggest that enabling touchscreen as a **setting** decreases efficiency relative to the reference line.

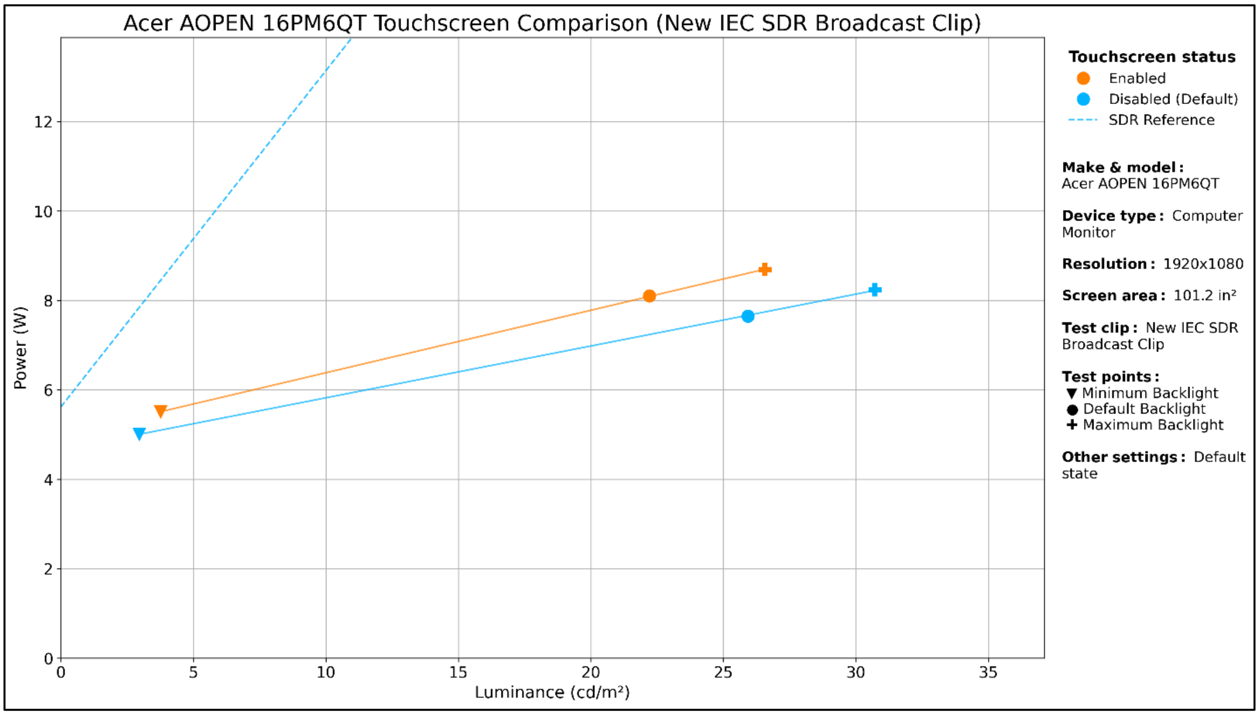


Figure 67: Touchscreen comparison on the Acer AOPEN 16PM6QT computer monitor

In this case, Power/Reference increased by about 6% when the touchscreen was enabled. The touchscreen being **enabled** both raised power demand and decreased screen luminance. It was not anticipated that the touchscreen setting would decrease the screen's light transmissivity; only a fixed power increase that would produce parallel dimming lines was expected. The cause of this behavior is unclear.

The monitor shown above required a USB-C connection to activate touch functionality. However, the same USB-C connection also delivered power to the connected laptop, potentially skewing energy measurements. To isolate the touchscreen's energy impact (as shown on Figure 67):

- Laptop charging was prevented by simultaneously charging it via a different port.
- A USB-C multimeter was used to verify that the laptop was not drawing power from the monitor.

Although this approach provided a clearer measurement of touchscreen energy use, USB-C multimeters have the potential to disrupt high-refresh-rate and high-resolution display connections. When attempting to use the multimeter while testing the Apple Studio Display, which is a 5k display, the laptop was unable to connect to the monitor. In this case, the monitor was moved to a different port in the computer that did not have computer charging enabled, per the laptop manufacturer's specifications.

1.1.1.13.15.2 Dataset Findings

In analyzing the impact of touchscreen **settings** on energy efficiency, mixed results were found across the datasets reviewed. All displays in these datasets were tested with the touchscreen enabled if the hardware supported it.

In the 2025 CEC MAEDbS dataset, when touchscreen was enabled in Active Mode, it correlated with improved energy efficiency. Specifically, PCL's regression analysis showed a 4.7% decrease in Power/Reference, indicating more efficient energy use.

In the 2020 ENERGY STAR Displays 8.0 dataset, the touchscreen setting was enabled whenever the display supported touch. In that dataset, an enabled touchscreen setting yielded a slightly negative effect on energy efficiency, increasing Power/Reference by 2.73%. This impact is smaller than what was observed in PCL's limited lab testing. The discrepancy may stem from the low baseline power consumption (8.1 W with touch enabled) of the computer monitor used in PCL's test.

Overall, the results are inconclusive. The opposing correlations observed between datasets (one suggesting a small improvement and the other a slight efficiency loss) likely reflect differences in product mix and measurement context rather than the intrinsic impact of touchscreen functionality. The absence of detailed information on the touchscreen technologies used (e.g., infrared, projected capacitive) further limits interpretation, as these would vary in optical transmittance and therefore in their influence on backlight power and energy use. Without this level of detail, isolating or generalizing the energy impact of touchscreen capability across models is not possible.

1.1.1.13.16HDR Content Format

Playing High Dynamic Range (HDR) content on an HDR-capable display increases contrast, brightness, and color depth, delivering richer visuals with deeper blacks, brighter highlights, and more vivid colors. To achieve this expanded luminance range, the display must drive its backlight and pixel control electronics more intensely. As a result, HDR playback has been generally understood to increase power consumption particularly in LCD models without local dimming, where the entire backlight, rather than only selected zones, must brighten to create highlights.

1.1.1.13.16.1 Test Results

Among the computer monitors tested, 10 supported HDR. Non-emissive LCD displays in the tested samples were found to be less efficient when playing HDR, with steeper luminance-power slopes in each case. These steeper slopes result from the high contrast ratio that HDR content seeks to create, as more light is emitted to support bright highlights yet blocked to achieve dark shadows. ANNEX C: DIMMING LINES FOR ALL DISPLAYS Tested, which contains dimming lines for all SDR PPSs in a monitor, also includes dimming lines for the default HDR PPS where available.

While HDR is a growing concern for televisions—where it is widely enabled by default for supported content—it may currently be less impactful for computer monitors. On most operating systems, including Windows and macOS, HDR is not enabled by default. As a result, many monitor users may not experience the increased energy use associated with HDR in typical day-to-day applications. However, as HDR adoption continues to grow, it becomes increasingly relevant for monitor efficiency policy. According to a Dataintelo report, the HDR computer monitor global market is expected to grow from 2.5 billion in 2023 to 6.9 billion by 2032.

1.1.1.13.16.2 Dataset Findings

The CEC MAEDbS and ENERGY STAR Displays 8.0 datasets do not have HDR test results that can be compared to PCL's.

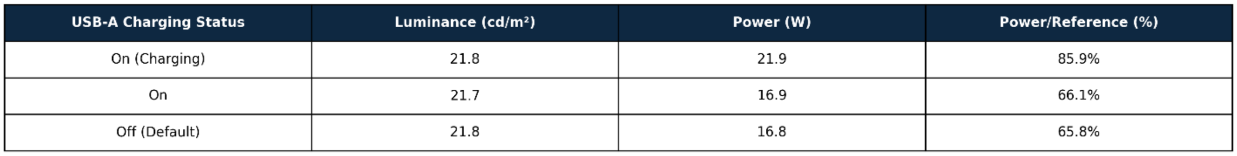
1.1.1.13.17 USB Charging Capability and Setting

Certain monitors offer the possibility of charging external devices using USB, whether it be via USB-A or USB-C ports.

1.1.1.13.17.1 Test Results

One of the models in the laboratory sample, the Lenovo ThinkVision T24T-20, allowed a USB-A charging **setting** to be turned on and off. Table 46 shows that enabling the setting used an additional 0.1 W when no devices were being charged.

Table 46: Impact of USB-A charging setting on the Lenovo ThinkVision T24T-20



USB-A Charging Status	Luminance (cd/m^2)	Power (W)	Power/Reference (%)
On (Charging)	21.8	21.9	85.9%
On	21.7	16.9	66.1%
Off (Default)	21.8	16.8	65.8%

1.1.1.13.17.2 Dataset Findings

The regression analysis of the 2020 ENERGY STAR Displays 8.0 dataset produced an inconclusive result for USB-C power delivery **capability**. It seemed to slightly improve efficiency, indicating a 0.27% reduction in Power/Reference. Since the ENERGY STAR test method does not ask testers to confirm that USB-C power delivery is enabled, it cannot be confirmed how the samples in this dataset were configured. Some of them may have had USB-C power delivery capabilities, but had the setting disabled.

PCL's (limited) testing shows USB charging has a very small impact on energy consumption; in the dataset analysis results, the impact is negligible.

PCL's analysis does not evaluate the efficiency of power transfer through USB in displays. The efficiency with which power is delivered to connected devices can vary depending on implementation and usage, potentially affecting overall energy performance. However, since USB power delivery is a secondary feature and not the primary function of displays, it is outside the scope of this research and was not tested as part of this analysis.

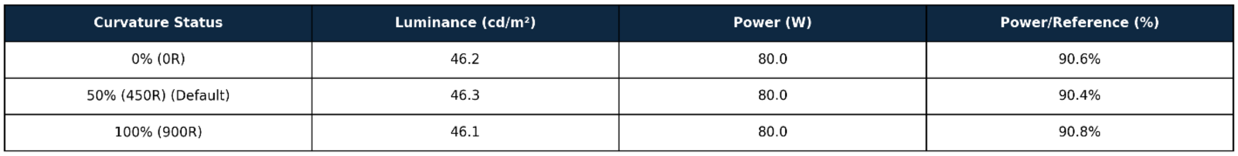
1.1.1.13.18Screen Curvature Capability and Setting

Screen curvature refers to the gentle bending of a monitor's display panel to create a concave shape that curves inward toward the viewer. This design is used to mimic the natural curvature of the human eye, allowing for a more immersive viewing experience. By reducing distortion at the edges and keeping the entire screen at a more consistent focal distance, curved monitors can enhance depth perception, reduce eye strain, and improve viewer focus. For the purposes of policy, this section explores the extent to which curvature (as a capability or as an adjustable setting, where available) is associated with changes in measured power and luminance under the applicable test conditions.

1.1.1.13.18.1 Test Results

The table below compares power consumption across different curvature **settings** on the same display:

Table 47: Power and luminance at different curvature levels in the LG 42 OLED Flex monitor



Curvature Status	Luminance (cd/m²)	Power (W)	Power/Reference (%)
0% (0R)	46.2	80.0	90.6%
50% (450R) (Default)	46.3	80.0	90.4%
100% (900R)	46.1	80.0	90.8%

PCL's testing found no difference in energy efficiency when evaluating the same display at different curvature levels.

1.1.1.13.18.2 Dataset Findings

Dataset regression analysis gives us the opportunity to review whether traditional curved displays that do not have a variable curvature setting (only a **capability,** which cannot be changed) have worse energy efficiency. Screen curvature as a **capability** had similarly negative impacts on energy efficiency in both the 2025 CEC MAEDbS and 2020 ENERGY STAR Displays 8.0 datasets, per Table 48.

Table 48: Impact of screen curvature on energy efficiency in the datasets

Dataset	Screen Curvature Coefficient Value
CEC MAEDbS	+9.14%
ENERGY STAR Displays 8.0	+6.08%

This shows that power adders related to screen curvature should be considered.

1.1.1.13.19KVM Switch Setting

KVM switch functionality allows a single keyboard, video display, and mouse to control multiple connected video-output devices (e.g., computers, game consoles, media players), improving workflow efficiency in multi-system setups.

1.1.1.13.19.1 Test Results

PCL's testing compared the same display with KVM switching enabled and disabled while showing an all-white pattern from either one or two laptops at once. No measurable difference in energy consumption was found. The table below summarizes PCL's findings:

Table 49: Comparison of the Dell U4021QW with and without KVM switch enabled

KVM Status	Luminance (cd/m²)	Power (W)
50/50 Dual Display	182.8	55.9
Single Display	182.7	55.8

1.1.1.13.19.2 Dataset Findings

Since ENERGY STAR excludes displays with KVM switch capabilities from qualification, there is no additional data from this dataset.

The 2025 CEC MAEDbS dataset only labels KVM switch capabilities when these computer monitors are designed for use in a data center. Given that there were only four models with this classification, all of them came from the same manufacturer, and consumer-grade monitors with KVM switches may exist that are not labeled as such, this data from PCL's regression analysis was excluded as the energy impact of this feature cannot be confidently isolated.

Overall, the limited evidence available does support the application of functional allowances or separate limits for KVM switch functionality in policy.

1.1.1.14 Non-Active Mode

This section reviews relevant Non-Active Modes for computer monitors and explore the energy impact of Non-Active Mode features.

1.1.1.14.1 What to Measure: Which Non-Active Modes

Computer monitors were tested in both D3hot and D3cold modes to determine whether both states are relevant Non-Active Modes for energy efficiency policy. Alternative "non-active" modes observed in the laboratory sample are also described.

In the laboratory observations, manually turning the monitor off generally resulted in the host device detecting a disconnection (consistent with a D3cold state). However, manual switch-off is an additional step that may not be taken when users step away from their devices. In typical use, the host device (likely a computer) may be left on, shut down, or put into a sleep mode. Computer shutdown is likely to place the monitor in a D3cold state, whereas computer sleep would typically place the monitor in D3hot. Thus, which power state is more representative depends on user behavior.

A consumer survey reported that 37% of American users shut down their work computers every night, while 23% never do so. No comparable figures for sleep mode use were identified, but it could be assumed more common than a full shutdown. For this reason, D3hot was prioritized when comparing

Non-Active Mode settings, except whereD3cold was used to better isolate the power impact of a given feature.

1.1.1.14.1.1 Test Results

15-minute power measurements were conducted in both D3hot and D3cold modes, after visually confirming from the power demand plot that readings had stabilized and showed no noticeable fluctuations. Table 50 summarizes the average power for each test.

Table 50: Standby values for computer monitors in D3hot and D3cold modes

Model	D3hot Power (W)	D3cold Power (W)
ASUS ROG Swift Pro PG248QP	13.6	12.1
Samsung Smart Monitor M8 M80C S32CM80	11.9	0.6
Apple Studio Display	9.5	0.3
MSI MEG 342C QD-OLED	9.4	0.7
LG 34WQ73A-B	3.8	0.2
ASUS ProArt Display PA279CRV	3.2	0.2
Dell U4021QW	0.5	0.5
Lenovo ThinkVision T24T-20	0.4	0.4
INNOCN 27M2V	0.4	0.2
Acer AOPEN 16PM6QT	0.4	2.4
MSI G274QPF-QD	0.3	0.2
AOC Q27G3XMN	0.3	0.3
Acer Nitro XV275U P3biipx	0.2	0.2
LG 42 OLED Flex 42LX3QPUA	0.2	0.3
Samsung Odyssey Neo G9 G95NA S49AG95	0.2	0.1
HP 524SH	0.2	0.1
Acer B277	0.2	0.1
Dell P2423D	0.1	0.1
Acer AOPEN 20E0Q	0.1	0.1
Lenovo L22e-40	0.1	0.1

Note: D3hot power was generally higher than D3cold power.

Additional “non-active” modes were observed in computer monitors with built-in operating systems. The LG 42" OLED Flex and the Samsung Smart Monitor M8 included “wallpaper” or “gallery” modes that display a sequence of static images instead of entering D3hot or D3cold. These modes are also becoming more widely available on televisions. Where enabled by default (observed only on the LG model), these modes were disabled for testing as they do not meet the IEC 62087 definition of a non-active mode.

Figure 68: Gallery mode being used on an LG TV

1.1.1.14.1.2 Dataset Findings

PCL’s testing shows significantly higher levels of Non-Active Mode power than those present in the 2020 ENERGY STAR Displays 8.0 dataset, where the highest ENERGY STAR Standby (D3hot equivalent) and ENERGY STAR Off Mode (D3cold equivalent) readings are 1.7 W and 0.46 W, respectively.[33] Figure 69 and Figure 70 show the distribution of these values.

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[33] Here, “ENERGY STAR Standby” and “ENERGY STAR Off” Modes are referenced specifically because they do not align with the definitions present in IEC 62087. ENERGY STAR Off Mode/D3hot may be considered a Standby or Off Mode per IEC 62087, as some computer monitors conserve secondary functions in D3cold (such as indicator lights and decorative RGB lighting).

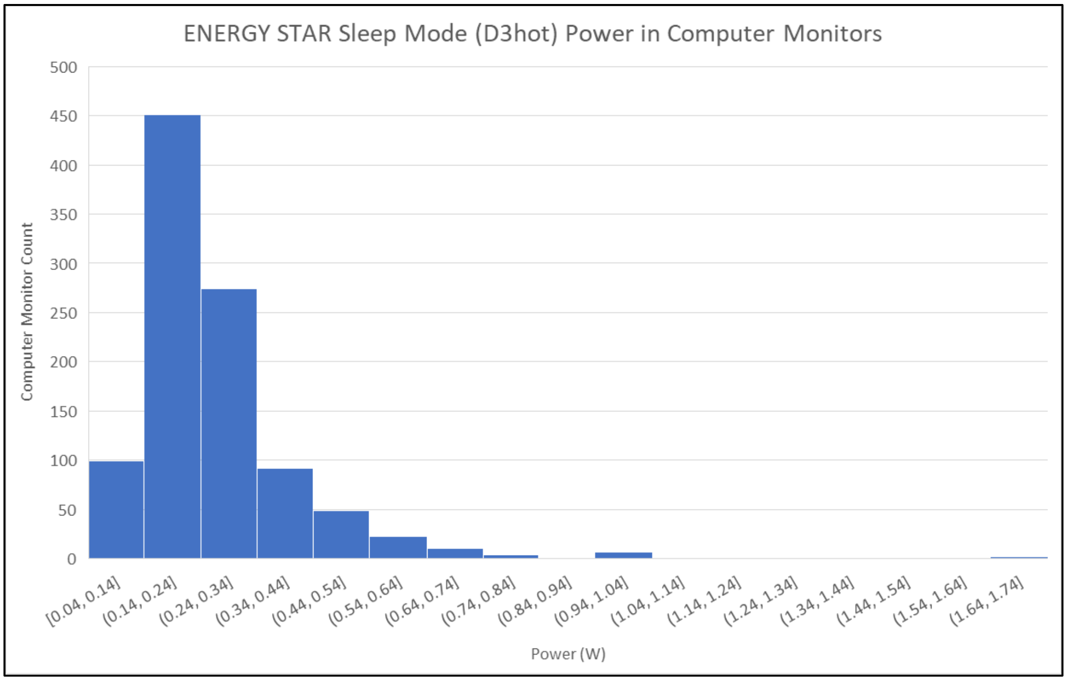

Figure 69: Distribution of ENERGY STAR Sleep Mode power in the 2020 dataset

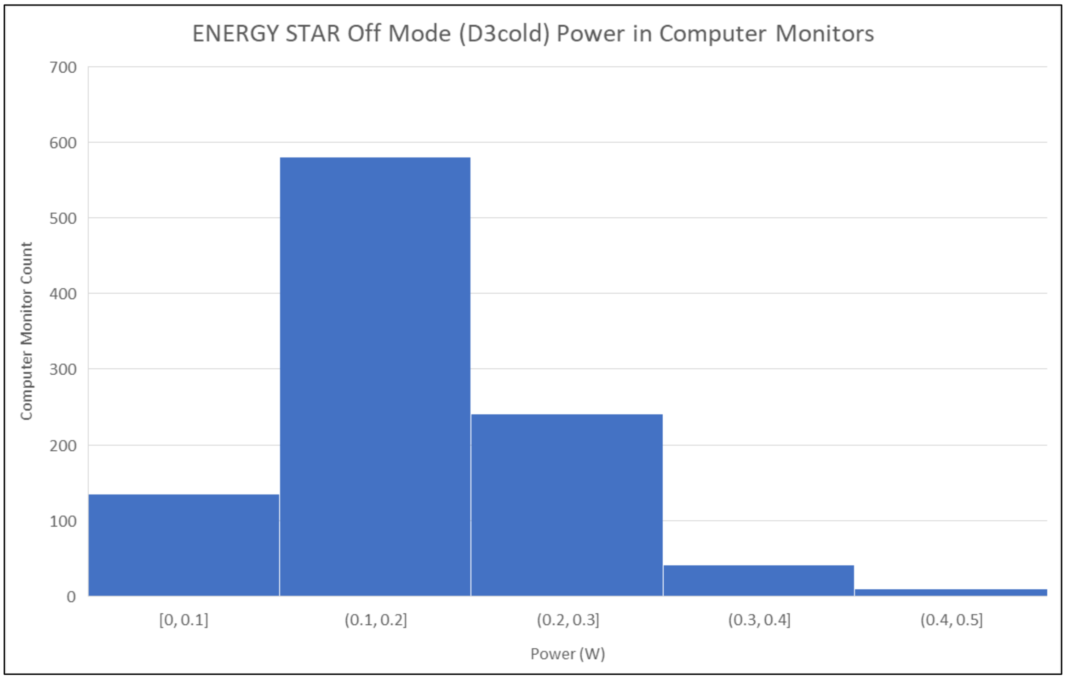

Figure 70: Distribution of ENERGY STAR Off Mode (D3cold) power in the 2020 dataset

The 2025 CEC MAEDbS dataset exhibited lower D3hot and D3cold (defined in their dataset as Standby and Off Mode, respectively) power values, with all being under 1 W. Some of PCL's results for models tested and results of the 2025 CEC MAEDbS dataset yielded discrepancies, as seen on Table 51. Models with significantly different results are highlighted in orange.

Table 51: CEC MAEDbS versus PCL Non-Active Mode results

Model	CEC Standby (D3hot) Power	CEC Off (D3cold) Power	PCL D3hot Power	PCL D3cold Power
ASUS ROG Swift Pro PG248QP	0.30	0.25	13.60	12.10
MSI G274QPF-QD	0.24	0.15	0.30	0.20
AOC Q27G3XMN	0.30	0.26	0.30	0.30
ASUS ProArt Display PA279CRV	0.27	0.24	3.20	0.20
MSI MEG 342C QD-OLED	0.42	0.16	9.40	0.70

No condition was identified in the CEC test method that would account for these differences. D3hot and D3cold were measured in the same manner as CEC Standby and CEC Off Mode. One potential difference not specified in the CEC test method is that the host device must be a computer.

In the case of the ASUS ROG Swift Pro PG248QP, the CEC Off Mode test method would have required that the decorative RGB lighting be turned off during testing. However, PCL's measurements showed that turning off this feature produced savings of only 1.8 W, rendering the large difference between the CEC data and laboratory test results unexplained.

1.1.1.14.2 Touchscreen Setting

Some computer monitors offer touchscreen during Non-Active Mode as a reactivation function. By touching the screen, a user can wake the monitor from Sleep Mode.

1.1.1.14.2.1 Test Results

Since no monitors in PCL's sample offered reactivation via touchscreen, the energy consumption of this capability was not able to be tested.

1.1.1.14.2.2 Dataset Findings

The 2025 CEC MAEDbS dataset labels computer monitors that have touchscreen enabled in CEC Sleep Mode (D3hot equivalent) and CEC Off Mode (D3cold equivalent).[34] Table 52 and Table 53 show the energy consumption of these models.

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[34] As a reminder, CEC MAEDbS uses the ENERGY STAR definitions of Sleep and Off Mode rather than the IEC 62087 definitions referenced throughout this document. These are equivalent to the D3hot and D3cold power states defined earlier; however, their test method does not require that the host device be a computer.

Table 52: Energy draw of computer monitors with touchscreen enabled in CEC Sleep Mode (D3hot)

Brand	Model	CEC Sleep (D3hot) Mode Power (W)
ViewSonic	VS19630	0.84
Lenovo	A23TIO24T	0.70
Acer	UT272U	0.60
Dell	P2424HTc	0.50
ViewSonic	VS18478	0.40
Lenovo	A23TIO22T	0.33
ViewSonic	VS19613	0.27
Acer	UT272	0.20
Philips	222B9TA	0.17

Table 53: Energy draw of computer monitors with touchscreen enabled in CEC Off Mode (D3cold)

Brand	Model	CEC Off (D3cold) Mode Power (W)
ViewSonic	VS18478	0.37
Lenovo	A23TIO24T	0.25
Lenovo	A23TIO22T	0.25
Philips	222B9TA	0.14

Although all models in the CEC dataset in Table 52 and Table 53 appear to consume less than 1 W when touchscreen is enabled in Non-Active Mode, PCL's earlier Active Mode testing indicates that enabling touchscreen adds approximately 1 W of power consumption, so it appears that there should be a power draw of about 1 W in Non-Active Mode when touchscreen is enabled. It is not understood why this is not reflected in the data above.

1.1.1.14.3 Quick Start and Deep Sleep Setting

Quick Start is a feature that allows a computer monitor to become operational more quickly, typically by keeping certain internal components partially powered in Standby Mode. This reduces reactivation times. Deep Sleep does the opposite by powering down more components, which can lead to longer reactivation times compared to lighter sleep states.

1.1.1.14.3.1 Test Results

Two of the computer monitors tested offered Quick Start. Table 54 and

Table 55 show that in either case, the impact on D3hot power consumption was small (0.1 W or lower) and did not change with the Quick Start setting.

Table 54: Acer AOPEN 20E0Q D3hot power consumption comparison with Quick Start

Quick Start Status	Power (W)
On	0.1
Off (Default)	0.1

Table 55: Acer Nitro XV275U P3biipx D3hot power consumption comparison with Quick Start

Quick Start Status	Power (W)
On	0.2
Off (Default)	0.2

Only one monitor in PCL's sample offered a Deep Sleep function ("Deep Level") which was disabled by default. Enabling this feature reduced D3hot power demand by approximately 3 W (Table 56).

Table 56: ASUS ProArt Display PA279CRV D3hot power consumption comparison with Deep Level

Deep Level Status	Power (W)
Off (Default)	3.2
On	0.2

1.1.1.14.3.2 Dataset Findings

The datasets reviewed offered no data on either Quick Start or Deep Sleep features. Though ENERGY STAR and CEC both require that all Sleep (D3hot) configurations available are tested and recorded, those configurations were not available in the datasets reviewed.

1.1.1.14.4 USB Charging Setting

As in Active Mode, computer monitors can offer the capability of charging external devices via USB when the monitor is in Non-Active Mode.

1.1.1.14.4.1 Test Results

One of the monitors tested offered USB-A charging when the monitor was in Non-Active Mode. This setting was disabled by default. When enabled, it increased energy consumption by 1.2 W even when no external USB device was connected (Table 57).

Table 57: INNOCN 27M2V D3cold power consumption comparison with USB Charging

USB Power (Sleep) Status	Power (W)
On	1.4
Off (Default)	0.2

1.1.1.14.4.2 Dataset Findings

The datasets reviewed did not indicate whether computer monitors had USB charging enabled in Non-Active Modes.

1.1.1.14.5 Decorative RGB Lighting Setting

Some computer monitors include decorative RGB lighting, which can remain switched on in Non-Active Mode.

1.1.1.14.5.1 Test Results

The ASUS ROG Swift Pro PG248QP has decorative RGB lighting (Figure 71) which is enabled by default in Active Mode.

Figure 71: Decorative RGB lighting on the ASUS ROG Swift Pro PG248QP

As Table 58 shows, leaving the RGB lighting active during D3cold Non-Active Mode increased power consumption by approximately 1.8 W compared with when the lighting was disabled.

Table 58: ASUS ROG Swift Pro PG248QP D3cold power consumption comparison with RGB

RGB Status	Power (W)
On (Default)	12.1
Off	10.3

1.1.1.14.5.2 Dataset Findings

The datasets reviewed did not have any data on decorative RGB lighting. Any models with RGB lighting enabled by default during Non-Active Mode would likely have had it on during testing.

Digital Signage Displays Findings and Discussion

For computer monitors, the energy impacts of different settings and features in DSDs were assessed both across different models and within the same model by enabling and disabling the relevant setting.

As mentioned in section 1.1.1.15.4: Regression Analysis Results Overview, the dataset-based regression analysis for DSDs did not produce conclusive insights and is therefore not discussed further in this section. The findings are thus based on laboratory test results, secondary research, and dataset review aside from regression analysis.

The key research questions for DSDs are highlighted in Table 59 below.

Table 59: Research questions for DSDs

Research Question	Computer Monitors	DSDs
Active Mode		
What to Measure		
Screen-Average versus Screen-Center Luminance	X	X
Broadcast Clip versus Test Patterns	X	X
Automatic Brightness Control		X
Effect on Energy Efficiency		
Panel Technologies		
Panel Type	X	
Modular Panels		X
Local and Pixel-Level Dimming Setting	X	X
Global Dimming Setting	X	X
Image Processing		
Color Gamut Setting and Capability	X	X
Contrast Ratio Capability	X	X
Viewing Angle Capability	X	X
AI Image Processing Setting	X	
Performance		
Duty Cycle Capability	X	X
Refresh Rate Capability and Setting	X	
Variable Refresh Rate Capability and Setting	X	
Response Time Setting	X	
Other		
Touchscreen Capability and Setting	X	X
HDR Content Format	X	
USB Charging Capability and Setting	X	
Screen Curvature Capability and Setting	X	
KVM Switch Setting	X	
Operating System Capability and Setting		X
Outdoor Use Capability		X
Non-Active Mode		
What to Measure		
Which Non-Active Modes	X	X
Effect on Energy Usage		
Touchscreen Setting	X	
Quick Start and Deep Level Setting	X	
USB Charging Setting	X	
Decorative RGB Lighting Setting	X	

Note: Legend for **Computer Monitors** and **DSDs** columns: [applies]; [does not apply]

As with computer monitors, a distinction is made between the energy impact of a feature being available (**capability**) and the impact when that feature is enabled (**setting)**.

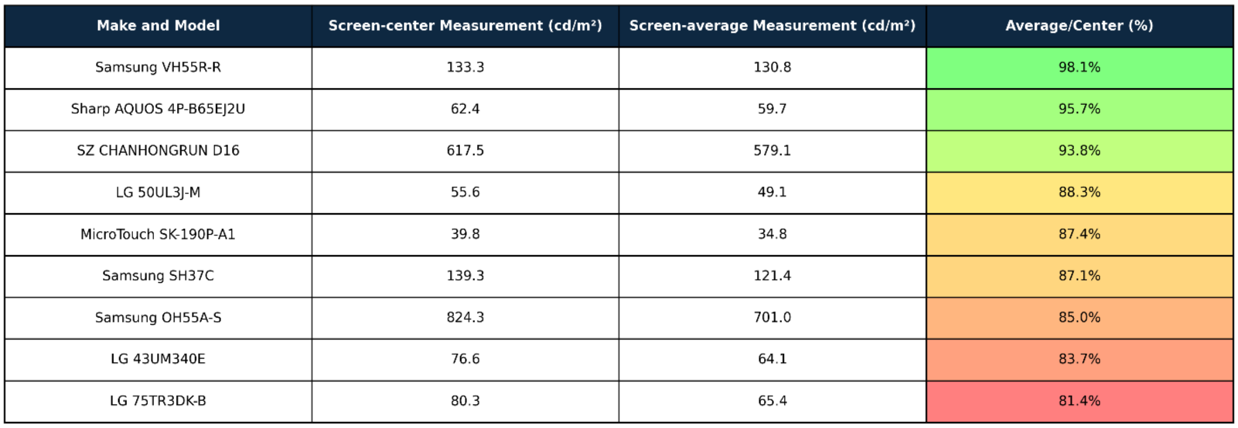
1.1.1.15 Active Mode

1.1.1.15.1 What to Measure: Screen-Average versus Screen-Center Luminance

1.1.1.15.1.1 Test Results

To assess screen uniformity in DSDs, screen-center and screen-average luminance measurements were compared using the gray pattern defined in Table 96. As shown in Table 60, the variation in the ratio of screen-average to screen-center luminance among DSDs is comparable to what was observed for computer monitors.

Table 60: Screen-center versus screen-average measurements of the gray pattern in DSDs



Make and Model	Screen-center Measurement (cd/m²)	Screen-average Measurement (cd/m²)	Average/Center (%)
Samsung VH55R-R	133.3	130.8	98.1%
Sharp AQUOS 4P-B65EJ2U	62.4	59.7	95.7%
SZ CHANHONGRUN D16	617.5	579.1	93.8%
LG 50UL3J-M	55.6	49.1	88.3%
MicroTouch SK-190P-A1	39.8	34.8	87.4%
Samsung SH37C	139.3	121.4	87.1%
Samsung OH55A-S	824.3	701.0	85.0%
LG 43UM340E	76.6	64.1	83.7%
LG 75TR3DK-B	80.3	65.4	81.4%

Figure 72 plots both measurements against each other.

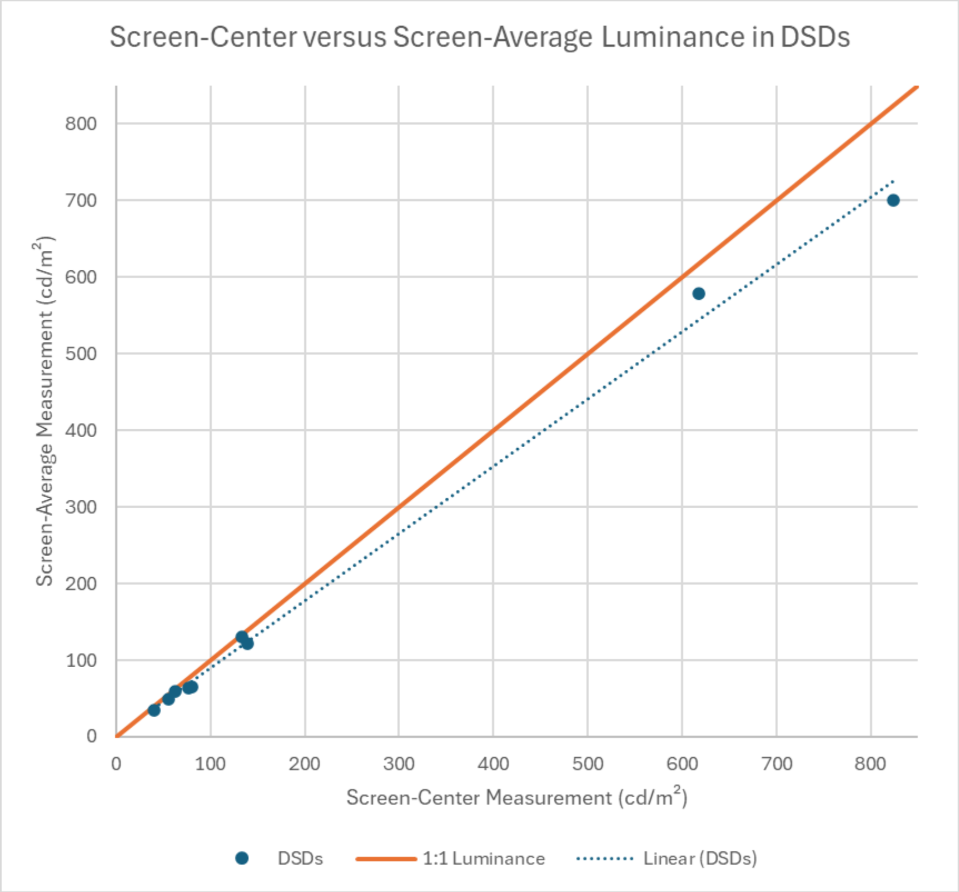


Figure 72: Screen-center versus screen-average measurements in DSDs

These results are similar to those for computer monitors, where the range of screen-average luminance to screen-center luminance varied between 72.6% and 95.5%. As for computer monitors, this range is too large for screen-center luminance to be a good predictor of screen-average luminance.

1.1.1.15.2 What to Measure: Dynamic Broadcast Clip versus Test Patterns

1.1.1.15.2.1 Test Results

The comparisons between static test pattern and dynamic broadcast clip luminance were repeated to assess if static screen-center measurements can reliably predict screen-average luminance under dynamic content in DSDs.

Table 61,

Table 62, and

Table 63 show that the ratios between static pattern and dynamic broadcast clip measurements vary too much across displays to make confident predictions.

Table 61: Three-bar video signal and new IEC SDR dynamic broadcast clip comparison

Make and Model	IEC SDR Broadcast Luminance (cd/m²) (Screen-Average)	3-Bar Luminance (cd/m²) (Screen-Center)	IEC SDR Broadcast/3-Bar (%)
Samsung OH55A-S	407.5	1805.9	22.6%
LG 43UM340E	44.6	221.4	20.2%
Samsung SH37C	88.1	482.2	18.3%
Samsung VH55R-R	78.9	449.9	17.5%
MicroTouch SK-190P-A1	22.4	135.7	16.5%
Sharp AQUOS 4P-B65EJ2U	44.1	287.8	15.3%
LG 50UL3J-M	32.0	242.5	13.2%
LG 75TR3DK-B	42.6	363.5	11.7%
SZ CHANHONGRUN D16	393.9	3895.7	10.1%

Table 62: VESA L80 pattern and new IEC SDR dynamic broadcast clip comparison

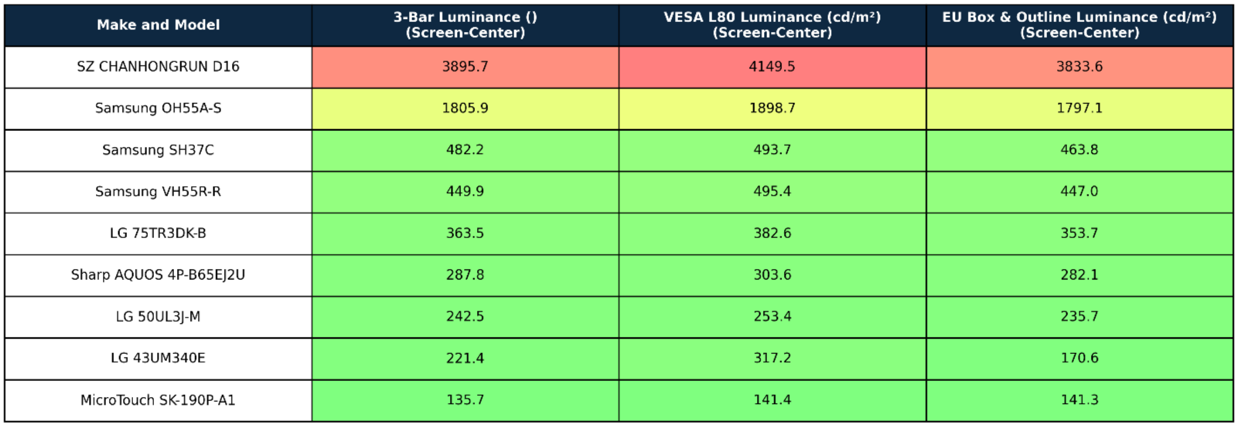
Make and Model	IEC SDR Broadcast Luminance (cd/m²) (Screen-Average)	VESA L80 Luminance (cd/m²) (Screen-Center)	IEC SDR Broadcast/VESA L80 (%)
Samsung OH55A-S	407.5	1898.7	21.5%
Samsung SH37C	88.1	493.7	17.8%
Samsung VH55R-R	78.9	495.4	15.9%
MicroTouch SK-190P-A1	22.4	141.4	15.8%
Sharp AQUOS 4P-B65EJ2U	44.1	303.6	14.5%
LG 43UM340E	44.6	317.2	14.1%
LG 50UL3J-M	32.0	253.4	12.6%
LG 75TR3DK-B	42.6	382.6	11.1%
SZ CHANHONGRUN D16	393.9	4149.5	9.5%

Table 63: Box-and-outline pattern and IEC broadcast clip comparison

Make and Model	IEC SDR Broadcast Luminance (cd/m²) (Screen-Average)	EU Box & Outline Luminance (cd/m²) (Screen-Center)	IEC SDR Broadcast/EU Box & Outline (%)
LG 43UM340E	44.6	170.6	26.2%
Samsung OH55A-S	407.5	1797.1	22.7%
Samsung SH37C	88.1	463.8	19.0%
Samsung VH55R-R	78.9	447.0	17.6%
MicroTouch SK-190P-A1	22.4	141.3	15.9%
Sharp AQUOS 4P-B65EJ2U	44.1	282.1	15.6%
LG 50UL3J-M	32.0	235.7	13.6%
LG 75TR3DK-B	42.6	353.7	12.0%
SZ CHANHONGRUN D16	393.9	3833.6	10.3%

Table 64 compares screen-center luminance across each pattern tested.

Table 64: Comparison of screen-center luminance across the three test patterns



Make and Model	3-Bar Luminance () (Screen-Center)	VESA L80 Luminance (cd/m²) (Screen-Center)	EU Box & Outline Luminance (cd/m²) (Screen-Center)
SZ CHANHONGRUN D16	3895.7	4149.5	3833.6
Samsung OH55A-S	1805.9	1898.7	1797.1
Samsung SH37C	482.2	493.7	463.8
Samsung VH55R-R	449.9	495.4	447.0
LG 75TR3DK-B	363.5	382.6	353.7
Sharp AQUOS 4P-B65EJ2U	287.8	303.6	282.1
LG 50UL3J-M	242.5	253.4	235.7
LG 43UM340E	221.4	317.2	170.6
MicroTouch SK-190P-A1	135.7	141.4	141.3

This matters for policy because test patterns are often used to demonstrate compliance, yet they may not represent typical on-screen luminance when displaying real content. As seen with computer monitors, test patterns produce inconsistent luminance results across different displays. Current policies like Ecodesign that rely on minimum luminance values derived these minimum values from older tests by Matsumoto et al., which used a 40% peak white pattern not employed in today's standards (CEC Title 20, Ecodesign, ENERGY STAR Displays 8.0). As a result, minimum-luminance assessments do not align well with contemporary data, which does not use a 40% peak pattern.

Additional issues include temporal instability: luminance can rise or fall over time when displaying test patterns, and some displays exhibit periodic power fluctuations that complicate determining when measurements have stabilized. These behaviors make it difficult to define a standardized observation window. Using real broadcast content mitigates these problems by enabling power and luminance averaging over 300 seconds, reducing the influence of periodicity.

The mismatch between test patterns and actual screen-average luminance becomes even more pronounced when local dimming is enabled, since displays can dim dark regions effectively, producing lower average luminance than pattern-based predictions.

1.1.1.15.3 Automatic Brightness Control

Outdoor and semi-outdoor "window" displays often include ambient light or Automatic Brightness Control (ABC) sensors to adjust screen brightness throughout the day as ambient light levels change. ABC capability is less common in indoor DSDs because they are typically installed in fixed locations (e.g., retail stores and airports) where the ambient lighting is relatively stable. ABC adds cost and can inadvertently affect how images are displayed (for example, if a person blocks or shadows the ambient light sensor). None of the indoor DSDs tested had ABC capabilities.

This section centers on the following research questions:

- How does the performance of outdoor and semi-outdoor DSDs change across ambient light levels (different lux levels) when ABC is enabled?
- What test method and policy approach (including metrics, and incentives) would be appropriate for ABC in outdoor and semi-outdoor DSDs?
    - Which ambient light (lux) levels and sensor illumination angles should be used for testing?
    - What type of lamp should be used to simulate ambient light (e.g., LED, Xenon, HID)?

Answering these research questions requires extensive discussion, provided in ANNEX I: ABC POLICY RECOMMENDATIONS FOR OUTDOOR DISPLAYS. In this section, test results are presented from ABC measurements on the single outdoor display included in the sample, the Samsung OH55A-S.

The display was tested using two different high-intensity lamps (commonly used in stage lighting) to assess:

- The ABC adjustment range and the impact of each lamp's spectral power distribution (SPD)
- Whether ABC lamp light reflecting on the display screen can be minimized and accounted for

1.1.1.15.3.1 Test Results

1.1.1.15.3.1.1 ABC Range and Impact of Lamp SPD

The Samsung OH55A-S (an outdoor display) was tested at various lux levels to identify the range in which the ABC sensor actively adjusted the screen's backlight. This testing helps inform the selection of appropriate ABC test points for future outdoor and semi-outdoor display policy.

During testing, the gray pattern introduced in Table 96 was displayed and screen-average luminance and power were recorded at each ambient light level. After each lux level was set, two minutes were allowed for the display to stabilize before taking measurements. This pattern was chosen because a stable test signal made it easier to detect fluctuations in screen-average luminance. Additionally, real-world content is often gray on average.

ABC testing for current TV policy uses an LED lamp. This study tested with an LED stage light with adjustable shutters ("barn doors") as well as a metal halide (HID) focused beam stage light (Figure 73).

Figure 73: HID focused beam stage light (left, SHEHDS) and LED stage light (right, Sparklingtrack)

Figure 74: LED lamp color temperature adjustment feature

Note: The LED lamp has two LEDs, warm (3000K) and cool white (6500K). The overall color temperature of this lamp can be adjusted by changing the relative brightness of each LED. It was set to the midpoint during testing.

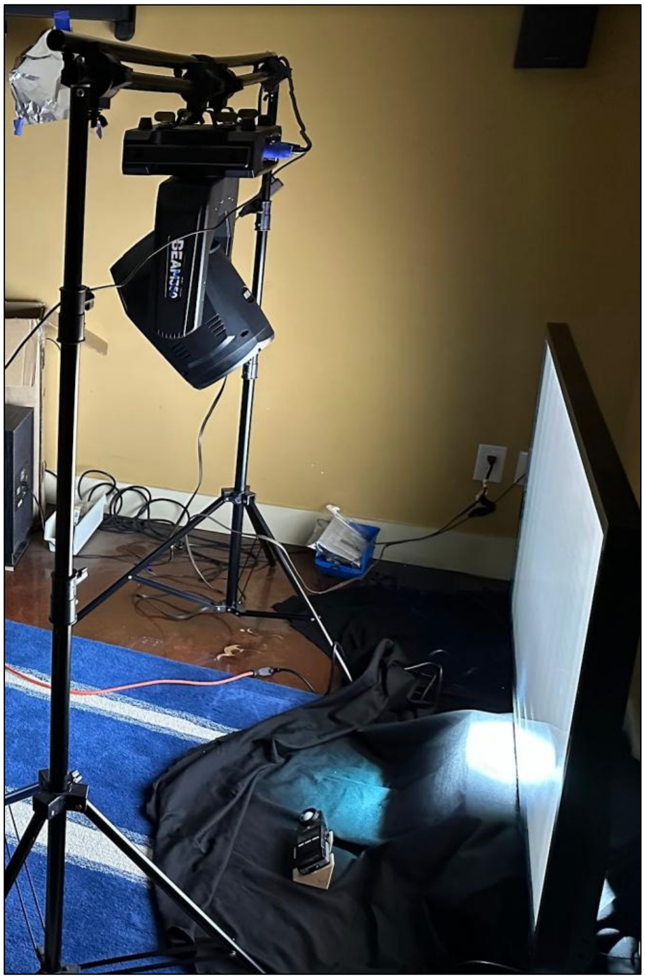


Figure 75: ABC lamp set-up in front of the Samsung OH55A-S

With the HID focused beam stage light, the ABC response appeared to begin between 300–700 lx and reached a maximum between 1,550 and 1,950 lx (Figure 76). No further change in luminance was observed above 1,950 lx, suggesting that the upper end of the ABC response had been reached under this test set-up.

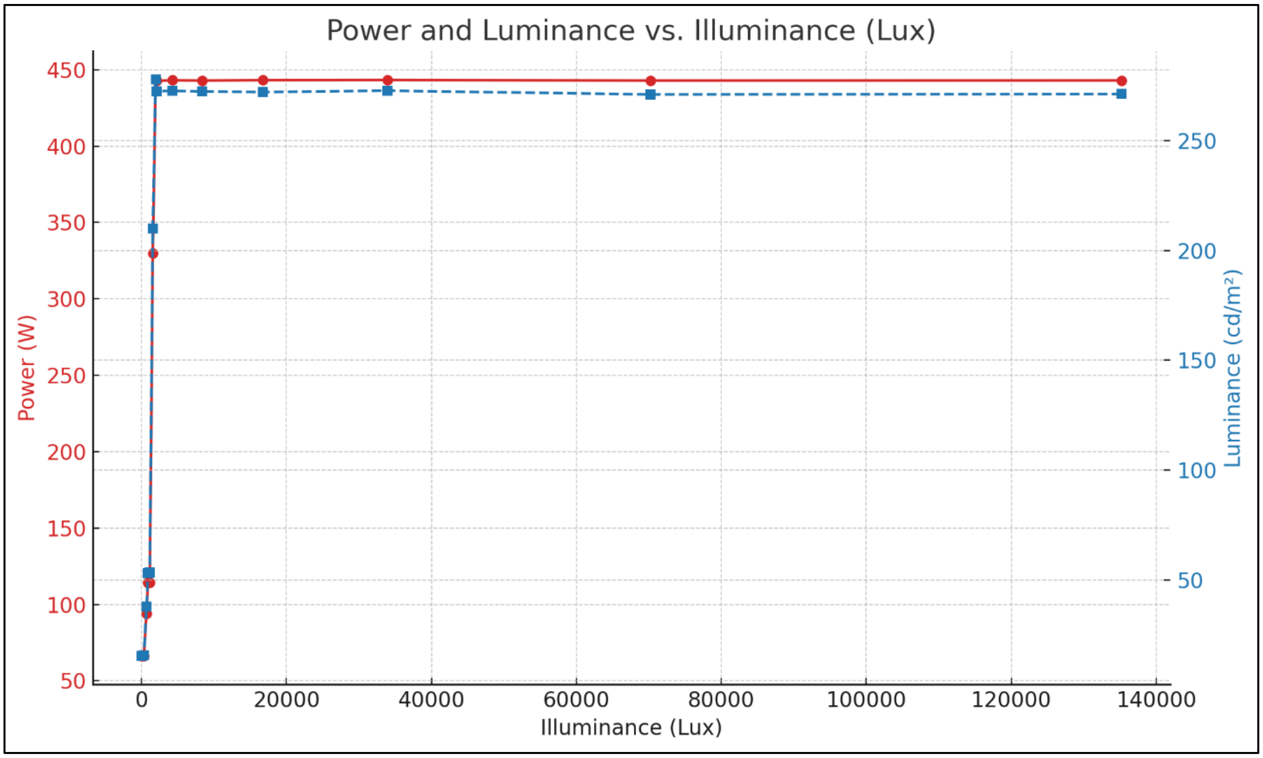


Figure 76: Power and luminance versus illuminance

Note: The focused beam stage light allows attainment of direct sunlight lux levels.

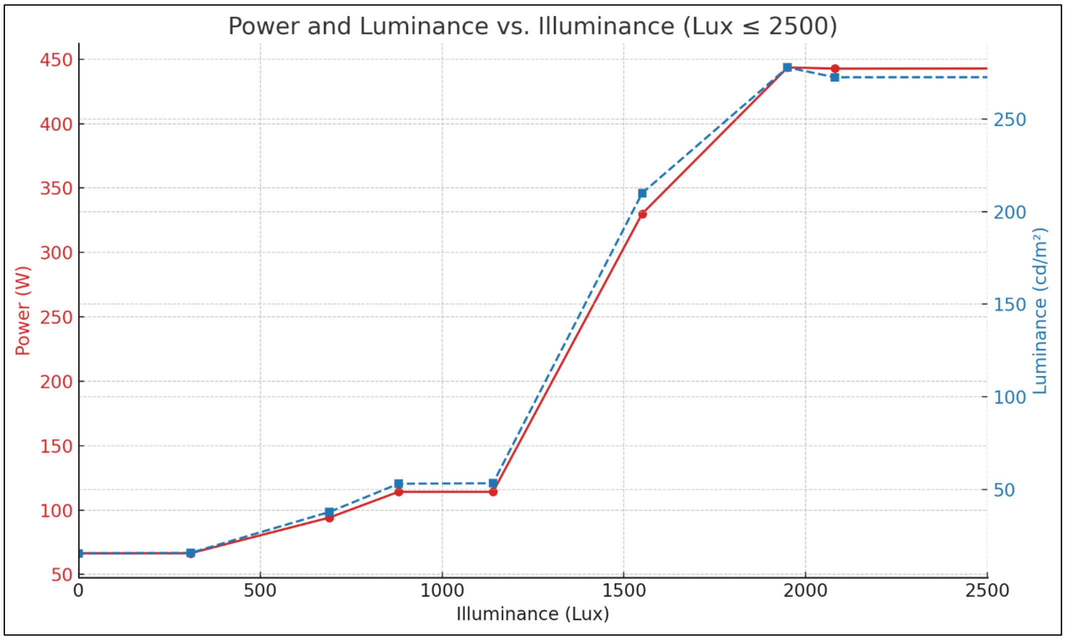


Figure 77: Close-up of power and luminance versus illuminance

With the LED lamp, the ABC response appeared to begin between 100–200 lx and reached a maximum at around 1,000 lx, as shown in Figure 78.

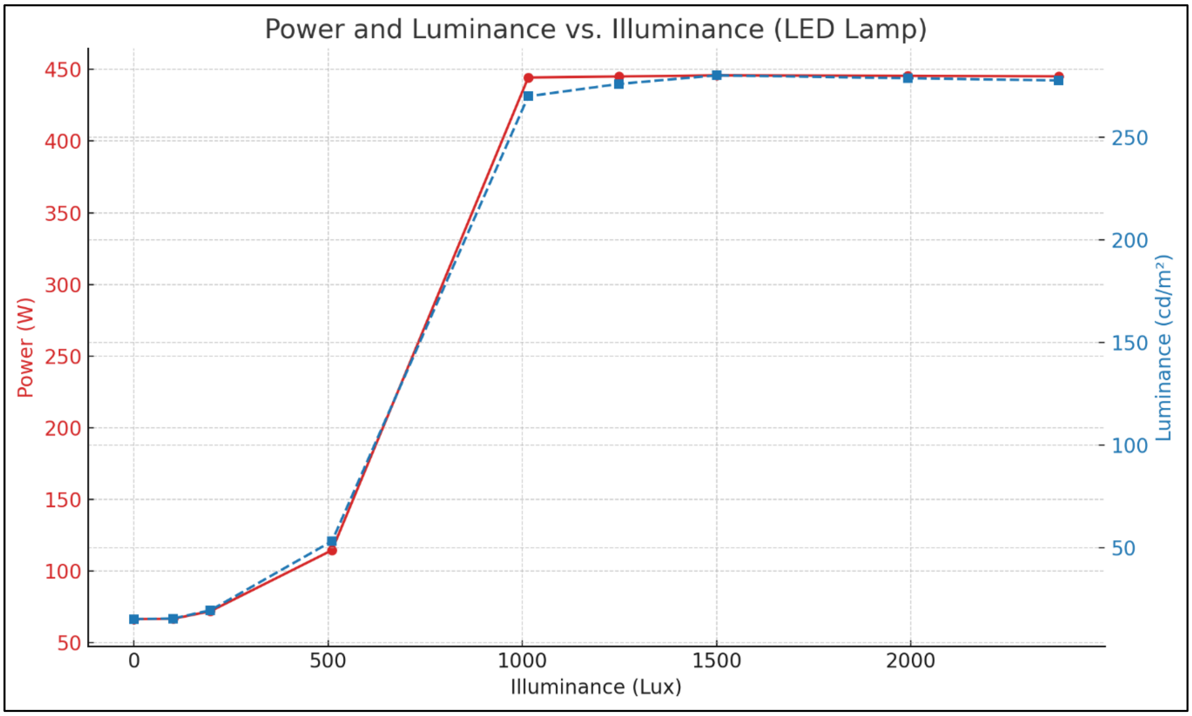


Figure 78: Power and luminance versus illuminance for the LED lamp

At the same illuminance (lux), the LED lamp produced a larger increase in measured luminance than the HID focused beam stage light (Figure 74), likely due to difference in spectral power distribution (the way the brightness of a light source is spread across different colors, see ANNEX I: ABC POLICY RECOMMENDATIONS FOR OUTDOOR DISPLAYS for detailed discussion and analysis).

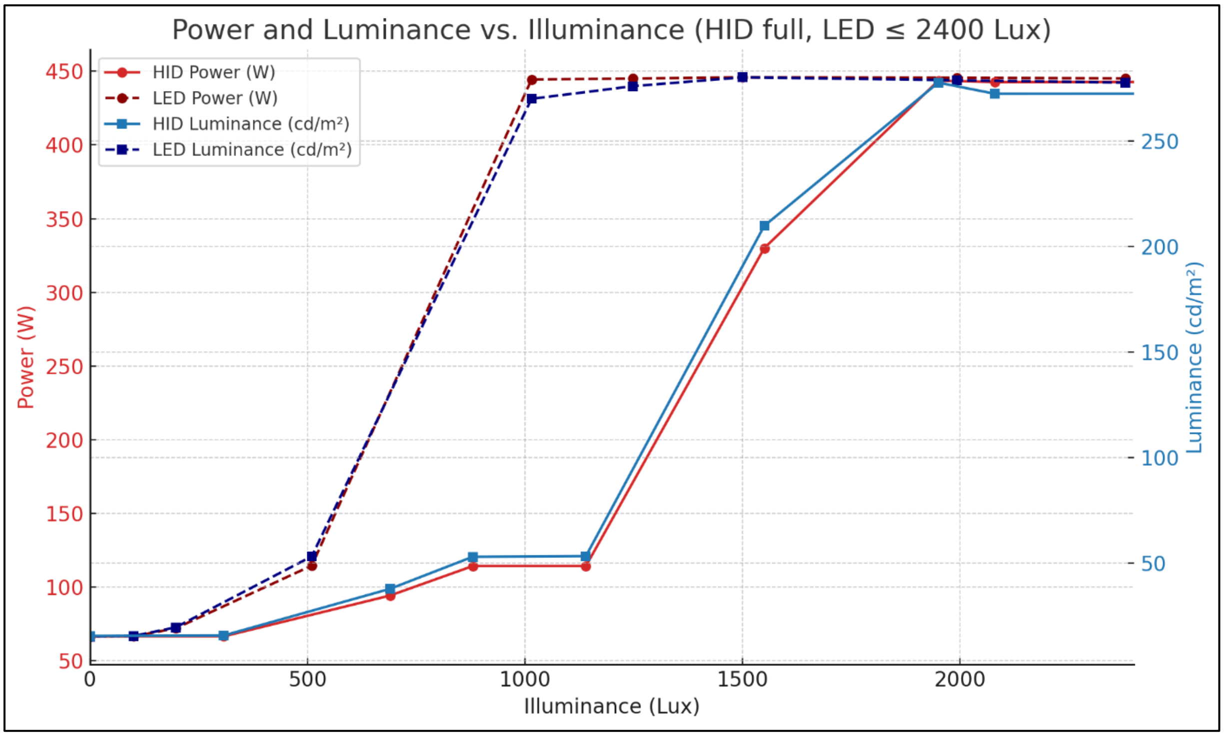


Figure 79: Comparison of the HID and LED lamps

1.1.1.15.3.1.1.1 Minimizing and Accounting for ABC Lamp Light

While the luminance a typical viewer perceives from a DSD includes a contribution from reflected ambient light, and including this component could therefore be considered representative, the choice was made to minimize the ambient light falling on the display screen and account for reflected light during testing because:

- Real-world ambient light is relatively uniform, whereas the ambient light simulated in ABC testing is not. Illuminance drops off rapidly moving away from the beam center.
- Including reflected light in a proposed efficiency metric would effectively reward displays that reflect more ambient light. Because proposed efficiency metrics treat light output as an amenity, this would be counterproductive. Reflected light generally degrades the viewing experience and is therefore not an amenity that should be credited in an energy efficiency metric. For this reason, the amount of light that falls on the screen should be minimized, and any remaining reflected light should be subtracted from the screen-average luminance measurements.

Figure 80 below illustrates how non-uniform this reflected light can be when using a focused beam lamp, in this case set to direct sunlight lux levels. The narrow beam angle (0.2 degrees) minimized the light on the screen. In the case of the LED lamp with barn doors, the beam angle is much broader, but the barn doors can be used to shield the screen from most of the light that would otherwise contact the screen surface.

Figure 80: PCL's ABC testing set-up

Using either lamp, it was possible to subtract the ambient light reflected (at each lux level) by measuring the screen-average luminance with the display off and subtracting that value from the active-mode screen-average luminance measurements.

1.1.1.15.4 Regression Analysis Results Overview

1.1.1.15.4.1 ENERGY STAR Displays 8.0 Dataset

Since the 2020 ENERGY STAR Displays 8.0 dataset comprised fewer DSDs (176) than computer monitors (797), DSDs exhibited lower feature diversity compared to computer monitors. Many DSDs lacked variation in attributes such as screen curvature and color gamut coverage range. Additionally, most were missing contrast ratio viewing angle data.[35] Several categorical and technical features had little or no variation across the DSD models, making them statistically insignificant for the regression. Other features were excluded altogether due to lack of data. This led to fewer coefficients being retained in the analysis, as reflected in Figure 81.

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[35] Per display industry expert Marques Girardelli, most DSD panels are 89° visible in all directions (contrast ratio ≥ 10:1).

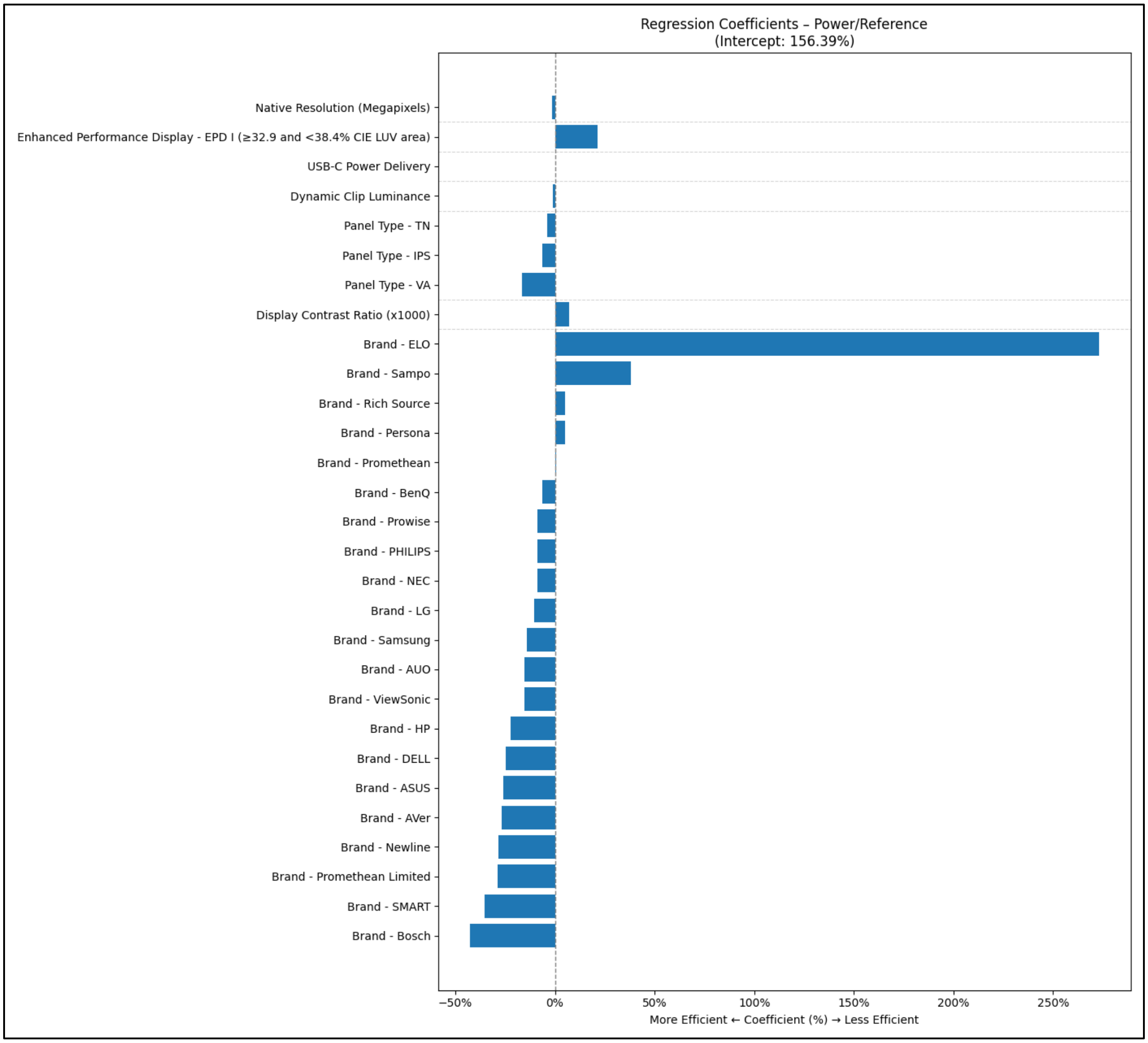


Figure 81: ENERGY STAR Displays 8.0 regression results for DSDs

This model had an R^2 value of 0.5593. Brand was the most significant coefficient, accounting for most of the model's predictive power. However, most brands had fewer than five samples, making it hard to quantify their true impacts on efficiency. Table 65 summarizes the number of DSDs per brand.

Table 65: DSD count per brand in the 2020 ENERGY STAR Displays 8.0 dataset

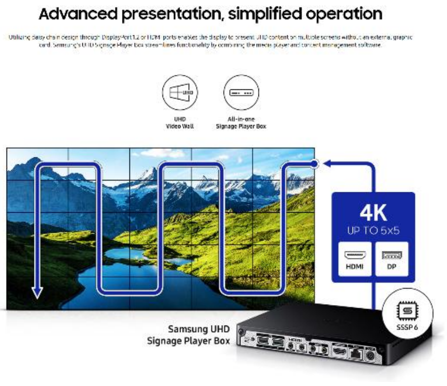
Brand	DSD Count
LG	65
Philips	20
Samsung	18
SMART	12
ViewSonic	11
NEC	9
AUO	7
Prowise	6
Newline	4
ASUS	3
Promethean Limited	3
BenQ	2
Bosch	2
Dell	2
ELO	2
HP	2
Persona	2
Promethean	2
Rich Source	2
AVer	1
Sampo	1

Missing coefficients may explain why certain brands have such high impacts on energy efficiency. For example, if a brand primarily manufactures displays with a feature that increases energy consumption, but that feature is not present in the data, the impact of that feature will correlate with the brand instead.

Because this regression analysis did not produce strong or conclusive insights, further regression analysis discussion is not included in the following sections.

1.1.1.15.5 Modular Panels

Modular panels—such as tiled video walls—are typically used with a separate control box, which can provide an operating system, remote management, and the distribution of a video signal across multiple screens.



Advanced presentation, simplified operation

Utilizing daisy chain design through DisplayPort 1.2 or HDMI ports enables the display to present UHD content on multiple screens without an external graphic card. Samsung's UHD Signage Player Box streamlines functionality by combining the media player and content management software.

Figure 82: Samsung control box, used with the VH55R-R tiles

Although many displays can be set up as part of a video wall using third-party solutions, PCL focused on the Samsung VH55R-R display, which is marketed as a video wall by its manufacturer. This model supports up to 5x5 modular configuration. PCL completed testing using the control box recommended by the manufacturer.

1.1.1.15.5.1 Test Results

The Samsung VH55R-R was tested in a 2x1 configuration via DisplayPort daisy chaining. Both displays were placed side-by-side in portrait orientation. When testing each display individually, their portrait orientation was kept.

Figure 83 shows this display's performance against the reference line.

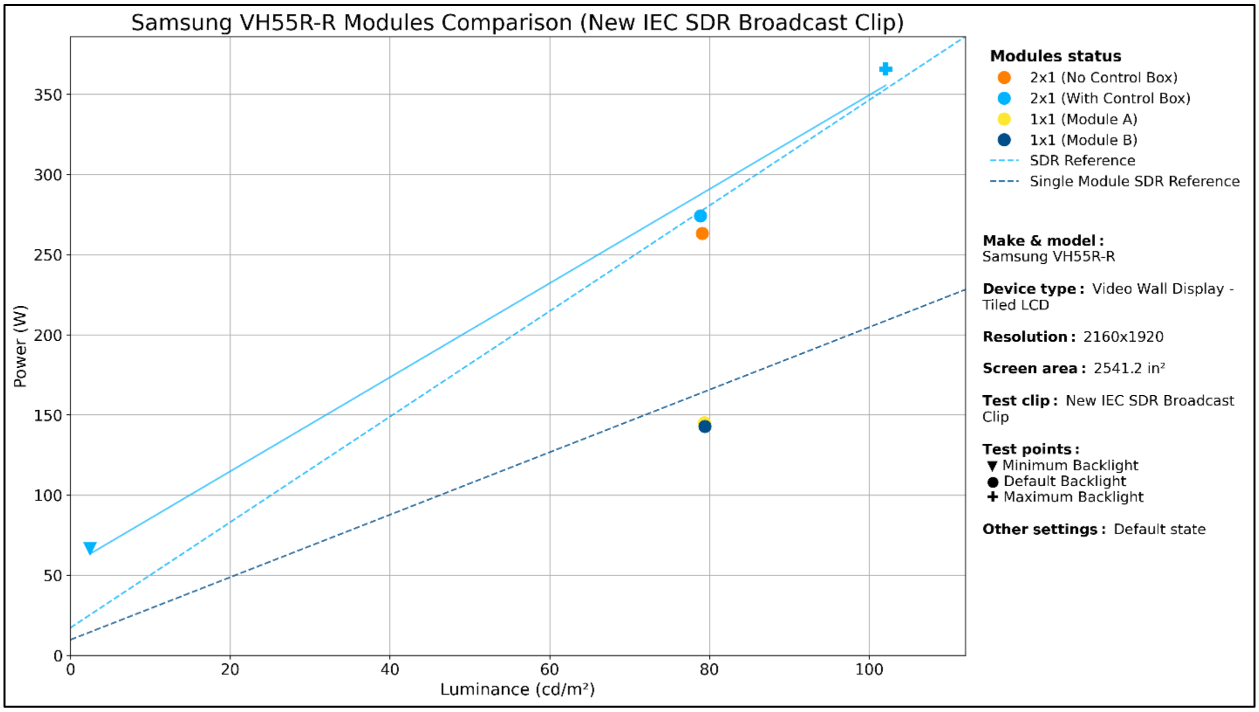


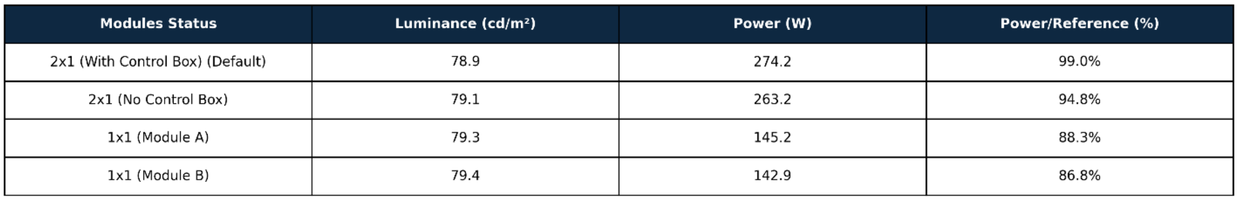
Figure 83: Dimming lines for different configurations of the Samsung VH55R-R

As seen above, in the tested 2x1 configuration, performance was close to the proposed power limit but baseline power consumption (y intercept) was high. When the control box was removed, the system power fell further below the limit line. When tested as standalone tiles (1x1), the applicable limit differs because screen area and native resolution differ. Without the control box, these tiles also fell below their applicable limit.

The control box used was the Samsung SBB-SSNU Signage Player Box, which provides the Tizen OS and enables remote content management via a MagicINFO server. Although this control box is not necessary to use the display in a modular configuration, it extends the capabilities of the display. During testing, the control box was connected to the internet and to a MagicINFO server, but content playback was done via a flash drive connected directly to the control box.

The control box introduces overhead power, which can negatively affect performance relative to the power limit—particularly when fewer displays are connected. As shown in Table 66, removing the control box from the 2x1 setup reduced system power consumption by 11 W, bringing it below the limit line.

Table 66: Power, luminance, and Power/Reference on the Samsung VH55R-R



Modules Status	Luminance (cd/m²)	Power (W)	Power/Reference (%)
2x1 (With Control Box) (Default)	78.9	274.2	99.0%
2x1 (No Control Box)	79.1	263.2	94.8%
1x1 (Module A)	79.3	145.2	88.3%
1x1 (Module B)	79.4	142.9	86.8%

Modular systems like this one that can operate without a control box are likely to perform best against the power limit when either:

- The control box is omitted, or
- The system is tested in a larger configuration, where the overhead power of the box can be distributed across a greater screen area and native resolution.

For policy purposes, it is necessary to consider whether external control boxes are included within testing and regulatory scope for modular systems and if included, to determine how their power is allocated across different modular configurations.

1.1.1.15.6 Pixel-Level Dimming

DVLED displays, which are currently only available on DSDs, offer the most precise pixel-level dimming control among non-OLED panel technologies. Unlike traditional LCD-based displays, these systems use individual LEDs as subpixels, eliminating the need for liquid crystals to block light.

Figure 84: DVLED displays control light emission at a sub-pixel level

Managing numerous individual LEDs can introduce some baseline power overhead (leading to a higher-power Y-intercept). However, power demand scales with screen-average luminance across single frame, resulting in a lower dimming line slope. This indicates that pixel-level dimming systems can reduce power usage for dark image regions. In contrast, LCD displays without local dimming cannot selectively dim dark areas, so their power consumption tends to be less responsive to darker image regions. The ability of pixel-level systems to dynamically adjust luminance across their screen area improves overall light efficiency, especially for content with mixed brightness levels.

1.1.1.15.6.1 Test Results

The only DSD tested with local or pixel-level dimming was a DVLED display, the SZ CHANHONGRUN D16 (shown later in APPENDIX D: LOW PIXEL DENSITY).

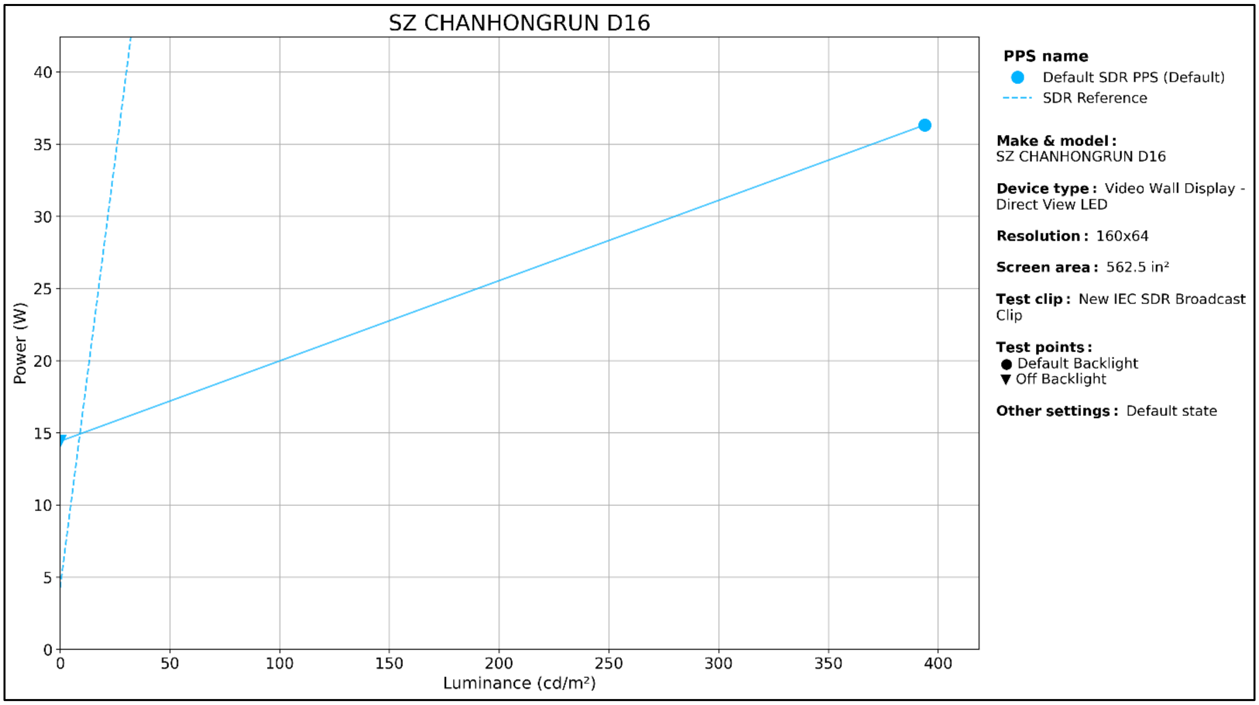


Figure 85: Power and luminance in the SZ CHANHONGRUN D16

As shown in the graph, this display operates well below the efficiency limit, with a much lower slope than the proposed limit line (close to 20 times lower). Its power-to-luminance relationship shown in Figure 86 demonstrates scalability.

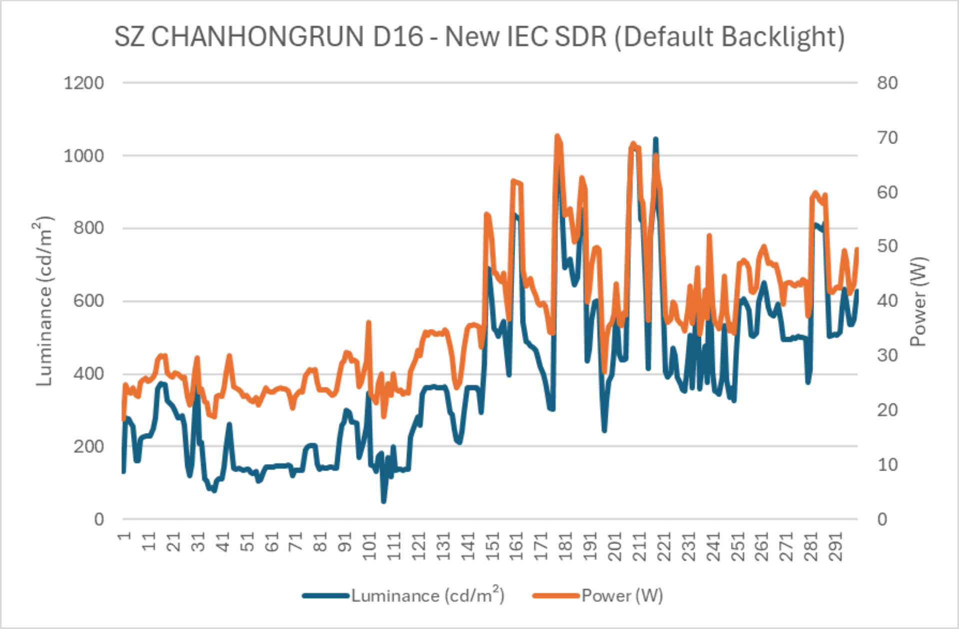


Figure 86: Power and luminance over time on the SZ CHANHONGRUN D16

1.1.1.15.7 Global Dimming Setting

1.1.1.15.7.1 Test Results

Of the nine DSDs tested, only the Samsung VH55R-R appears to have global dimming capabilities. Global dimming was on by default and there was no option to turn it off. No settings were found related to global dimming (like "Dynamic Backlight" or similar) in any of the DSDs tested, so it could only be identified it by looking at a plot of power and luminance over time (Figure 87).

This display shows how power can scale with luminance with an effective global dimming algorithm. Without global dimming, it can be assumed that power in the display would have stayed static at its highest point of 175 W. Instead, average power for this test run was 145 W, indicating 17% savings.

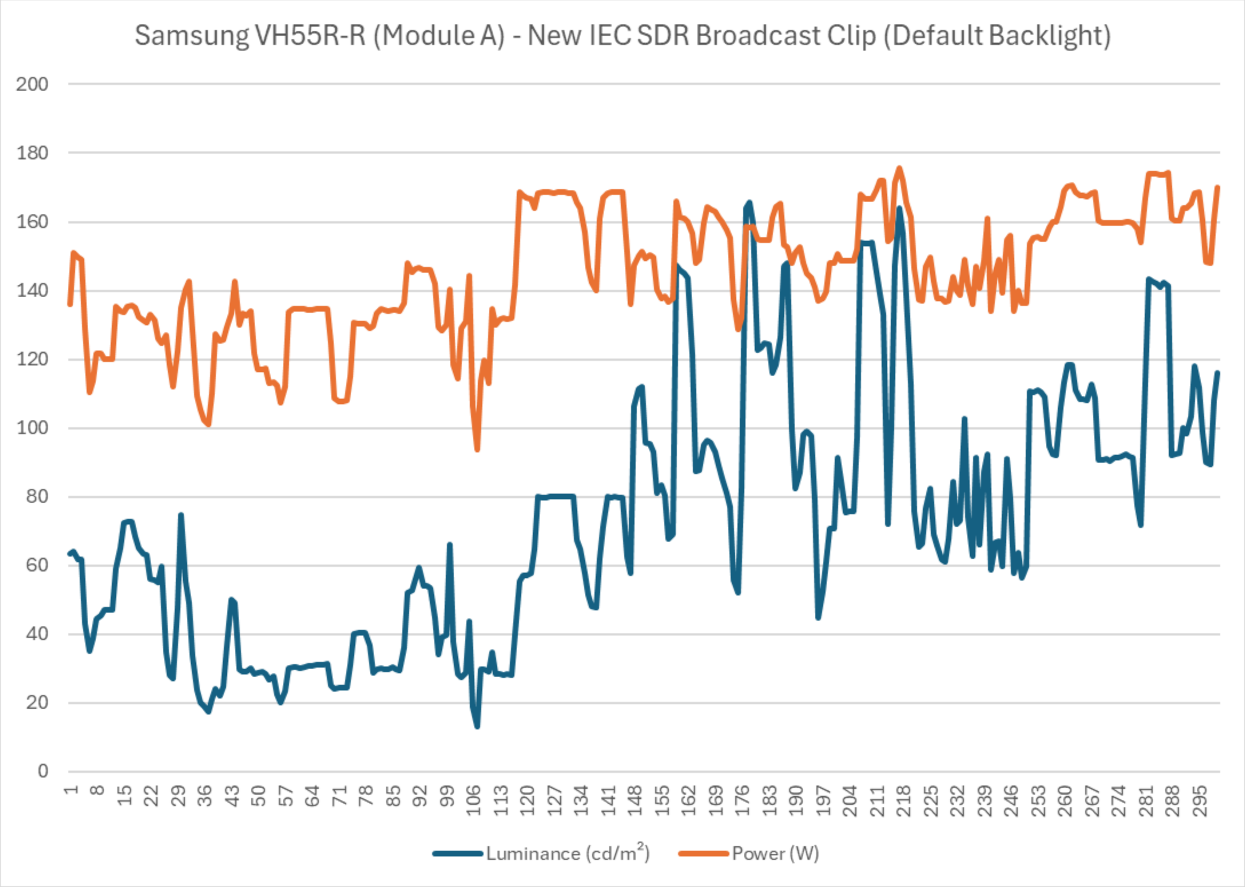


Figure 87: Power and luminance over time on the Samsung VH55R-R

1.1.1.15.8 Color Gamut Capability

1.1.1.15.8.1 Test Results

As was the case with computer monitors, DSDs with a higher color gamut area **capability** correlate with worse performance against the limit line.

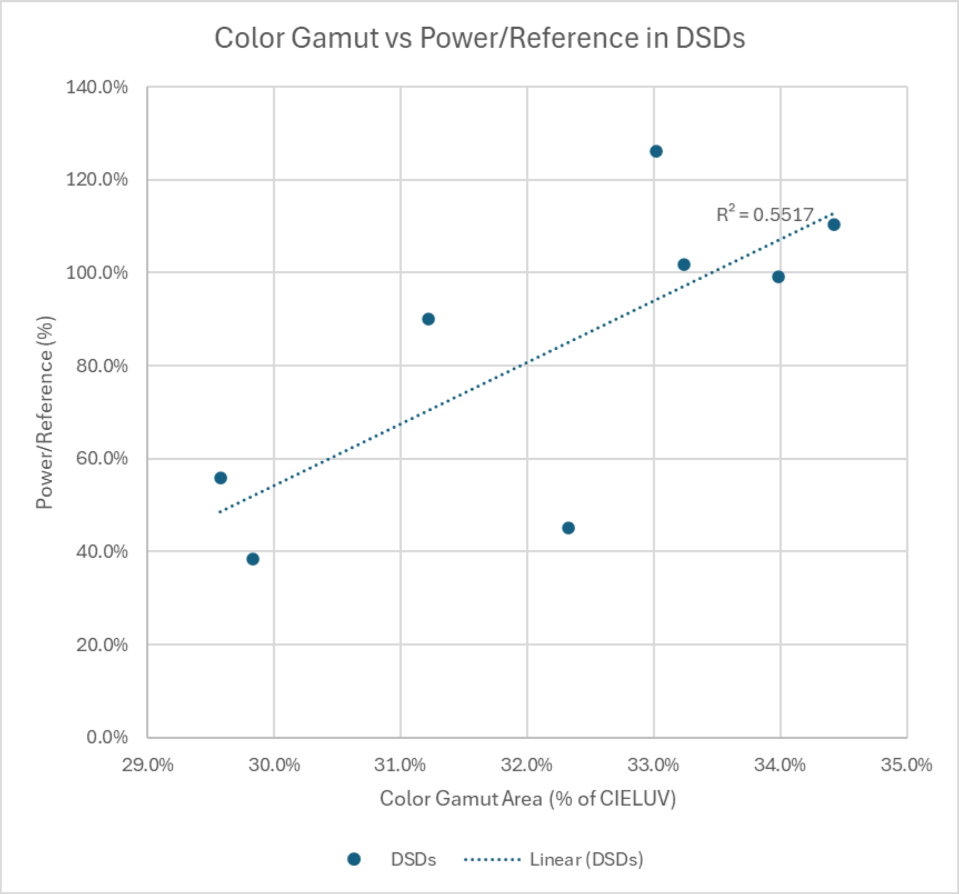


Figure 88: Color gamut versus Power/Reference in DSDs

The impact of color gamut on DSDs seems higher than on computer monitors per PCL's test results. However, the DSD sample was limited and diverse, so one cannot draw clear conclusions and this relationship should not be interpreted as a causal result.

1.1.1.15.9 Contrast Ratio Capability

1.1.1.15.9.1 Test Results

As observed for computer monitors, higher contrast ratios in DSDs in this sample were associated with worse energy efficiency. The relationship was weak (R^2 value of 0.23)—likely due to the small sample size) as seen in Figure 89. The only DSD tested with local dimming was excluded from this graph to avoid skewing the results.

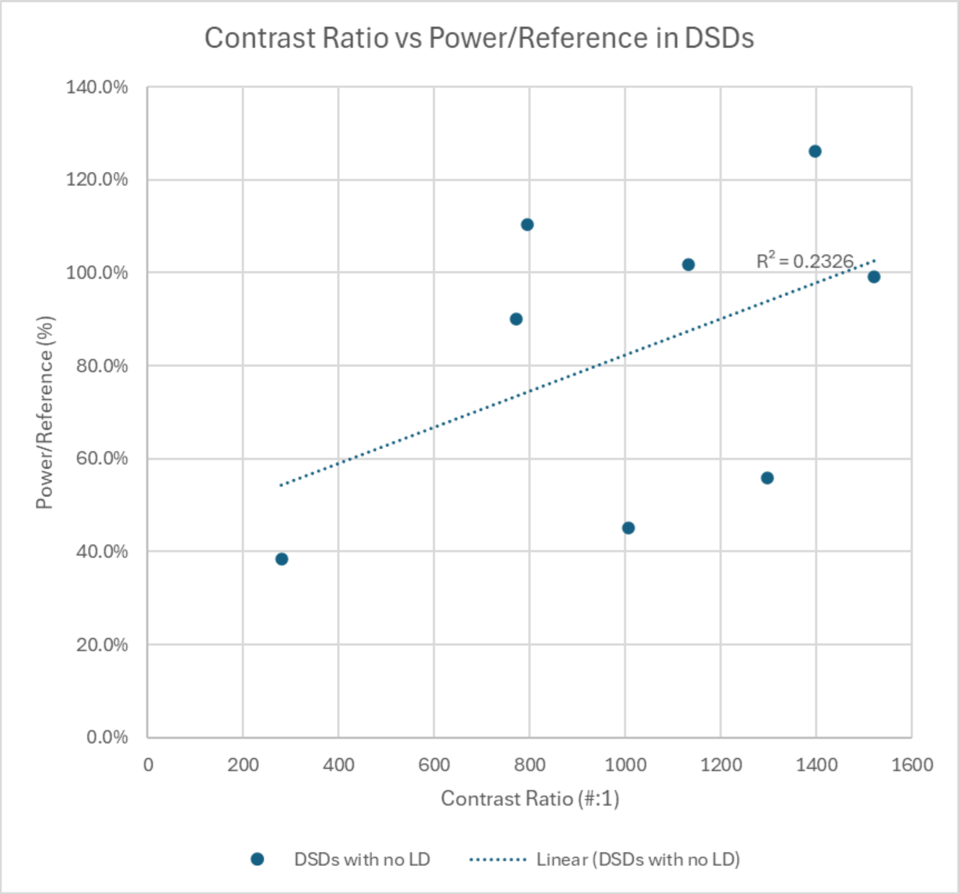


Figure 89: Contrast ratio versus Power/Reference in DSDs

Of course, as with color gamut, many other variables involved make it hard to draw clear conclusions from testing alone.

1.1.1.15.10 Viewing Angle Capability

1.1.1.15.10.1 Test Results

As observed with computer monitors, no clear correlation was observed between changes in color gamut area at wider viewing angles and efficiency performance (Figure 90).

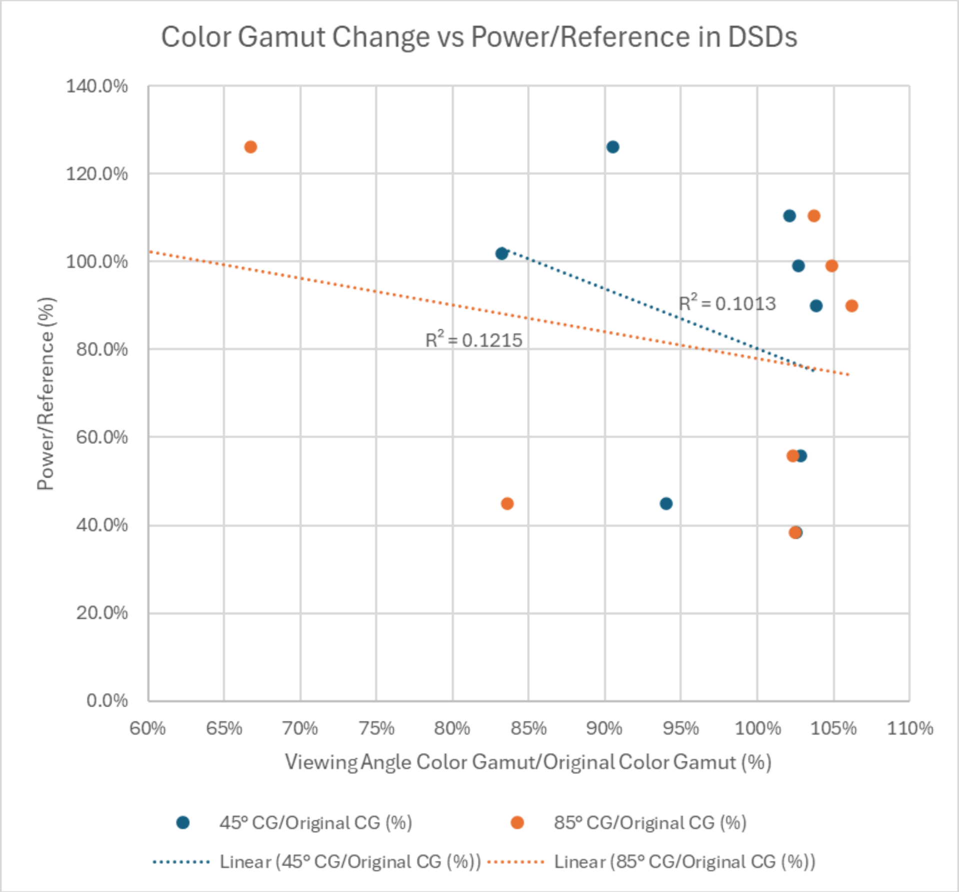


Figure 90: Color gamut area viewing angle versus Power/Reference in DSDs

The initial hypothesis was that better contrast ratio performance at wider viewing angles would increase power demand in LCDs, because achieving wider-angle performance may require additional optical compensation layers that block light and therefore require more backlight power to reach the same screen luminance. To avoid confounding findings, the only DSD with local dimming was excluded from this comparison.

Unexpectedly, the testing showed a correlation between better contrast ratio performance at wider viewing angles and better energy efficiency performance in DSDs (Figure 91).

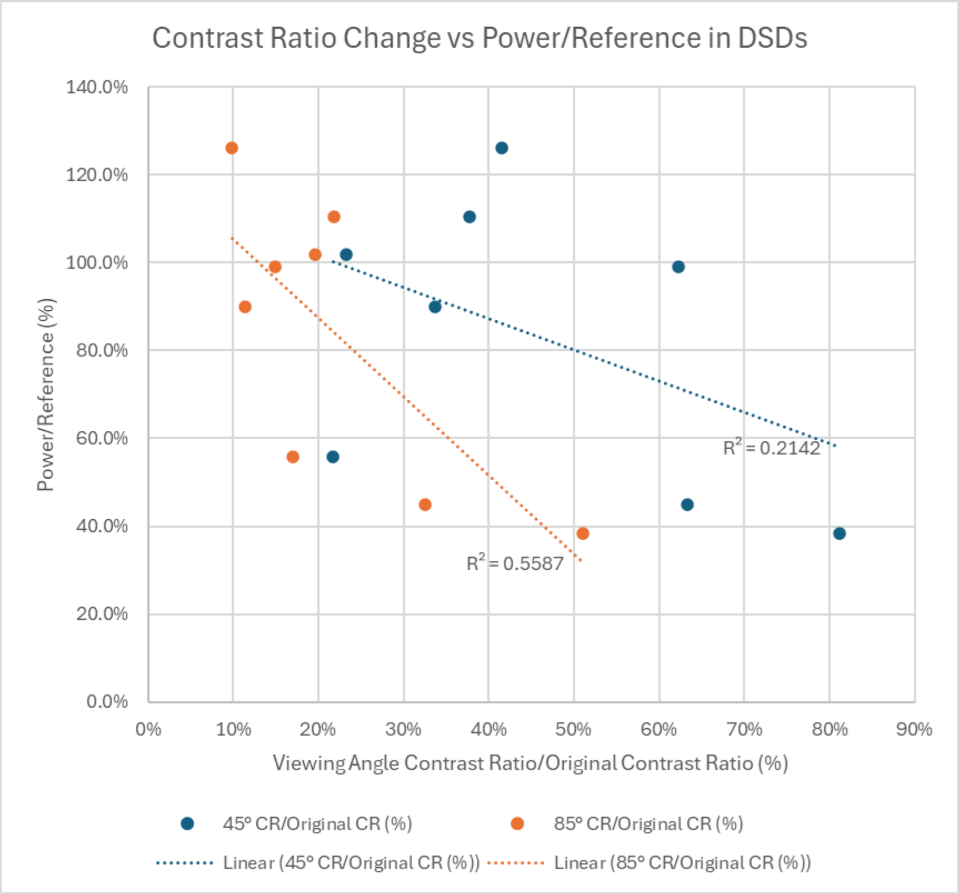


Figure 91: Contrast ratio viewing angle versus Power/Reference in DSDs

This should not be interpreted as a causal relationship given the small sample size. One plausible explanation is that higher-end DSDs—often produced by manufacturers like LG and Samsung—may combine both wider-angle contrast ratio performance and higher energy efficiency. Based on the computer monitor testing and regression analysis, viewing angle performance by itself is not expected to improve energy efficiency.

1.1.1.15.11 Duty Cycle Capability

Duty cycle ratings indicate how many hours per day and days per week a display is designed to operate—common ratings include 16/7 (16 hours a day, 7 days a week) and 24/7 (continuous operation). This is different from the actual duty cycle that may be used for Annual Energy Consumption (AEC) calculations.

Supported duty cycles reflect the display's intended usage and build quality, including thermal management and component durability. Displays rated for 24/7 duty cycles may include more robust cooling or internal hardware, which could lead to a higher baseline power consumption.

1.1.1.15.11.1 Test Results

The displays tested with 24/7 duty cycles generally performed better against the efficiency limit than the 16/7 duty cycle displays (Table 67). However, this result is heavily confounded by other factors. In particular, all 24/7 models in the sample were Samsung models, which tended to be relatively efficient in the tested sample.

Table 67: Comparison of 16/7 and 24/7 supported duty cycles in DSDs

Make and Model	Duty Cycle	Power/Reference (%)
Sharp AQUOS 4P-B65EJ2U	16/7	126.1%
LG 75TR3DK-B	16/7	110.5%
LG 50UL3J-M	16/7	101.8%
LG 43UM340E	16/7	90.1%
Samsung VH55R-R	24/7	99.0%
Samsung OH55A-S	24/7	55.9%
Samsung SH37C	24/7	45.0%

1.1.1.15.12 Touchscreen Setting

1.1.1.15.12.1 Test Results

Similar to the findings for computer monitors, PCL found that enabling touchscreen functionality increased power consumption for the same luminance in the display. In the case of the MicroTouch SK-190P-A1 display—typically used as a checkout kiosk—enabling touchscreen functionality also made the display emit luminance less efficiently, as seen by its steeper slope in Figure 92.

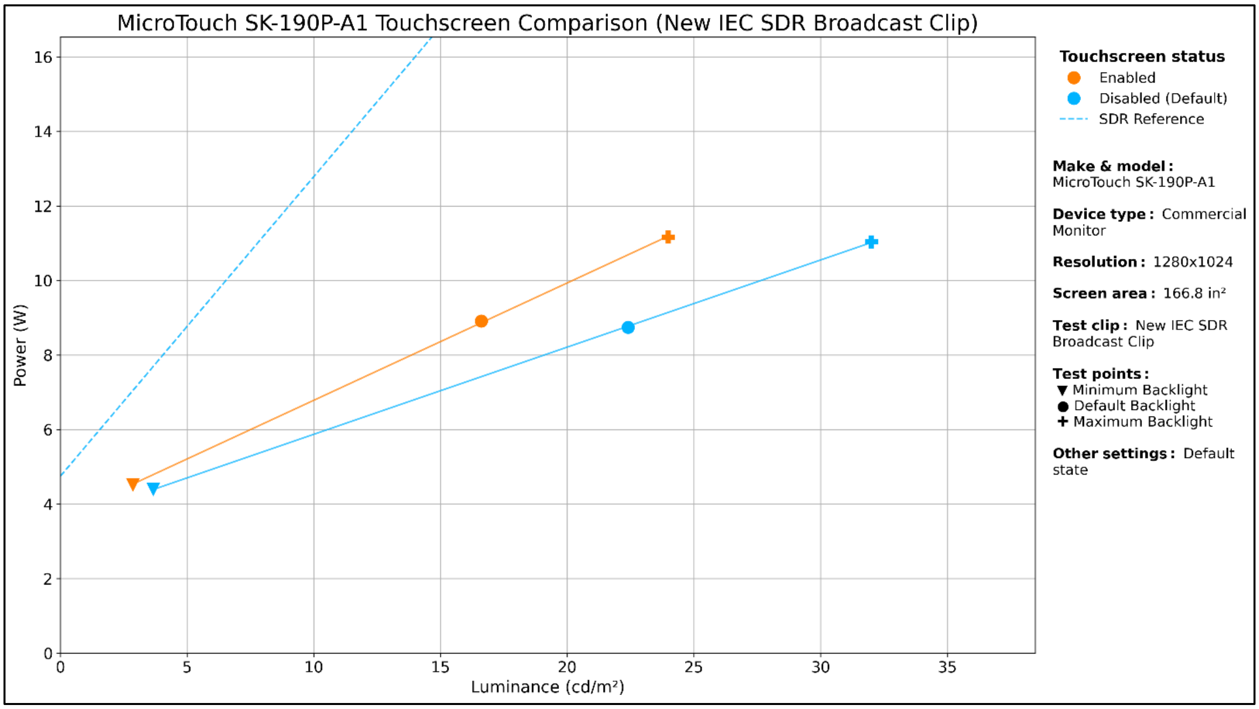
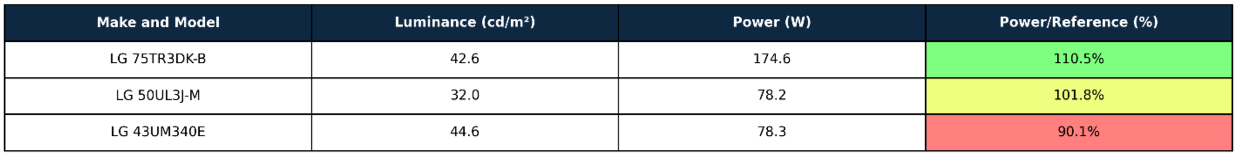


Figure 92: Touchscreen comparison on the MicroTouch SK-190P-A1 DSD

As mentioned in section 1.1.1.13.15: TOUCHSCREEN CAPABILITY AND SETTING, the reason for the reduced luminance efficiency observed with touchscreen **enabled** in these tests is not known.

The other touchscreen DSD in the dataset, the LG 75TR3DK-B, uses infrared touchscreen technology. While the touchscreen could not be disabled to isolate its impact on power consumption, it was observed that its performance against the power reference line was worse than other LG displays tested. This difference cannot be attributed to touchscreen hardware as the touchscreen could not be disabled. Other factors besides the touchscreen that could have an influence are the different market segment for this 75" display (it is marketed for collaboration in classroom settings), and its support for an Android-based operating system.

Table 68: Comparison of different LG DSD models



Make and Model	Luminance (cd/m²)	Power (W)	Power/Reference (%)
LG 75TR3DK-B	42.6	174.6	110.5%
LG 50UL3J-M	32.0	78.2	101.8%
LG 43UM340E	44.6	78.3	90.1%

1.1.1.15.13 Operating System Capability and Setting

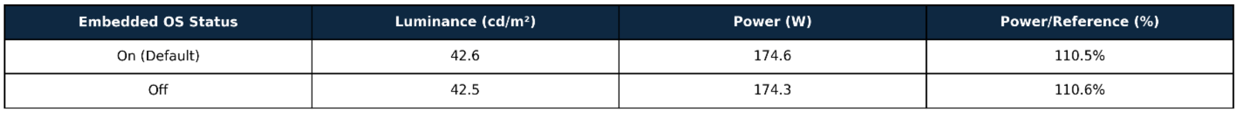
Operating systems in DSDs can provide support features such as scheduled media playback, remote device management, integration with cloud-based signage platforms, and interactive applications. Because these systems use processors and memory, they can increase power demand.

Of nine displays tested, five of them had operating systems.

1.1.1.15.13.1 Test Results

The embedded operating system **setting** was disabled on the LG 75TR3DK-B to assess the overhead power associated with the operating system running. However, as shown in Table 69, no meaningful difference in overall energy consumption was observed under the tested conditions.

Table 69: Embedded OS comparison on the LG 75TR3DK-B



Embedded OS Status	Luminance (cd/m²)	Power (W)	Power/Reference (%)
On (Default)	42.6	174.6	110.5%
Off	42.5	174.3	110.6%

The measured difference was 0.3 W, which could be within measurement uncertainty.

Across the displays tested, no clear pattern was observed between the presence of an embedded operating system (a **capability**) and poorer performance against the efficiency reference line. This finding should be treated as preliminary because the sample is small and the operating system models in the sample were concentrated in brands that tended to perform well in efficiency testing (LG and Samsung).

Table 70: Comparison of Power/Reference and Operating Systems

Make and Model	Operating System	Power/Reference (%)
Sharp AQUOS 4P-B65EJ2U	-	126.1%
LG 43UM340E	-	90.1%
MicroTouch SK-190P-A1	-	38.4%
SZ CHANHONGRUN D16	-	7.7%
LG 50UL3J-M	webOS	101.8%
Samsung VH55R-R	Tizen	99.0%
Samsung OH55A-S	Tizen	55.9%
Samsung SH37C	Tizen	45.0%
LG 75TR3DK-B	Android	110.5%

1.1.1.15.14 Outdoor Use Capability

Outdoor displays have features in their enclosures that protect them from environmental conditions such as heat, cold, rain, snow, and dust. Some displays incorporate active cooling systems, like fans, which can increase energy consumption. Others may include an additional layer of protective glass, potentially impacting screen luminance.

The outdoor displays tested are the Samsung OH55A-S, the MicroTouch SK-190P-A1, and the SZ CHANHONGRUN D16.

1.1.1.15.14.1 Test Results

The behavior of the cooling fans on the Samsung OH55A-S display was checked by running the display overnight while displaying a gray test pattern (Figure 93). This was done to confirm that the fan behavior was stable and would not affect test results by turning on and off at uncontrolled intervals.

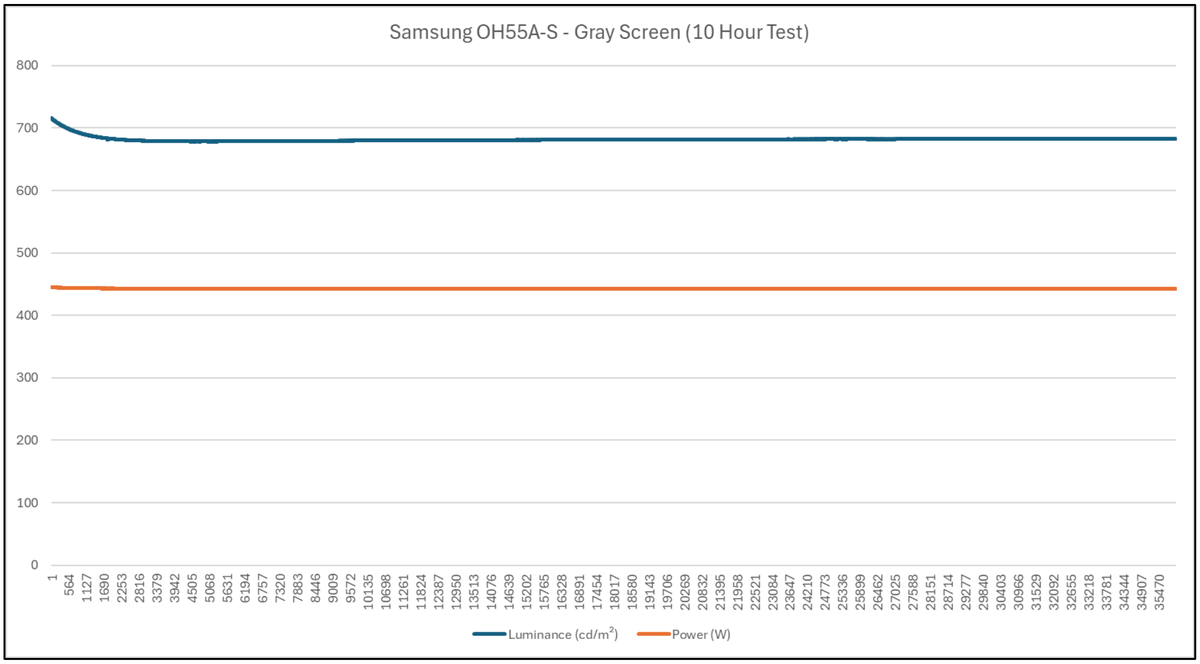


Figure 93: Power consumption and luminance over a 10-hour test run

After an initial drop in luminance from 715 to 683 cd/m2 during the first 30 minutes of the test, both power and luminance remained stable over the remainder of the 10-hour run. This indicates that fan operation remained steady and no additional control for fan cycling was necessary for this model during testing.

As shown in Table 71, outdoor displays correlated with better performance against the efficiency limit than did their indoor counterparts.

Table 71: Outdoor versus indoor DSD performance

Make and Model	Indoor Outdoor	Power/Reference (%)
Samsung OH55A-S	Outdoor	55.9%
MicroTouch SK-190P-A1	Outdoor	38.4%
SZ CHANHONGRUN D16	Outdoor	7.7%
Sharp AQUOS 4P-B65EJ2U	Indoor	126.1%
LG 75TR3DK-B	Indoor	110.5%
LG 50UL3J-M	Indoor	101.8%
Samsung VH55R-R	Indoor	99.0%
LG 43UM340E	Indoor	90.1%
Samsung SH37C	Indoor	45.0%

While it would be expected the D16 display to perform well against the reference line given its local dimming capabilities, the Samsung OH55A-S and the MicroTouch display also performed well when compared to their counterparts despite having active fan cooling and touchscreen capabilities, respectively. This initial data leads us to believe that outdoor-proofing mechanisms do not significantly affect a display's efficiency.

1.1.1.16 Non-Active Mode

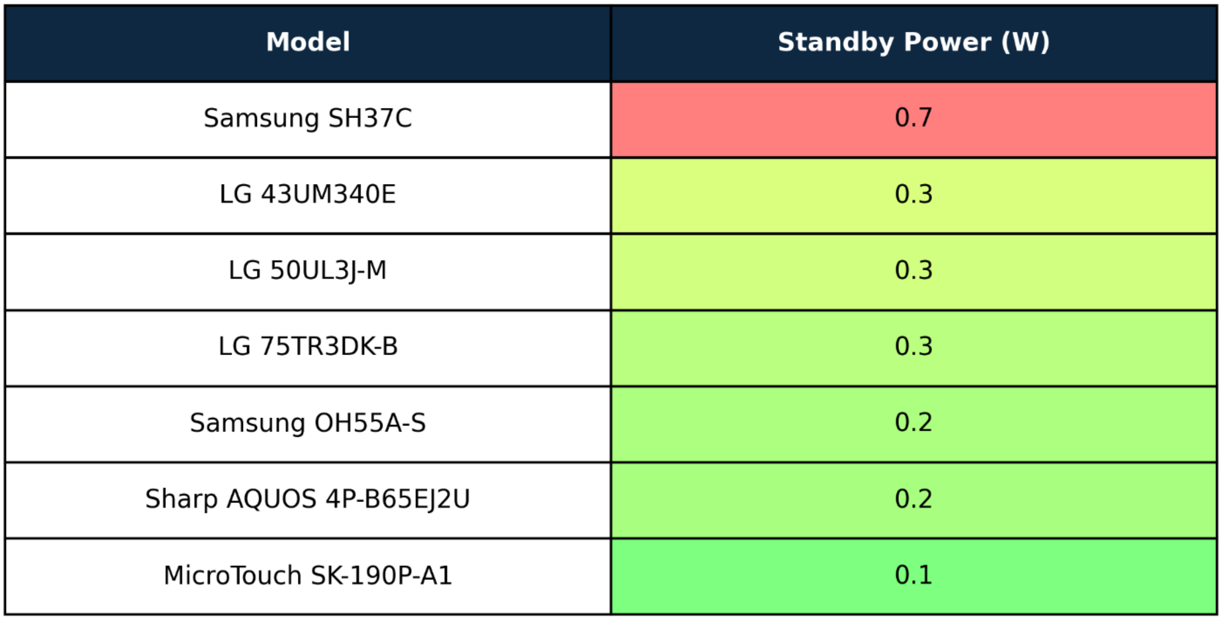
1.1.1.16.1 What to Measure: Which Non-Active Modes

1.1.1.16.1.1 Test Results

The DSD Non-Active Mode testing was focused on Standby as previous data for Off Mode power consumption in televisions shows that the energy consumption in this mode is negligible. Standby offers the most potential for energy savings, particularly as new reactivation functions emerge that may use additional power.

Table 72 shows Standby power draw across DSDs.

Table 72: Standby performance in DSDs



Model	Standby Power (W)
Samsung SH37C	0.7
LG 43UM340E	0.3
LG 50UL3J-M	0.3
LG 75TR3DK-B	0.3
Samsung OH55A-S	0.2
Sharp AQUOS 4P-B65EJ2U	0.2
MicroTouch SK-190P-A1	0.1

These initial findings suggest that Standby implementations in the types of DSDs tested here are fairly energy efficient.

Policy Recommendations

This section presents the recommendations for how to extend this report's policy approach, developed initially for TVs, to address computer monitors and DSDs. These recommendations, developed in 2025, are distinct from the 2024 proposed TV limits used in this document for research comparisons.

While specific recommendations are presented here, they are offered along with the fundamental principles involved, as a starting point for broader stakeholder discussions of policy variants and options. PCL's goal is to enable informed stakeholder discussion. A comprehensive recommendation is presented, to convey how all the pieces would fit together.

The recommended product scope is outlined first. Initial guidance on energy metrics, power limits, and the test sequence needed to support those determinations is then provided. Finally, detailed recommendations for test methods are presented.

This section provides general recommendations as well as special considerations for specific display types. It also shares the approaches other leading policy tools and standards in use in the US and Europe:

- **CEC Title 20**
- **Ecodesign and EU Energy Label**
- **ENERGY STAR TVs version 9 and Displays version 8.0**
- **U.S. Department of Energy Test Method (ANSI/CTA-2037-D)**
- **International TV Test Method: IEC 62087 parts 1–3**

This report focuses on these policy tools to limit its complexity, and because the added detail of other geographies would not provide significant additional insight.

Product Scope

To develop a policy proposal covering televisions, computer monitors, and digital signage, PCL suggests specifying product definitions and explicit scope inclusions and exclusions. Each recommendation is followed by justification based on PCL's research and comparisons to existing policy implementations.

PCL considers whether products are in or out of scope:

- **Out:** Products not included in policy
- **In:** Products included in the policy at one of the described policy levels: MEPS, Label, Information Reporting

For each product category included, one of the following **policy levels** is suggested:

1. **MEPS (Mandatory Energy Performance Standards):** Products that must meet minimum energy performance requirements to be sold. These would also be subject to energy labeling and information reporting requirements.

2. **Label:** Products covered by an energy label that communicates efficiency information to consumers. These would also be subject to information reporting requirements.
3. **Information Reporting:** Products subject to testing and reporting requirements to support data collection, also known as "test-and-list."

The goal is for information reporting requirements to provide the necessary foundation for future MEPS and labeling requirements development, while applying MEPS to products for which PCL has enough data to determine efficiency requirements.

Table 73 and Table 74 show the recommended policy level, indicating whether a product is subject to information reporting, energy labeling, or MEPS requirements, as determined by their product class.

Table 73: Proposed scope for displays based on high-level product class

Scope – High-Level Product Classes	Recommendation
Televisions	MEPS
Computer Monitors	MEPS
Digital Signage Displays	MEPS

Table 74 shows exceptions to the above levels of policy coverage. For example, a curved DSD would fall under outside policy scope instead of being included in MEPS, in line with the curved DSDs exception listed below.

Table 74: Policy level exceptions to the product class-based scope

Scope – Policy Level Exceptions and Exclusions	Recommendation
Transparent OLEDs	Information Reporting (Active Mode) MEPS (Non-Active Mode)
Video walls – LCD Tile or DVLED Cabinet [1]	Information Reporting (Active Mode) MEPS (Non-Active Mode)
Video walls – All-in-Ones [2]	Information Reporting (Active Mode) MEPS (Non-Active Mode)
Projectors with integrated screens	Information Reporting
Standalone projectors	Out [3]
Integrated displays (e.g., automotive)	Out
Medical displays	Out
Studio mastering displays	Out
Curved DSDs	Out
Other niche markets	Out

[1] See 1.1.1.21: VIDEO WALLS – LCD TILES OR DVLED CABINETS for definition details.
[2] Video Wall All-in-Ones are those offered by a panel OEM where both the panel modules and any control components are made by the panel OEM; the assembly has a unique model number; and it is assembled into an integrated unit.
[3] Information reporting is recommended pending development of a standardized test method for standalone projector units. This would involve standardizing a screen surface and test geometry.

Table 75 summarizes the scope inclusion and exclusion (not policy level) recommendations based on product specifications such as screen area and native resolution. Where included ranges are defined, anything outside of the included range is excluded. These recommendations apply across all product classes.

Table 75: Summary of the proposed scope for displays based on specifications

Scope – Specification Limits		Scope Recommendation
Screen area		
Imperial	**Metric**	
15.5 - TBD in² [1]	1- TBD dm²	In
Pixel density		
Imperial	**Metric**	
≥ 17.9 pixels/in²	≥ 2.8/cm²	In
Luminance (cd/m²)		
SDR or HDR Peak Luminance ≤ 10,000 cd/m²		In
Other		
Outdoor displays		Information Reporting (Active Mode) MEPS (Non-Active Mode)
Battery-operated displays [2]		In

[1] It is recommended that policymakers work with stakeholders to determine appropriate upper screen area limits. See discussion in section 1.1.1.33: SCREEN AREA regarding suggested scope expansion.
[2] In line with current Ecodesign scope. PCL has not independently tested this product class in this research project.

High-Level Definitions and Policy Levels

The following section defines each product class and provides a recommended level of policy inclusion for the class. PCL defines exceptions later in this report.

Under PCL's proposal, a product is considered in scope if it meets the definition of a covered product class, satisfies the relevant specifications outlined in section SPECIFICATIONS, and is not covered by an exclusion detailed in section POLICY LEVEL EXCEPTIONS OR EXCLUSIONS.

1.1.1.17 Televisions

1.1.1.17.1 Definition

The following definition is proposed for televisions as it applies to the scope of this policy:

Television: Electronic display intended for the reception and presentation of broadcast, streamed, or recorded video and audio content and marketed for consumer use.

PCL's proposed definition focuses on the primary function of the device: the reception and presentation of audiovisual content, whether broadcast, streamed, or recorded. This approach accounts for the ongoing shift in consumer usage patterns and technological advancements, as many modern televisions prioritize internet streaming over traditional broadcast signals. As more consumers rely on online streaming services, the tuner/receiver requirement in existing television definitions becomes less relevant and may no longer reflect how the average consumer interacts with these devices.

To clarify how the proposed definition aligns with and differs from existing regulatory definitions, below are the definitions of television from several TV policies and standards reviewed:

- **CEC Title 20:** *Means an analog or digital device designed primarily for the display and reception of a terrestrial, satellite, cable, Internet Protocol TV (IPTV), or other broadcast or recorded transmission of analog or digital video and audio signals. TVs include combination TVs, television monitors, component TVs, and any unit that is marketed to the consumer as a TV. "Television (TV)" does not include computer monitors.*
- **Ecodesign and EU Energy Label:** *Means an electronic display designed primarily for the display and reception of audiovisual signals and which consists of an electronic display and one or more tuners/receivers.*
- **ANSI/CTA-2037-D:** *Equipment whose primary function is reception and display of television broadcast and similar services for terrestrial, cable, satellite and broadband network transmission of analogue and/or digital signals.*
- **U.S. Department of Energy:** *Means a product designed to produce dynamic video, contains an internal TV tuner encased within the product housing, and that is capable of receiving dynamic visual content from wired or wireless sources including but not limited to: (1) Broadcast and similar services for terrestrial, cable, satellite, and/or broadband transmission of analog and/or digital signals; and/or (2) Display-specific data connections, such as HDMI, component video, S-video, composite video; and/or (3) Media storage devices such as a USB flash drive, memory card, or a DVD; and/or (4) Network connections, usually using Internet Protocol, typically carried over Ethernet or wi-fi. 10 CFR 430.2.*
- **IEC 62087:** *Equipment whose primary function is reception and display of analogue or digital video signals from terrestrial broadcast, cable, satellite and/or broadband sources.*

1.1.1.17.2 Policy Level

It is recommended that TVs be covered under **MEPS**. This choice is supported by the use of established test procedures and leverages existing datasets (such as the CEC Title 20 television database) to inform initial efficiency requirements. This recommendation is further explained in section METRICS, POWER LIMITS, AND TEST SEQUENCE given PCL's suggested implementation of MEPS differs from current policy.

Televisions are covered under the ENERGY STAR Televisions 9.1 specification, which follows the ANSI/CTA-2037-D test method. The same method is also used by CEC Title 20 for information gathering for an open rulemaking to consider MEPS.

Of the policies reviewed, only Ecodesign and the EU Energy Label apply the same test method (different from ANSI/CTA-2037-D) to televisions, computer monitors, and DSDs. Under both policies, televisions must comply with MEPS, labeling, and information reporting requirements.

1.1.1.18 Computer Monitors

1.1.1.18.1 Definition

The following definition is proposed for computer monitors:

Computer Monitor: Electronic display intended to be used in a desk setting with a host device such as a computer, usually by a single user.

This proposed definition focuses on the intended use case of computer monitors and their user context. It does not limit a computer monitor's host device to just computers but allows for the inclusion of other devices such as gaming consoles or docking stations. This reflects common use cases for computer monitors and aligns with the functional intent captured across existing policies. In addition, requirements around specifications (such as screen size and pixel density) are intentionally excluded to avoid unnecessarily constraining the definition as display technologies evolve.

Computer monitor definitions from CEC Title 20, European policy, ENERGY STAR Displays 8.0, and IEC 62087 are below:

- **CEC Title 20:** *Means an analog or digital device of diagonal screen size greater than or equal to 17 inches and less than or equal to 61 inches, that has a pixel density of greater than 5000 pixels per square inch, and that is designed primarily for the display of computer generated signals for viewing by one person in a desk-based environment. A computer monitor is composed of a display screen and associated electronics.*

  A computer monitor does not include:

  (1) Displays with integrated or replaceable batteries designed to support primary operation without AC mains or external DC power, (e.g., electronic readers, mobile phones, tablets, battery-powered digital picture frames); or

  (2) A television or a signage display.
- **Ecodesign and EU Energy Label:** *Means an electronic display intended for one person for close viewing such as in a desk based environment.*
- **ENERGY STAR Displays 8.0:** *An Electronic Display intended for one person to view in a desk-based environment.*
- **IEC 62087:** *Product for the display of data, visual and video signals from a computer.*

1.1.1.18.2 Policy Level

This report recommends that computer monitors be covered under **MEPS**.

Computer monitors are in scope for ENERGY STAR and European policy. For European policy, they must comply with MEPS, labeling, and information reporting requirements.

1.1.1.19 Digital Signage Displays

1.1.1.19.1 Definition

The following definition is proposed for digital signage displays:

Digital Signage Display: Electronic display designed primarily for the presentation of visual content in commercial or public environments, including displays with embedded operating systems or media playback capabilities, provided that any embedded computing functionality is limited to display operation, content management, or communication and is not intended or marketed for use as a general-purpose computing device or not enabled by default for such purpose.

PCL's use-based definition captures the intended application context. It avoids additional specification-based restrictions that may become obsolete or unintentionally capture other product classes over time. For example, many high-brightness TVs now meet the first three requirements of the ENERGY STAR Displays 8.0 definition for a DSD.[36] By focusing on functional intent rather than technical specifications, this definition also excludes displays that incorporate general-purpose computing modules with substantially higher and more variable energy consumption than regular displays.

In contrast, definitions like the one used in European policy below to be overly restrictive, as the justification for the stipulations besides point (e), and (c) is unclear and risks unintentionally excluding some displays that may otherwise be intended to be categorized as signage displays.

DSDs are defined in CEC Title 20, European policy, and ENERGY STAR Displays 8.0 as follows:

- **CEC Title 20:** *Means an analog or digital device designed primarily for the display of computer-generated signals that is not marketed for use as a computer monitor or a television*.
- **Ecodesign and EU Energy Label:** *Means an electronic display that is designed primarily to be viewed by multiple people in non-desktop based and non-domestic environments. Its specifications shall include all of the following features:*

  (a) unique identifier to enable addressing a specific display screen;

  (b) a function disabling unauthorised access to the display settings and displayed image;

  (c) network connection (encompassing a hard-wired or wireless interface) for controlling, monitoring or receiving the information to display from remote unicast or multicast but not broadcast sources;

  (d) designed to be installed hanging, mounted or fixed to a physical structure for viewing by multiple people and not placed on the market with a ground stand;

  (e) does not integrate a tuner to display broadcast signals.

- **ENERGY STAR Displays 8.0:** *An Electronic Display intended for multiple people to view in non-desk-based environments, such as retail or department stores, restaurants, museums, hotels, outdoor venues, airports, conference rooms or classrooms. For the purposes of this specification, a Display shall be classified as a Signage Display if it meets three or more criteria listed below:*

  (1) Diagonal screen size is greater than 30 inches;

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[36] For example, a 30-inch, FHD (1920×1080 resolution) display with the appropriate brightness could qualify as a DSD under this definition.

(2) Maximum Reported Luminance is greater than 400 candelas per square meter;

(3) Pixel density is less than or equal to 7,000 pixels per square inch;

(4) Ships without a mounting stand designed to support the display on a desktop, or is configured to be mounted vertically on a wall; or

(5) Contains RJ45 or RS232 physical ports.

1.1.1.19.2 Policy Level

PCL suggests subjecting indoor DSDs to MEPS. Applying MEPS across the diverse range of DSD products would establish consistent energy efficiency requirements while also supporting the systematic collection of comparable data across different DSD form factors, technologies, and use-case scenarios.

PCL offers certain exceptions to the recommendation of MEPS for DSDs, which are detailed in the following section.

This recommendation is consistent with existing policy approaches. Under CEC Title 20, DSDs are subject to MEPS, and ENERGY STAR Displays Version 8.0 includes DSDs within its scope. In contrast, current European policy limits requirements for DSDs primarily to energy labeling and information reporting.

Policy Level Exceptions or Exclusions

This section outlines exceptions to the recommended policy level described for each product class. These exceptions or exclusions are based on the following considerations:

- The product is niche, and regulatory burdens may outweigh potential energy savings.
- The test method to evaluate the product’s energy performance needs further development (e.g., standalone projectors).
- The market prioritizes performance characteristics over energy efficiency (e.g., medical displays).

Table 76 summarizes these exceptions or exclusions.

Table 76: Policy level exceptions to the product class-based scope

Scope – Policy Level Exceptions and Exclusions	Recommendation
Transparent OLEDs	Information Reporting (Active Mode) MEPS (Non-Active Mode)
Video walls – LCD Tile or DVLED Cabinet [1]	Information Reporting (Active Mode) MEPS (Non-Active Mode)
Video walls – All-in-Ones [2]	Information Reporting (Active Mode) MEPS (Non-Active Mode)
Projectors with integrated screens	Information Reporting
Standalone projectors	Out [3]
Integrated displays (e.g., automotive)	Out
Medical displays	Out
Studio mastering displays	Out
Curved DSDs	Out
Other niche markets	Out

[1] See 1.1.1.21: VIDEO WALLS – LCD TILES OR DVLED CABINETS for definition details.

[2] Video Wall All-in-Ones are those offered by a panel OEM where both the panel modules and any control components are made by the panel OEM; and the assembly has a unique model number; and it is assembled into an integrated unit.

[3] Information reporting is recommended pending development of a standardized test method for standalone projector units. This would involve standardizing a screen surface and test geometry.

The sections that follow detail why given display categories are not excluded in the recommendations despite being excluded by previous display policies.

1.1.1.20 Transparent OLEDs

1.1.1.20.1 Definition

The following definition is proposed for this category:

Transparent OLEDs: A television, computer monitor, or digital signage display which uses a transparent OLED (or T-OLED) panel.

1.1.1.20.2 Policy Level

It is proposed to include transparent OLEDs under Active Mode information reporting requirements and Non-Active Mode MEPS since there is currently a lack sufficient data on their Active Mode energy performance to support the development of Active Mode MEPS.

Transparent OLED displays are not explicitly addressed by any of the policies reviewed, so in most cases they would be expected to fall under the same scope and test method as other DSD types, unless explicitly excluded.

1.1.1.21 Video Walls – LCD Tiles or DVLED Cabinets

1.1.1.21.1 Definition

Video walls and related components are defined as follows:

Video Wall Display: A large-format display system that consists of multiple LCD tiles or DVLED cabinets (or modules in the case of DVLED all-in-one displays) to function as a single display.

Video Wall Controller: A hardware device that accepts video inputs and maps visual media across an array of video wall tiles, cabinets, or modules.

LCD Video Wall Tile: A field-replaceable LCD subunit marketed primarily for use as part of a video wall display.

DVLED Video Wall Module: A field-replaceable DVLED subunit marketed primarily for use as part of a video wall display.

DVLED Video Wall Cabinet: A video wall display subassembly composed of multiple DVLED modules, integrated power supplies, and associated electronics, marketed as a single installable unit.

For additional details on the DVLED market and the differences between tiles/cabinets and modules, please review section DIGITAL SIGNAGE DISPLAYS.

1.1.1.21.2 Policy Level

Our policy-level recommendations are as follows:

- **LCD Video Wall Tiles:** In scope and subject to MEPS for both Active and Non-Active Mode
- **DVLED Video Wall Cabinet**: In scope and subject to information reporting requirements for Active Mode and MEPS for Non-Active Mode
- **DVLED Video Wall Module:** This component level is out of scope. Modules are addressed by policy in that they are components of DVLED all-in-ones and DVLED cabinets, which are in scope
- **Video Wall Displays:** Out of scope at the system level except for all-in-one DVLED video walls (section 1.1.1.22: VIDEO WALLS – ALL-IN-ONES). PCL recommends addressing non-all-in-one video wall displays at the cabinet level because they are often sold at the component level; it would be too complex to address all component combinations, including third-party controllers, with policy

If an LCD tile or DVLED cabinet cannot function without a control box and its power draw cannot be isolated and measured separately from the control box, PCL suggests the tile or cabinet would be out of scope. Most LCD tiles and DVLED cabinets can be tested using standard AC power outlets (even when designed for direct wiring into an electrical system) so it is expected that most will be in scope.[37]

Standby power levels for DVLED cabinets are typically much higher than LCD tiles, as DVLED cabinets often implement Standby Mode by displaying a black image and leaving most of the internal electronics powered up. This consumes many times more power than a typical LCD tiles' Standby Mode power.

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[37] Outdoor DVLED is typically designed to connect to a power distribution box or be hardwired into AC circuitry, while still accepting standard 100–240 VAC (or, in some cases, 200–240 VAC) input power.

The EU Energy Label regulation explicitly excludes display tiles that are designed to be integrated as part of a larger display screen area.

CEC Title 20 defines a subset of modular systems as “professional signage displays” and exempts them from Active Mode and Non-Active Mode power requirements.

To qualify for this exclusion under CEC Title 20, a system must meet all the following criteria:

- *Composed of an area greater than 1,400 in^2;*
- *Composed of two or more display panels, each with a diagonal size greater than 12“;*
- *Designed to be operated by an external data controller; and*
- *Designed and marketed for viewing by multiple people in a non-desk-based environment. Examples of such environments include stadiums, airports, and convention centers.*

As most tiled LCD displays are designed to be used with an external video wall controller, this would put them out of CEC Title 20’s scope.[38]

ENERGY STAR 8.0 is the only policy reviewed to include modular display systems in its scope. These systems are tested in their maximum tiled configuration, meaning the largest number of tiles supported by the system’s external controller and power supply. The full system, including all display tiles and support tiles, must be tested as a single unit to evaluate energy performance. The same power and luminance requirements used for standalone signage displays apply to these systems.

1.1.1.22 Video Walls – All-in-Ones

1.1.1.22.1 Definition

The following definition is proposed for video wall all-in-ones:

Video Wall All-in-One: A video wall display system sold with a single OEM model number and for which the final assembled unit has integrated modules and control components.

These displays may require some assembly, but the assembled unit is analogous to a typical LCD display in that all the display and control components are integrated into one unit. This contrasts with typical DVLED video wall systems in which control components are not integrated and are sometimes sited in a different physical location than the display components.

One example of a video wall all-in-one is the LG DVLED MAGNIT All-in-One (Figure 94), which is sold as a set that includes micro-LED modules, an embedded system controller, and built-in speakers.

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[38] For example, the Samsung VH55R-R display tested for this study would not be excluded as it can be used without an external data controller.

Figure 94: The LG DVLED MAGNIT All-in-One is a video wall all-in-one

1.1.1.22.2 Policy Level

PCL recommends that video wall all-in-one systems be included under information reporting requirements for Active and MEPS for Non-Active Mode.

Existing policies reviewed treat video wall all-in-ones differently based on their assembly status. In cases where these systems are shipped in pieces, they would typically be treated as tiled displays (see the previous section). If shipped fully assembled, they would be treated the same way as other DSD types, in line with section 1.1.1.19: Digital Signage Displays.

1.1.1.23 Projectors with Integrated Screens

1.1.1.23.1 Definition

The following definition is proposed for projectors with integrated screens:

Projector with Integrated Screen: A projector (rear-projection or front-projection) sold as a bundled unit together with a projection screen.

These products are typically marketed as replacements for large televisions.

1.1.1.23.2 Policy Level

It is recommended to include projectors with integrated screens under information reporting requirements. The existing test method is compatible with projectors with integrated screens. This data will support the development of future MEPS for this category.

IEC 62087 includes televisions of all technologies (including projection) within its scope, which means that projectors with integrated screens marketed as televisions are in scope for this standard.

1.1.1.24 Standalone Projectors

1.1.1.24.1 Definition

Standalone Projector: A projector (rear-projection or front-projection) that is not sold with a projection screen.

This report recommends that standalone projectors be excluded from the scope of energy efficiency policies due to the need to develop a suitable test method for these products. These include standard or long-throw projectors, short-throw projectors, and ultra short throw (UST) projectors.

Research to develop a test method would need to address key questions such as:

- What is the appropriate projection image size and viewing distance that should be used for standardized testing?
- What type of screen specification should be used to ensure results are consistent and repeatable across different test environments?

1.1.1.24.2 Policy Level

Projectors in general are not explicitly addressed in either ENERGY STAR 8.0 or CEC Title 20, but the definitions of covered display products in both policies suggest that projectors fall outside their intended scope. In contrast, both the EU Ecodesign Regulation and the EU Energy Label Regulation explicitly list projectors as excluded from their respective scopes, clearly excluding them from MEPS and labeling requirements.

1.1.1.25 Integrated Displays

1.1.1.25.1 Definition

PCL defines this category:

Integrated Display: A display that is built into another product. The host product has an intended primary usage other than displaying video signal, and the display cannot be operated independently from the host product.

Figure 95: Several cars, such as the Tesla Model S, feature integrated displays

1.1.1.25.2 Policy Level

We do not recommend including integrated displays in scope due to the difficulty of isolating and measuring the energy efficiency of the display component independently from the overall system.

This exclusion does not apply to:

- Displays with an embedded computing module (either as an optional add-on or included as shipped), such as the LG 75TR3DK-B tested
- Displays used in checkout kiosks, provided they can operate independently of the rest of the kiosk system (i.e., card readers and scanners)

The display definitions in ENERGY STAR Version 8.0 and CEC Title 20 exclude displays that are part of larger integrated systems—such as those embedded in appliances, gaming consoles, industrial equipment, and control panels.

Both Ecodesign and the EU Energy Label explicitly exclude integrated displays from their scope.

1.1.1.26 Medical Displays

1.1.1.26.1 Definition

The following definition is proposed for this category:

Medical Display: A display marketed and sold exclusively as a medical device intended for the diagnosis, monitoring, or treatment of disease or other medical conditions, that is certified to IEC 60601-1 and IEC 60601-1-2 or equivalent national standards (e.g., FDA 510(k) clearance).

1.1.1.26.2 Policy Level

We do not recommend including medical displays within the scope of display efficiency policy. These products may be subject to specialized performance requirements that prioritize reliability, accuracy, and continuous operation over energy efficiency. As such, PCL believes it is reasonable to maintain their exclusion from current regulatory frameworks focused on energy performance.

Medical displays are explicitly excluded from the Ecodesign and EU Energy Label regulations, ENERGY STAR 8.0, and CEC Title 20. Our recommendation is in line with their approaches.

1.1.1.27 Studio Mastering Displays

1.1.1.27.1 Definition

Studio Mastering Display: A display not intended for general consumer or commercial signage application that fulfills all the following criteria:

- Hardware-based color calibration system, or integrated 3D lookup table (LUT) calibration with a manufacturer-supplied probe or validated external calibration workflow
- Real-time signal analysis tools integrated into the display, including at least one of: waveform monitor, vectorscope, RGB clipping indicators, or input signal metadata display (e.g., resolution, frame rate, interlace/progressive status, chroma subsampling, bit depth)
- At least one professional video input, such as Serial Digital Interface (SDI at 3G-SDI or above, or 12G-SDI) or uncompressed IP video (e.g., SMPTE ST 2110), natively integrated
- Demonstrated conformity with EBU Tech 3320 Grade 1 specifications for luminance and chromaticity uniformity
- Support for native 10-bit signal processing and display, including HDR Electro Optical Transfer Functions (EOTFs) such as PQ or HLG in accordance with ITU-R BT.2100
- Supports HDR (ST 2084)
- HDR (ST 2084) black level ≤ 0.001 cd/m²
- HDR (ST 2084) peak brightness ≥ 1,000 cd/m²

1.1.1.27.2 Policy Level

PCL proposes to exclude studio mastering displays from energy efficiency policy consideration.

1.1.1.28 Curved Digital Signage Displays

1.1.1.28.1 Definition

Curved Digital Signage Display: A digital signage display with a non-flat screen geometry, including convex, concave, or mixed curvature profiles.

Figure 96 illustrates a DSD with a mixed curvature profile which includes convex and concave sections.

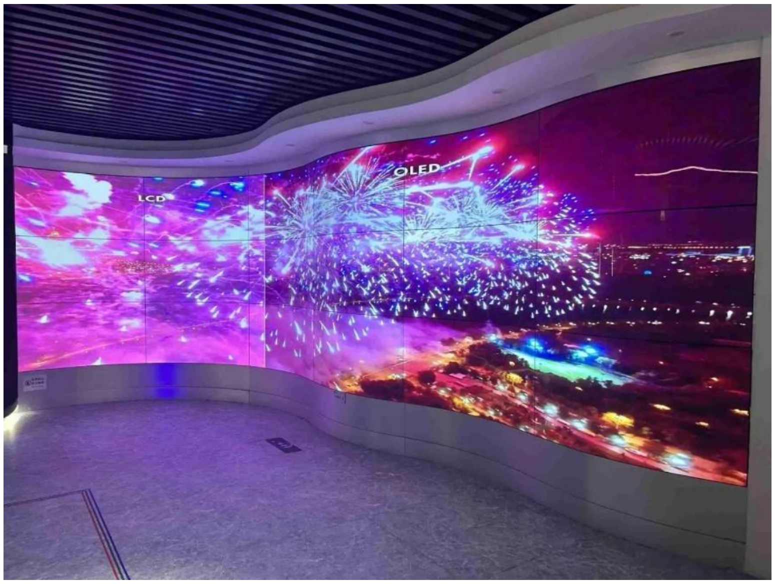

Figure 96: A curved OLED display from LCD Office

1.1.1.28.2 Policy Level

Curved DSDs are proposed to be excluded from scope because curvature can reduce the reliability of camera-based luminance measurements, particularly where the screen shape cannot be consistently detected and corrected during testing.

1.1.1.29 Security Displays

1.1.1.29.1 Definition

PCL proposes using the same security display definition present in Ecodesign and the EU Energy Label.

Security Display: A security display must include all the following:

> *(a) self-monitoring function capable of communicating at least one of the following items of information to a remote server:*
>
> *— power status;*
>
> *— internal temperature from anti-overload thermal sensing;*
>
> *— video source;*
>
> *— audio source and audio status (volume/mute);*
>
> *— model and firmware version;*
>
> *(b) user-specified specialist form factor facilitating the installation of the display into professional housings or consoles;*

Security displays can be a subtype of either DSDs or computer monitors.

1.1.1.29.2 Policy Level

PCL proposes subjecting security displays under MEPS, despite their exclusion from previous European regulation. Our review of commercially available models listed online revealed no functional or technical reasons that would justify continued exclusion. These displays operate similarly to other professional display types and are capable of being evaluated under the proposed test method.

Security displays are treated as digital signage displays in ENERGY STAR 8.0 and CEC Title 20. They are excluded by Ecodesign and the EU Energy Label.

1.1.1.30 Broadcast Displays

1.1.1.30.1 Definition

The broadcast display definition used by European policy is recommended:

> *"Broadcast display" means an electronic display designed and marketed for professional use by broadcasters and video production houses for video content creation. Its specifications shall include all of the following features:*
>
> - *colour calibration function;*
> - *input signal analysis function for input signal monitoring and error detection, such as wave-form monitor/vector scope, RGB cut off, facility to check the video signal status at actual pixel resolution, interlace mode and screen marker;*
> - *Serial Digital Interface (SDI) or Video over internet Protocol (VoIP) integrated with the product;*
> - *not intended for use in public areas.*

1.1.1.30.2 Policy Level

It is proposed to include broadcast displays under MEPS requirements. These displays are excluded from MEPS under Ecodesign and do not have to comply with EU Energy Label requirements.

1.1.1.31 Professional Displays

1.1.1.31.1 Definition

Professional displays are displays used in video and content creation. These are typically higher-end computer monitors that do not use specialized technologies but are distinguished by tighter performance requirements (e.g., color accuracy, uniformity, and contrast) rather than by niche form factors.

If policymakers decide to define a distinct policy treatment for professional displays (for example, to explicitly enforce their inclusion, or to grant exclusion from MEPS), then the following criteria are recommended to define the category:

- **Contrast ratio of at least 2500:1:** As measured using Section 7.4 Darkroom contrast ratio of IEC 62977-2.

- **≥2.3 megapixels resolution:** This threshold ensures the display meets a baseline for pixel density and image detail necessary for professional video and graphics work. It aligns with common editing formats and exceeds Full HD (1920x1080).
- **10-bit color depth (native or validated FRC):** Displays must support at least 10-bit color depth per channel, either natively or using Frame Rate Control (FRC) validated for professional applications. This requirement supports HDR workflows and smooth gradients without banding.
- **≥95% Rec.709 or ≥90% DCI-P3 color gamut:** This ensures the display can reproduce a wide and accurate range of colors suitable for video editing and grading. Rec.709 is the HD broadcast standard, while DCI-P3 is the standard for digital cinema and HDR production. Refer to ITU-R BT.709 and DCI-P3 specifications.
- **Average ΔE ≤ 2.0 (no color error > 3.0):** This criterion ensures high color accuracy. ΔE (Delta E) measures perceptual color difference; a value below 2 is typically imperceptible. This is used in calibration protocols by RTINGS, VESA DisplayHDR, and EBU Tech 3325 for reference displays.
- **EBU Tech 3320 Grade 1 or 2 uniformity only:** Displays must meet Grade 1 or 2 luminance and chromaticity uniformity as defined by the European Broadcasting Union (EBU Tech 3320). This prevents displays with visible brightness or color shifts across the screen from qualifying. Grade 3 is excluded due to leniency.
- **Explicit marketing for broadcast/editing use and sale via professional channels**

Table 77 compares the proposed definition with the one currently used by European policy.

Table 77: Comparison of professional display definitions

Criterion	Ecodesign and Energy Label Definition	Proposed Definition
Design and marketing	Designed and marketed for professional use for editing video and graphic images	Same
Contrast ratio	Contrast ratio of at least 1000:1 measured at a perpendicular to the vertical plane of the screen and at least 60:1 measured at a horizontal viewing angle of at least 85° relative to that perpendicular and at least 83° from the perpendicular on a curved screen, with or without a screen cover glass	Contrast ratio of at least 2500:1 measured per IEC 62977-2, section 7.4 [1]
Native resolution	Native resolution of at least 2,3 mega pixels	Same
Color gamut	Color gamut support greater than or equal to 38,4% of CIELUV	≥95% Rec.709 or ≥90% DCI-P3 color gamut
Uniformity	Color and luminance uniformity as specified for grade 1, 2 or 3 monitors in EBU Tech. 3320, as applicable to the professional application of the display	Color and luminance uniformity as specified for grade 1 or 2 monitors in EBU Tech. 3320, as applicable to the professional application of the display
Color depth		10-bit color depth (native or validated FRC)
Color error		Average ΔE ≤ 2.0 (no color error > 3.0)
HDR support		Supports HDR (ST 2084)

[1] Contrast ratio of at least 2500:1 aligns with RTINGS.com's grading scale for their test results.

1.1.1.31.2 Policy Level

PCL recommends that professional displays are included in scope.

1.1.1.32 Other Niche Displays

Many niche product classes operate under regulatory burdens that likely outweigh the potential benefits of energy savings. Below some product classes were identified that may meet that criteria. It is recommended that policymakers work with stakeholders during rulemaking to finalize a list of display classes that should be granted a policy exception.

Examples of potential niche product classes are provided below:

- **Legacy Format Reference Monitors:** Displays specifically designed for monitoring very old or niche broadcast formats (e.g., specific analog standards no longer in widespread use, or highly specialized telecine monitors). These would be replacement-driven in very specific archive or niche transfer facilities.
- **Highly Ruggedized or Environmental-Specific Field Monitors:** Displays built to extreme specifications for outdoor broadcast in harsh conditions (e.g., extreme temperatures, dust, vibration) or military broadcast applications. These are often custom or very low-run productions.
- **Highly Specialized "Analyzer" Displays:** Monitors designed to visualize very specific, non-standard broadcast signals for deep diagnostics or research, rather than general program viewing. Think of displays showing waveform, vector scope, and other technical data in an integrated, highly specialized visual format that isn't commonly available.
- **Monitors for Highly Secure/Shielded Environments:** Displays designed to meet extreme electromagnet interference (EMI)/radio frequency interference (RFI) shielding requirements for secure government or defense broadcast operations, often requiring custom fabrication.
- **Industrial Displays for Extreme Environments (Beyond Ruggedized):** Displays built for specific, highly corrosive, explosive, or radioactive environments in industrial settings, where custom materials and shielding are paramount and production runs are small.
- **Custom-Built Large Format Displays for Unique Architectural Installations:** While LED video walls are common, a bespoke, non-standard display for a unique museum exhibit or art installation might be a one-off or very limited run.
- **Legacy System Replacement Displays with Custom Form Factors:** For very old, critical infrastructure (e.g., power grid control, legacy manufacturing lines), replacement displays might need custom dimensions or interface compatibility that limits them to a tiny, "end-of-life" market.
- **Warranty/Service Parts and Replacements:** Since regional regulations such as CEC’s and the EU’s require that service parts remain available for a period of some years, new display policy should not prevent their distribution.
- **Aerospace and Air Traffic Control (ATC) Displays with Niche Certifications:** Displays designed for critical aviation systems, requiring specific certifications for shock, vibration, temperature range, and reliability that limit their market to a few manufacturers and highly regulated customers.

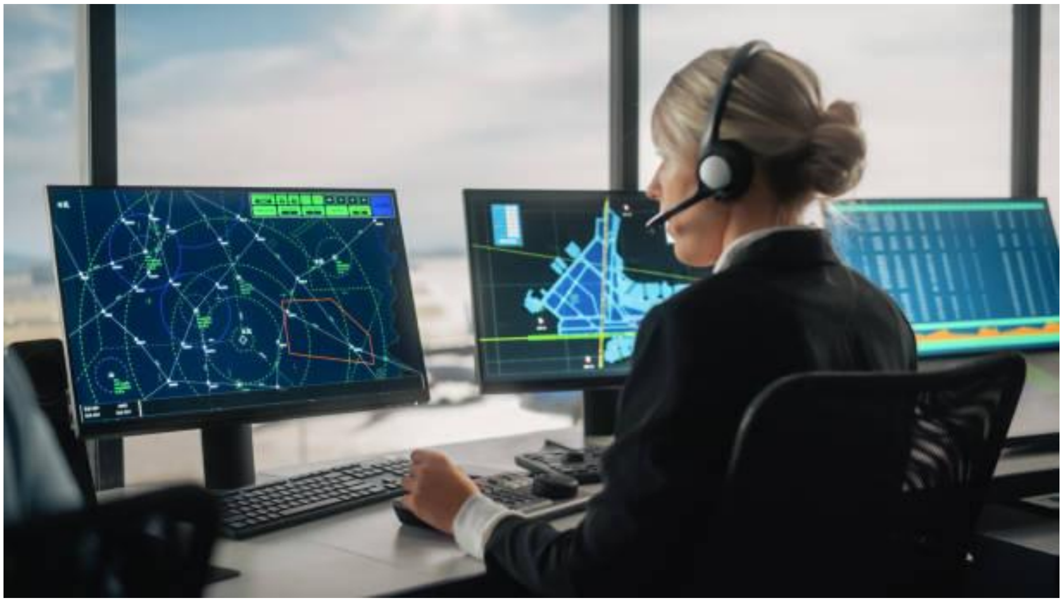

Figure 97: Standalone ATC certified displays

Figure 98: Integrated ATC displays

Specifications

The specification-based limits below are intended to determine whether products are included in or excluded from scope. They are not intended to set the stringency of policy requirements, but are important to consider in terms of proportionality of test burden to manufacturers, the avoidance of loopholes, etc.

Table 78 summarizes the scope recommendations based on specifications. The following sections provide the technical justifications for these inclusions and exclusions.

Table 78: Summary of the proposed scope for displays based on specifications

Scope – Specification Limits		Scope Recommendation
Screen area		
Imperial	**Metric**	
15.5 - TBD in^2 [1]	1- TBD dm^2	In
Pixel density		
Imperial	**Metric**	
$\geq$ 17.9 pixels/in^2	$\geq$ 2.8/cm^2	In
Luminance (cd/m^2)		
SDR or HDR Peak Luminance $\leq$ 10,000 cd/m^2		In
Other		
Outdoor displays		Information Reporting (Active Mode) MEPS (Non-Active Mode)
Battery-operated displays [2]		In

[1] PCL recommends that policymakers work with stakeholders to determine appropriate upper screen area limits. See discussion in section 1.1.1.33: SCREEN AREA regarding suggested scope expansion.

2] In line with current Ecodesign scope. PCL has not independently tested this product class in this research project.

1.1.1.33 Screen Area

When referring to screen area, the updated definition included in the IEC 62087-1 Edition 2 committee draft is used. Screen area is the logically addressable, viewable surface of display capable of showing text, images or videos.

The section MINIMUM CAMERA SCREEN WIDTH CONSTRAINT in ANNEX D: MODIFYING THE PCL CAMERA SYSTEM shows that typical camera systems can test screen areas as small as 12.15 in^2 when using a commonly available lens with a focal length of 6mm. Given the niche market size for displays smaller than 15.5 in^2, which is the lower area limit for inclusion in European policy, PCL recommends keeping this as the lower limit for screen area scope inclusion.

PCL recommends that policymakers work with stakeholders to understand appropriate upper screen area limits for all product classes. While computer monitors have a natural screen area limit based on their desktop use, televisions and DSDs are now available in larger sizes that can exceed 220” diagonally. PCL proposes addressing DVLED DSDs at the cabinet level, in part to address this concern. Typical cabinet screen area is 0.25 m^2.

For all product classes, any upper limit on screen area should account for laboratory space constraints. Under the proposed test method, the measurement distance scales with screen width (1.77 x width for TVs and DSDs, 1.28 x width for computer monitors) of these screen sizes, which can require very large test rooms for ultra large displays.

1.1.1.33.1 *Existing Policy* Approaches

In EU Energy Label and Ecodesign:

- TVs and computer monitors with a screen area of 100 cm^2 or less are excluded.

- DSDs are excluded from regulation if their screen area is less than 30 dm² (465 in²) or greater than 130 dm² (2015 in²).

The only limitation in ENERGY STAR Displays 8.0 is that a DSD may need to have a screen diagonal greater than 30" if it does not meet other criteria. CEC Title 20 also does not impose minimum or maximum screen areas as general rules, but defines computer monitors as having a diagonal screen size between 17" and 61".

1.1.1.34 Pixel Density

Figure 99 illustrates displays with different pixel densities, classified in this picture by pixel pitch (distance between pixels in millimeters).

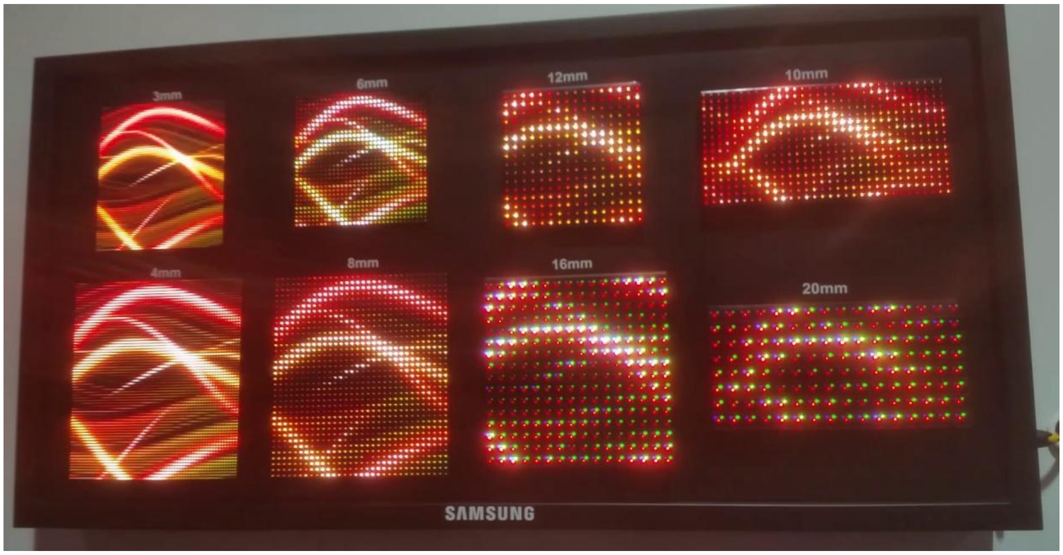

Figure 99: Comparison of different pixel densities (expressed here as pixel pitch) from Samsung

The pixel pitches in Figure 99 translate to the following pixel densities. The bold text indicates pixel pitches/densities that would be included in the scope proposal.

- **3 mm ≈ 71.7 pixels/in² (≈11.1 pixels/cm²)**
- **4 mm ≈ 40.3 pixels/in² (≈ 6.25 pixels/cm²)**
- **6 mm ≈ 17.9 pixels/in² (≈ 2.78 pixels/cm²)**
- 8 mm ≈ 10.1 pixels/in² (≈ 1.56 pixels/cm²)
- 10 mm ≈ 6.45 pixels/in² (≈ 1.00 pixels/cm²)
- 12 mm ≈ 4.48 pixels/in² (≈ 0.69 pixels/cm²)
- 16 mm ≈ 2.52 pixels/in² (≈ 0.39 pixels/cm²)
- 20 mm ≈ 1.61 pixels/in² (≈ 0.25 pixels/cm²)

Given the testing and development detailed in ANNEX D: LOW PIXEL DENSITY, PCL has confidence that a typical camera system can handle pixel densities as low as 17.9 pixels/in² (or 2.8 pixels/cm²).[39]

Therean opportunity exists to include in scope displays with even lower pixel densities. Our original sample plan included a display with a pixel density of 5.33 pixels/in², but it could not be procured it due to availability issues. Follow-up testing may allow us to expand the scope recommendation to include these displays.

This report proposes not having an upper pixel density limit as the Limit 1 equation (previously introduced in section ENERGY EFFICIENCY DETERMINATION) already takes into account resolution. Additionally, measuring screen-average luminance in high-pixel density displays poses no methodological issues.

1.1.1.34.1 Existing Policy Approaches

ENERGY STAR Displays 8.0 sets a maximum pixel density of 7,000 pixels/in² (close to a 27" FHD 1080p display) for a display to qualify as a signage display.

Similarly, the EU Energy Label regulation excludes digital signage displays from labeling requirements if their pixel density is less than 230 pixels/cm² (1,484 pixels/in², a low pixel density usually only seen in direct LED signage) or more than 3,025 pixels/cm² (19,516 pixels/in², close to a 27" 4K display). These thresholds correspond to pixel pitches of approximately 0.66 mm (for the minimum density) and 0.18 mm (for the maximum density).

While CEC Title 20 does not enforce a general pixel density requirement for inclusion in scope, it defines computer monitors as having a pixel density greater than 5,000 pixels/in² (close to a 31" FHD 1080p display).

1.1.1.35 Luminance

The proposed peak luminance scope limit is 10,000 cd/m^2 as determined by a screen-center measurement made with the EUT set to its maximum luminance level while playing the IEC 62977-2-1 10% pattern area center box pattern. This peak luminance level reflects the upper end of the market reviewed for this study.

1.1.1.35.1 Existing Policy Approaches

Only the EU Energy Label imposes a peak luminance limit for DSDs in SDR, which is set at 1,000 cd/m². This is relatively low considering that recommended brightness for indoor DSD could be as high as 2,500 cd/m^2, with levels potentially even higher for outdoor use. Therefore, the recommendation to include products with peak luminance up to 10,000 cd/m² would significantly broaden the scope of this policy.

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[39] Pixels/in² is not the same as the common industry term pixels per inch (PPI), which refers to pixels per linear inch.

1.1.1.36 Other

1.1.1.36.1 Outdoor Displays

It is recommended that both indoor and outdoor displays be included in the policy scope. Including outdoor displays ensures that the policy remains comprehensive and aligned with the evolving use cases and technology landscape of commercial signage.

While the outdoor units tested have energy efficiency levels similar to those of efficient TVs, insufficient data is currently available to reliably develop MEPS for such displays. This energy efficiency performance may partly reflect default picture tuning (outdoor displays often use lower gamma values) rather than being due to hardware alone. Given such unknowns, PCL recommends that they are initially included under information reporting requirements.

1.1.1.36.1.1 Existing Policy Approaches

The EU Energy Label explicitly excludes outdoor DSDs from its scope. ENERGY STAR Displays 8.0 and CEC Title 20 do not have such exclusions.

1.1.1.36.2 Battery-Operated Displays

It is recommended that battery-operated displays are included within the scope of energy efficiency policy. While this product class was not tested during this research, it is believed it is feasible to assess energy efficiency in this product class by using the camera system to measure luminance, alongside the Ecodesign method to measure Active Mode (on-mode in this policy's terminology) power in battery-operated devices.

1.1.1.36.2.1 Existing Policy Approaches

Battery-operated displays are in scope for both Ecodesign and the EU Energy Label.

ENERGY STAR 8.0 explicitly excludes displays designed to support primary operation without AC mains or external DC power. CEC Title 20 excludes battery-operated monitors but is unclear as to whether battery-operated DSDs are in scope.

Metrics, Power Limits, and Test Sequence

This section presents an illustrative set of efficiency metrics and power limits for Active Mode and Non-Active Mode across key product classes, including feature-based adders where applicable. This is provided to illustrate one integrated approach; alternative policy solutions are possible. Given ongoing policy discussions in Europe, PCL provides a complete worked example showing how metrics, MEPS limits, labeling limits, test sequence, and total energy and savings calculations can be assembled into a coherent policy recommendation. Strengths, weaknesses, and alternatives to this example's approach are also discussed.

Active Mode is discussed in four parts: 1) a review of a key technical concepts, 2) recommended metrics, limits, test sequence, 3) rationale and alternatives, and 4) implications for energy consumption reporting and savings calculations under light efficiency metrics.

Additional details on how other policies implement their metrics and power limits are available in ANNEX J: OVERVIEW OF CURRENT DISPLAY POLICIES.

Key Concept Review

Before reading the policy recommendations section, it may be helpful to review section KEY CONCEPTS AND CORE PRINCIPLES. Some aspects are briefly summarized below for convenience.

Display power generally scales with the light source setting (often termed as “backlight” or “brightness”), which may be adjusted either manually via menu settings or automatically by the display based on the ambient light level in the room. Emissive displays and LCDs with global or local dimming can scale their power more closely with the light produced on the screen. More localized dimming (more zones) usually enables improved power scaling.

Basic LCDs can waste significant backlight energy because darker areas are created by blocking light coming from the backlight, rather than by reducing the backlight power and light output in the first place. As a result, for basic LCDs, apparent efficiency improvements can be achieved through compromising picture-setting changes (e.g., by adjusting contrast settings to make darker parts of the image brighter or more washed out). On the other hand, emissive displays (e.g., OLEDs) and LCDs with local dimming inherently scale power to actual content. These displays are more strongly incentivized by light-efficiency metrics to achieve software and component-level energy efficiency gains.

If regulators apply too much pressure to basic LCDs, manufacturers may respond by brightening midtones and shadow detail (for example by lowering the gamma setting). This can make the image look flatter (reduced perceived contrast) and more suited for brightly lit rooms. In other words, policy could end up driving changes in picture processing (the way an incoming video signal is translated into light output, referred to as signal-to-light mapping) rather than driving genuine improvements in energy efficiency.

The controls required to scale power in emissive displays and LCDs with many local dimming zones adds a fixed baseline power load. This can be observed as a lower dimming line slope (more power scaling as images get darker) along with a higher y-intercept.

The different ways in which the limits can be achieved presents a policy challenge because limits are intended to reward genuine efficiency improvements, not changes in picture settings for testing. The limit will work best if it tracks the way a display’s power typically changes as it gets brighter or dimmer, especially near the compliance threshold. If the limit is not designed in this way, it might mean that the easiest way to improve a display’s score may be to tweak brightness defaults for the test, rather than improve the hardware.

Light efficiency metrics require a paradigm shift in thinking, from focusing on power at a single test condition to addressing the relationship between power and delivered light. This has implications for the development of MEPS, labels, energy reporting, and savings calculations. This is discussed further later in this section.

MEPS

An example MEPS implementation is provided below as a complete worked example that makes the trade-offs and alternatives easier to assess. After the example, a discussion of policy fundamentals and alternatives is provided.

1.1.1.37 Active Mode

The example provided uses light efficiency-based metrics to establish maximum allowable Active Mode power consumption limits. This approach scales power allowances with known energy drivers of screen luminance, area, and resolution, to arrive at limits that apply roughly similar regulatory pressure across a wide range of display sizes and resolutions.

To avoid unintended and negative impacts on signal-to-light mapping, this example applies only modest policy pressure on all display product classes in the near term. Setting modest limits will allow data collection to inform stricter MEPS in the future. Engagement with hardware and software supply chain actors who market energy saving innovations to OEMs could help clarify the feasibility of tighter power limits over time.

From initial observations, computer monitors generally exhibited better baseline efficiency than did TVs and most DSDs. Therefore, even modest MEPS could be set more stringently for this product class while remaining achievable. While specific coefficients are not being recommended here, computer monitors showed on average a 48% lower Power/Reference than DSDs and TVs.[40] This gap suggests that the market for monitors is already operating at a comparatively efficient level, although the effect could be due to lower gamma values being used in computer monitors.

1.1.1.37.1 Example Requirements

Measurements are taken for each HDR and SDR preset picture setting (PPS), tested with automatic brightness control (ABC) off, and the light source/backlight set to default.

This limit function reflects the fact that both the slope and intercept depend on screen area and pixel resolution.

The equation is in the form **Limit = Scaling Factor * (slope * measured dynamic luminance + y-intercept)**, with several coefficients included based on a detailed analysis of the datasets.

The power of the display must be less than or equal to Limit 1 (below) plus any relevant adders.

Where Limit 1 is:

---

[40] Per PCL's analysis of the 2025 CEC MAEDbS dataset, computer monitors had an average Power/Reference of 44%, while in PCL's limited testing DSDs had an average Power/Reference of 83%. To determine an average Power/Reference for DSDs, the DVLED display tested was removed as this was a clear outlier with a much lower Power/Reference value of 8%.
According to CEC data, TVs have an average Power/Reference of 84%.

Table 79: Limit 1 equation per content format

Content Format	Limit 1 (W): Efficiency limit
SDR	SDR_SF * ((SDRa + SDRb * A + SDRc * PR) * DL + (SDRd + SDRe * A + SDRf * PR))
HDR10	HDR_SF * ((HDRa + HDRb * A + HDRc * PR) * DL + (HDRd + HDRe * A + HDRf * PR))

Where:

- Scaling Factor (SF) is a key determinant of the overall stringency of Limit 1.
- Dynamic Luminance (DL) is obtained by measuring the screen-average luminance of a display throughout the run of the new IEC SDR dynamic broadcast clip (shown in Table 96).
- Screen Area (A) refers to the viewable and logically addressable screen area (represented in square inches in this case).
- Pixel Resolution (PR) refers to the display’s native screen resolution, expressed as the total number of physical pixels across the screen.
- Other coefficients vary between SDR and HDR as shown in Table 80 below.

Table 80: Limit 1 coefficients

Coefficient	SDR	HDR
Scaling Factor	0.724673	0.817364
a	0.838099	1.472072
b	0.001413	0.002407
c	2.72E-08	5.7E-08
d	3.119322	3.486500
e	0.004866	0.004848
f	2E-06	1.91E-06

Adders are as defined in

Table 81.

Table 81: MEPS Active Mode power adders

Category	Adder Amount
All Display Types in Scope	
Touchscreen setting	1 W [1]
Touchscreen technology type	TBD [2]
Computer Monitors Only	
Contrast ratio	2% per 1,000:1 increase in contrast ratio up to a 15% total
Screen curvature	7% [3]
Native refresh rate	0.04% per hertz over 60Hz
Maximum refresh rate	0.03% per hertz over 60Hz
Software-based Variable Refresh Rate supported	6%
Hardware-based Variable Refresh Rate supported	14%

[1] Only if touchscreen is enabled by default and therefore enabled during the test.
[2] More data needs to be collected about the energy efficiency performance of different touchscreen technologies to determine an appropriate adder, as it is expected that some of them (particularly PCAP) may lead to a reduction in luminance emission.
[3] For flexible screens that can curve, only if the screen is curved by default in Active Mode and therefore curved during the test.

Figure 100 below illustrates how MEPS compliance would work for one of the DSDs tested, which was not eligible for any of the Active Mode adders. Several of the SDR default backlight test points fall above the SDR limit, so even though the HDR default backlight test point is below the HDR limit, the product would not pass.

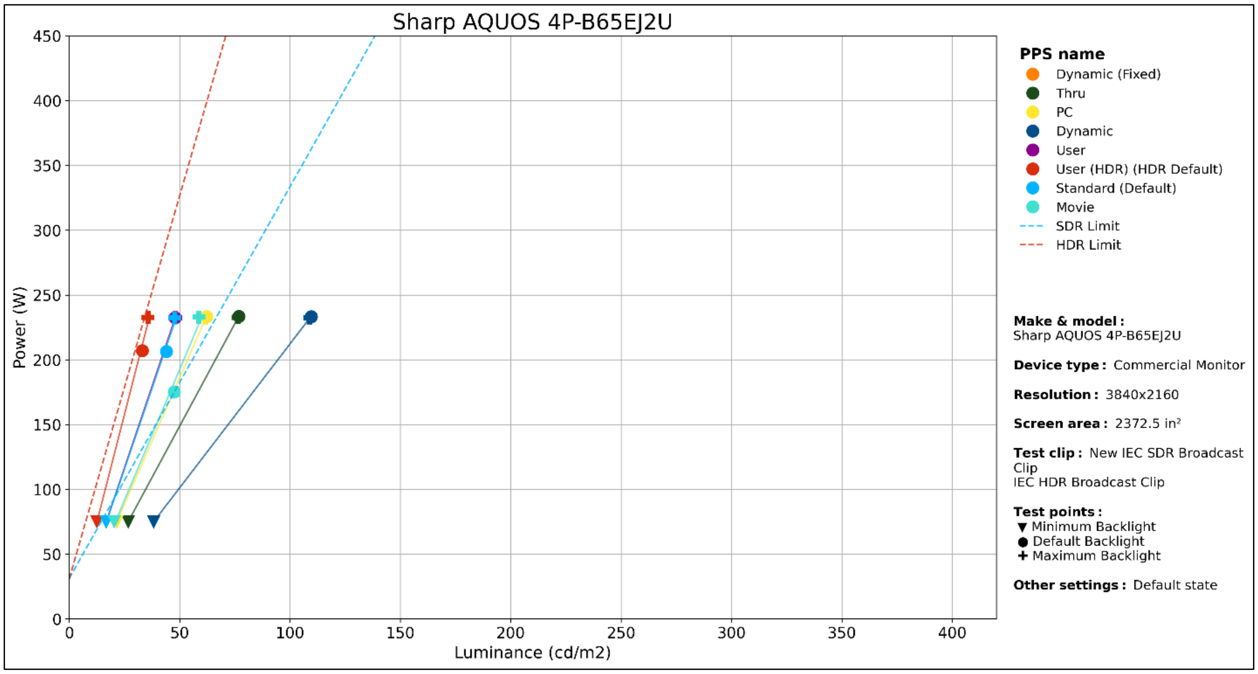

Figure 100: Active Mode limit line performance example

1.1.1.38 Non-Active Mode

Table 82 summarizes the example MEPS requirements for Non-Active Modes. It includes six Non-Active Mode limits in total: Four standby limits apply to TVs and DSDs (supported by four separate tests), and two additional limits (D3cold and D3hot) apply to computer monitors only. Depending on regional priorities, it may be possible to reduce the test burden by only requiring smart standby and hands-free wake limits because these represent the most feature-intensive connected standby states and are expected to bound power use in simpler standby modes. They therefore represent the largest savings opportunities.

Table 82: MEPS for Non-Active Modes

Non-Active Mode	Required function	MEPS
D3cold [1]	Reactivation by power button or remote control	≤ 0.5 W (Computer monitors)
D3hot [1] [2]	Input signal reactivation	≤ 0.5 W (Computer monitors)
Standby [3]	Reactivation	≤ 0.5 W (All in-scope display classes except DVLED cabinets) ≤ 4 W (DVLED cabinets) [6]
Networked Standby [3]	Network reactivation	≤ 1 W
Smart Standby [3] [4]	As many of the specified smart standby functions as possible [4]	≤ 1 W
Hands-free Wake [3] [5]	As many of the specified hands-free wake functions as possible	≤ 6 W

[1] For computer monitors only.

[2] When supported, computer monitors should be tested in the Non-Active Mode subtypes that include additional functions, using D3hot as the starting point. For example, if the monitor supports Smart Standby features, those features should be enabled when the monitor is in the D3hot power state, and the corresponding Non-Active Mode test (Smart Standby) should be performed.

[3] For TVs and DSDs where supported. For video walls, this limit applies at the LCD tile or DVLED cabinet level where applicable.

[4] The Smart Standby test is conducted in networked standby with additional Smart Wake features enabled. In this test, as many Smart Standby sub-functions as possible should be activated: reactivation, networked reactivation, wake-by-remote-control-app, wake-on-cast, wake-by-smart-speaker, and Bluetooth speaker link maintenance.

[5] In this test, as many hands-free wake sub-functions as possible should be enabled: voice activation, gesture recognition, presence detection, mobile-device proximity.

[6] In the case of DVLED cabinets, the reactivation function is typically provided by an external control box.

These example MEPS include a near-term 4 W Standby limit for DVLED cabinets based on recommendations by an industry expert familiar with the current state of power optimization in DVLED components and also based on input from a receiver card manufacturer. We suggest that policymakers consult with industry stakeholders and determine a timeframe for lowering this requirement to 1 W, the level on which this report’s long-term savings potential estimates are based. The 1 W long-term level is also based on industry input.

Energy Label

Developing an energy label is more complicated than developing MEPS levels. While MEPS can reasonably be based on light efficiency, applying a light-efficiency approach to a labeling scheme is more challenging. The example below illustrates one possible light efficiency-based labeling approach.

In PCL's example, classes are determined separately for several Active Mode and Non-Active Mode components. The overall label class is set to the lowest (least efficient) class across these components.

1.1.1.39 Primary Components

Power and luminance are measured for each HDR and SDR preset picture setting (PPS) with automatic brightness control (ABC) disabled and the light source/backlight set to default. In contrast to the MEPS recommendation, power caps are included while labeling reference lines. While this is somewhat arbitrary, PCL's thinking is as follows: it is not considered appropriate to limit the sale of a display with a MEPS based on its default luminance setting; however, PCL proposes that it may be appropriate to include power caps in a labeling scheme in line with the principle of sufficiency. Including power caps here also lets us introduce this policy option to familiarize readers with the way it works.

The core formula (Limit 1) and power cap (Limit 2) are shown below. The formula follows the same structure as the MEPS formula except 1) a grading factor (GF) is included depending on the labeling grade and 2) there is a power cap.

The power cap does not cap the display's luminance; rather it caps the luminance level for which additional power allowance is granted in the grading calculation. This is intended to prevent displays from earning larger power allowances simply by configuring displays to have higher measured luminance during testing (for example, via picture-processing/signal-to-light mapping choices). It keeps grading anchored to a representative luminance level, so the label reflects hardware efficiency rather than brightness tuning. A power cap is appropriate for labeling to keep grades comparable at a representative luminance and to avoid rewarding higher test brightness with a larger power allowance. It was not applied in the MEPS, because a cap risks penalizing legitimate higher-luminance operation and incentivizing default brightness reductions rather than genuine hardware efficiency improvements.

To determine the labeling grade of the display, the measured power of the display would be compared against the labeling grades calculated using Limit 1 (below) combined with the power cap plus any relevant adders.

Table 83: Power – ABC credit where applicable ≤ (Minimum of Limit 1 and Limit 2) + Adders

Content Format	Limit 1 (W): Efficiency limit	Limit 2 (W): Power cap
SDR	SDR_SF*(GF*(SDRa+SDRb*A+SDRc*PR)*DL+(SDRd+SDRe*A+SDRf*PR))	Limit1_SDR at 150 cd/m^2
HDR10	HDR_SF*(GF*(HDRa+HDRb*A+HDRc*PR)*DL+(HDRd+HDRe*A+HDRf*PR))	Limit1_HDR at 70 cd/m^2

Where:

- Limit 2 acts as a power cap such that power is allowed to increase with luminance only up to 150 cd/m2 for SDR and 70 cd/m2 for HDR[41]
- Grading Factor (GF) adjusts the stringency of grading levels
- Scaling Factor (SDR_SF or HDR_SF) is a key determinant of the overall stringency of Limit 1
- Dynamic Luminance (DL) is the screen-average luminance measured throughout the run of the new IEC SDR dynamic broadcast clip (shown in Table 96)
- Screen Area (A) refers to the viewable and logically addressable screen area (represented in square inches in this case)
- Pixel Resolution (PR) refers to the display’s native screen resolution, expressed as the total number of physical pixels across the screen
- Other coefficients vary between SDR and HDR per Table 84 below

Table 84: Class grading factors

Class	Grading Factor
A	0.53
B	0.59
C	0.66
D	0.73
E	0.81
F	0.90
G	1.00

Note: Each factor is 10% below the factor below it in the table. In other words, each grade is 10% tougher than the adjacent lower grade.

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[41] The luminance levels at which the power caps kick in were designed in this example so that almost all of today’s TV grading points fall below the power for all SDR PPSs and for the default HDR PPS. Unfortunately, there is no test data for the brightest HDR PPS, so it is less certain that the power cap would be above all HDR PPS grading points.

Table 85: Limit 1 coefficients

Coefficient	SDR	HDR
Scaling Factor	0.724673	0.817364
a	0.838099	1.472072
b	0.001413	0.002407
c	2.72E-08	5.7E-08
d	3.119322	3.486500
e	0.004866	0.004848
f	2E-06	1.91E-06

Adders are defined in Table 86.

Table 86: Energy Label Active Mode power adders

Category	Adder Amount
All Display Types in Scope	
Touchscreen setting	1 W [1]
Touchscreen technology type	TBD [2]
Computer Monitors Only	
Contrast ratio	2% per 1,000:1 increase in contrast ratio up to a 15% total
Screen curvature	7% [3]
Native refresh rate	0.04% per hertz over 60Hz
Maximum refresh rate	0.03% per hertz over 60Hz
Software-based Variable Refresh Rate supported	6%
Hardware-based Variable Refresh Rate supported	14%

[1] Only if touchscreen is enabled by default and is therefore enabled during the test

[2] More data must be collected on the energy efficiency performance of different touchscreen technologies to determine an appropriate adder, as it is expected that some of them (particularly PCAP) may lead to a reduction in luminance emission.

[3] For flexible screens that can curve, only if the screen is curved by default in Active Mode and therefore curved during the test.

Figure 101 below illustrates what these grading lines would look like for 65" 4K TVs with no adders or ABC credit.

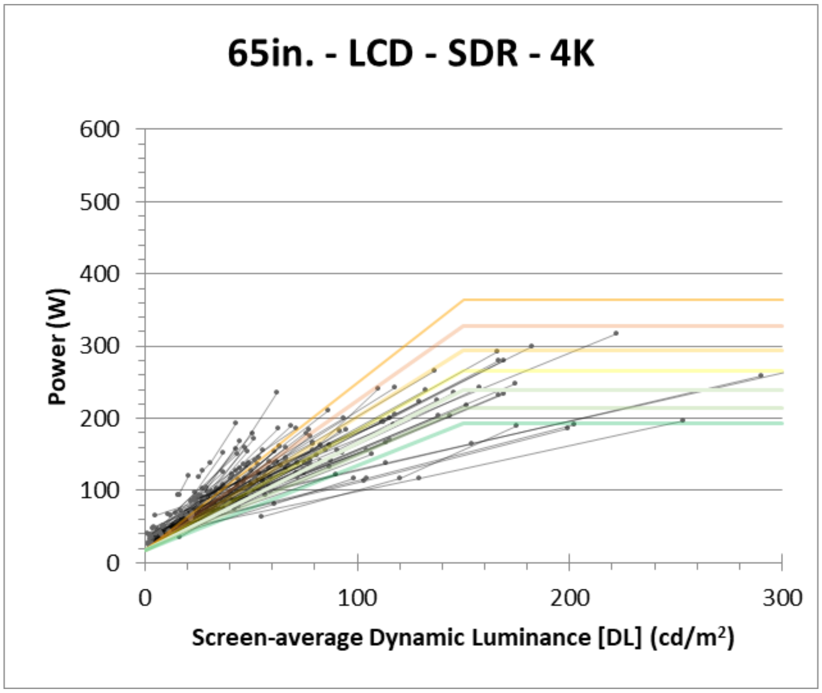

Figure 101: Example limits for energy label implementation

The power cap can be observed in Figure 101, where the same luminance level at which power is capped (i.e., 150 cd/m^2) is held constant across all the labeling levels. However, the luminance level at which power is capped could be different for each grade depending on policy objectives. Caution should be taken in the application of power caps given the limited insights available on consumer preference, real-world settings, and motivations behind OEM default setting decisions.

In this labeling approach, the Y-intercept is constant, and the rest of the line is reduced to different percentages of the original values. It may appear counterintuitive to hold the Y-intercept constant, as in many cases TVs with more efficient components would have a lower Y-intercept. However, local dimming, a feature that can significantly reduce the slope and thereby improve energy efficiency, can also increase the Y-intercept as it requires additional processing power to dynamically manage the backlight level across potentially thousands of dimming zones. Holding the Y-intercept constant therefore keeps label differentiation focused on slope-related efficiency improvements and provides some flexibility for the additional baseline power that such improvements may require.

1.1.1.40 ABC Eligibility Criteria

ABC allowances are applied separately for each PPS, rather than being applied once after all the modes are averaged together into a single overall result.

An ABC allowance can only be applied if the display's ABC performance meets the eligibility criteria. Eligibility is assessed for each PPS using the tables below, where power and luminance are measured using the appropriate broadcast test clip (SDR or HDR10). ABC eligibility is predicated on ABC being enabled by default for the given PPS. The entity commissioning the test must specify which PPSs should be assessed for ABC eligibility. If no PPSs are specified, then the test lab should not apply ABC eligibility assessments to any PPSs.

Table 87: ABC credit eligibility criteria for indoor displays

ABC	Lux Levels	Power	Luminance
Off	-	-	-
On	141	≥100% of ABC off	≥100% of ABC off
On	85	≤91% of level at max lux	65%–95% of level at max lux
On	49	≤85% of level at max lux	50%–80% of level at max lux
On	17	≤80% of level at max lux	35%–70% of level at max lux

As discussed in ANNEX I: ABC POLICY RECOMMENDATIONS FOR OUTDOOR DISPLAYS, developing ABC eligibility requirements for outdoor displays is challenging. The example approach below aligns with the analysis in ANNEX I but would require industry consultation before being adopted.

Table 88: ABC credit eligibility criteria for outdoor and semi-outdoor displays

ABC	Lux Levels	Power	Luminance
Off	-	-	-
On	2 * Peak Brightness (cd/m^2)	≥100% of ABC off	≥100% of ABC off
On	1.2 * Peak Brightness (cd/m^2)	≤91% of level at max lux	65%–95% of level at max lux
On	0.7 * Peak Brightness (cd/m^2)	≤85% of level at max lux	50%–80% of level at max lux
On	0.24 * Peak Brightness (cd/m^2)	≤80% of level at max lux	35%–70% of level at max lux

Industry sources indicate that nearly every outdoor display has an ambient light sensor, usually located to receive indirect sunlight, but they are often perceived as unreliable. Most DSD customers are using a scheduler to adjust luminance (e.g., around sunrise and sunset transition times) rather than relying on ABC. Bearing in mind the uncertain savings linked to ABC in outdoor displays, the simplest and possibly most appropriate policy path would be to offer ABC allowances for indoor displays only.

Total Energy Consumption (TEC)

TEC reporting is important for informing consumers and for making national energy consumption estimates because it supports comparable estimates of annual energy use and savings. Given the lack of research into duty cycle estimates, this simplified approximation is offered:

Equation 7: Unit energy consumption

$$\begin{aligned} &Unit\ Energy\ Consumption\ (UEC)\ (kWh) \\ &\quad = (Average\ of\ all\ measured\ PPS\ power\ levels\ (default\ LSS) \\ &\quad * hours\ in\ Active\ Mode + Average\ of\ all\ standby\ test\ power\ levels \\ &\quad * hours\ in\ Non-active\ Mode) * 365\ days / 1000 \end{aligned}$$

Energy Savings Calculation Method

Many possible ways are available to calculate savings for removing from the market units not compliant with the Limit 1 MEPS. The approach used here estimates annual energy savings for non-compliant units being replaced by compliant units via Equation 8.

Equation 8: Unit energy savings

$$Unit\ energy\ savings\ (kWh) = UEC - UEC\ of\ limits$$

Where UEC of limits is defined by

Equation 9.

Equation 9: UEC of limits

$$\begin{aligned} UEC\ of\ limits\ =\ (&Average\ of\ all\ measured\ PPS\ power\ limit\ levels\ *\ hours\ in\ Active\ Mode \\ &+\ Average\ standby\ test\ power\ limits\ *\ hours\ in\ Non-active\ Mode) \\ &*\ 365\ days\ /\ 1000 \end{aligned}$$

Detailed estimated savings calculations and duty cycle assumptions are provided in ANNEX K: ENERGY SAVINGS.

Limits and Adders Development

This section provides the research basis for the limits and adders included in the example policy approach detailed above.

1.1.1.41 Active Mode

1.1.1.41.1 Base levels (Limits 1 and 2)

Setting light efficiency power limits in support of the Active Mode policy approach requires careful analysis of a relatively large dataset that covers the full range of screen sizes, resolutions, and panel types. The required steps are:

- Remove outlier dimming lines. These include dimming lines that have no slope because the display does not support backlight adjustment, or that are excessively curved,[42] or that have negative y-intercepts.
- Run multiple linear regression analyses to identify the linear relationships between area, luminance and resolution (predictor variables) on both slope and y-intercept (outcome variables). Because manufacturer and technology can be important predictor variables, identify which manufacturers and panel types most impact slope or y-intercept, and include them as predictor variables in the regression analyses.
  - Regression 1: Default SDR slope as a function of area and resolution
  - Regression 2: Default SDR Y-intercept as a function of area and resolution
  - Regression 5: Default HDR slope as a function of area and resolution
  - Regression 6: Default HDR Y-intercept as a function of area and resolution
- Plot these limits against all display size and resolution bins and tweak the parameters until the limit lines are generally parallel to the dimming lines closest to the limit lines. This removes the policy incentive for a manufacturer to manipulate the default backlight level, either up or down, to comply.
- Check that the resulting limits yield broadly comparable pass rates across panel technologies, sizes, and resolutions.

A small sample of the analysis that contributed to development of these levels is shown below:

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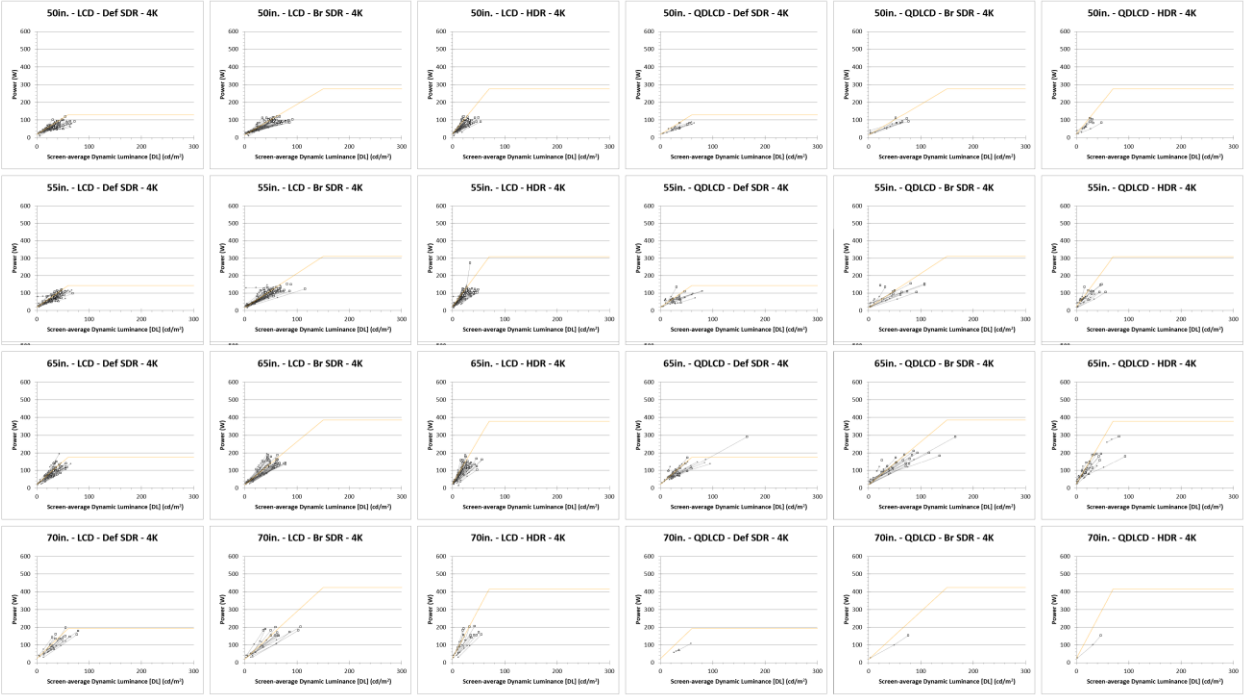
[42] Although some displays legitimately exhibit excessively curved dimming lines, this outlier behavior complicates regression analysis such that their removal is more appropriate.



50in. - LCD - Def SDR - 4K
50in. - LCD - Br SDR - 4K
50in. - LCD - HDR - 4K
50in. - QDLCD - Def SDR - 4K
50in. - QDLCD - Br SDR - 4K
50in. - QDLCD - HDR - 4K
55in. - LCD - Def SDR - 4K
55in. - LCD - Br SDR - 4K
55in. - LCD - HDR - 4K
55in. - QDLCD - Def SDR - 4K
55in. - QDLCD - Br SDR - 4K
55in. - QDLCD - HDR - 4K
65in. - LCD - Def SDR - 4K
65in. - LCD - Br SDR - 4K
65in. - LCD - HDR - 4K
65in. - QDLCD - Def SDR - 4K
65in. - QDLCD - Br SDR - 4K
65in. - QDLCD - HDR - 4K
70in. - LCD - Def SDR - 4K
70in. - LCD - Br SDR - 4K
70in. - LCD - HDR - 4K
70in. - QDLCD - Def SDR - 4K
70in. - QDLCD - Br SDR - 4K
70in. - QDLCD - HDR - 4K

Figure 102: Analysis used in development of levels

The CEC TV data analysis workbook used to make these calculations can be shared if necessary. The Limit 1 coefficients used result in a modest model-weighted (not sales-weighted) Active Mode energy savings of 1.7% and pass rate of 77%, per ANSI/CTA-2037-D test method and average performance of default SDR, brightest SDR, and default HDR PPS.

Computer monitors and DSDs have no equivalent light-based efficiency dataset. However, this research report and historic CEC data suggest that computer monitors are slightly more efficient than TVs, perhaps because they often are set to a lower gamma level (2.2 vs. 2.4) since they are intended for use in bright office spaces. So, the use of TV limits for computer monitors presents a low risk of overreach while additional light-based efficiency data is directly gathered for computer monitors. The data collected along with feedback from hardware component and operating system vendors can form the basis of possibly more stringent limits for computer monitors in the future.

1.1.1.41.2 Adders

An adder is an allowance that increases the applicable power limit for products with certain features, so that the policy does not unintentionally discourage those features. To address technology-specific differences, adders are specified for features that demonstrably increase energy consumption and provide user value, such as wide color gamut, touchscreens, or high contrast ratios in LCDs. Further data collection was conducted where available to calibrate appropriate adder amounts.

1.1.1.41.2.1 Contrast Ratio

Basic LCD displays with high native contrast ratios often exhibit higher power demand compared to the luminance they emit, given they block more light in dark areas in order to exhibit a broad dynamic range.

High contrast ratios are essential for legibility, accessibility, and visual impact, particularly in professional, educational, and signage applications where displays must remain readable under varied lighting conditions. Contrast is also a key enabler for effective HDR performance. As such, displays that offer high contrast should be recognized in policy through a power adder so as to not discourage this picture quality attribute.

Based on analysis of linear regression coefficients relating contrast ratio to energy consumption, the recommended contrast ratio adder is **2% per 1,000:1 increase in native contrast ratio, up to a maximum of 15%**. For example, a 3,000:1 native contrast ratio would correspond to a 6% adder. This adder would scale proportionally with display contrast ratio performance. Emissive displays, which have perfect contrast ratios, would automatically get a 15% adder.

As contrast ratio may vary by PPS, it should be measured separately for each PPS tested, and the adder should be applied individually to each PPS's dimming line.

1.1.1.41.2.1.1 Existing Policy Approaches

ENERGY STAR Displays 8.0 and CEC Title 20 reward contrast ratio performance via the Enhanced Performance Display designation. ANNEX J: OVERVIEW OF CURRENT DISPLAY POLICIES details how these adders are calculated based on color gamut and the calculated maximum total energy consumption. In both policies, the display must achieve a contrast ratio of 60:1 measured at a horizontal viewing angle of at least 85° (along with other performance requirements) to qualify for this power adder.

1.1.1.41.2.2 Screen Curvature

Based on the dataset analysis, curved displays were associated with higher power at a given luminance. Therefore, a **power adder of 7% for displays featuring screen curvature** is recommended to avoid penalizing the availability of this feature.

1.1.1.41.2.2.1 Existing Policy Approaches

Both ENERGY STAR Displays 8.0 and CEC Title 20 grant percentage-based adders for curved screens of 15% and 20%, respectively.

1.1.1.41.2.3 Touchscreen

Given testing and dataset analysis, a **fixed power adder of 1 W** is recommended for displays in which touchscreen is enabled by default.

Although touchscreen may increase energy consumption in several ways, this study was not able to confirm which mechanisms result in a display emitting luminance less efficiently when touchscreen is enabled.

1.1.1.41.2.3.1 Existing Policy Approaches

Previous policies grant power allowances for touchscreen computer monitors in Active Mode, but the scope and methodology vary:

- **ENERGY STAR Displays 8.0:** Includes a touchscreen power adder of 17% if touchscreen is enabled by default in Active Mode.
- **CEC Title 20:** Grants a 1 W power adder for touchscreens in modes where touch is enabled.

1.1.1.41.2.4 Refresh Rate

Given that higher refresh rates are associated with increased power demand, refresh rate-based adders are proposed for computer monitors to fairly account for performance differences while preserving manufacturer flexibility in default settings.

Rather than prescribing or penalizing specific default refresh rates, separate adders based on PCL's linear regression analysis are recommended for:

- **Native refresh rate:** apply an adder of 0.04% per hertz over 60 Hz for the default (native) refresh rate.
- **Maximum refresh rate capability:** apply an adder of 0.03% per hertz over 60 Hz for the maximum supported refresh rate (regardless of whether it is enabled as default).

This dual-adder structure ensures that both the baseline energy use and the potential power demand of high-performance displays are recognized.

1.1.1.41.2.4.1 Existing Policy Approaches

CEC Title 20 grants a refresh rate adder based on a display's maximum refresh rate in line with the equations listed in

Table 129 in ANNEX J: OVERVIEW OF CURRENT DISPLAY POLICIES.

1.1.1.41.2.5 Variable Refresh Rate (VRR)

In addition to PCL's previously stated refresh rate adders, a percentage-based adder for computer monitors that support Variable Refresh Rate (VRR) is recommended depending on its implementation:

- 14% for hardware-assisted VRR.
- 6% for non-hardware-assisted VRR.

To qualify for either adder, the computer monitor documentation or marketing materials must clearly state both 1) that it supports VRR and 2) whether the VRR implementation is hardware-assisted.

The current CEC Title 20 adder approach gives higher adders for specific hardware pathways. CEC grants a basic allowance to computer monitors that support VRR and a larger allowance where VRR is supported by additional hardware (e.g., dedicated VRR modules). A preferred approach is to develop a performance-based framework that rewards the actual capabilities and benefits delivered to end users, rather than being tied to the method used to achieve them. This was not pursued because existing VRR testing methodologies were found to be largely qualitative (relying on visual confirmation that VRR is active such as reduction or absence of screen tearing or during gameplay). No standardized quantitative method was identified to reliably measure benefits such as latency reduction or frame timing improvements across different implementations.

Given this limitation, an adder structure similar to CEC Title 20 is proposed so as not to discourage computer monitors with hardware-assisted VRR from remaining available on the market.

1.1.1.41.2.5.1 Existing Policy Approaches

As previously mentioned, CEC Title 20 grants power adders for computer monitors that support VRR (referred to as "Gaming Monitors" in their policy). The adder is 20% if VRR is implemented without incremental hardware-based assistance, and 30% with hardware-based assistance.

1.1.1.42 Non-Active Mode

Non-Active Mode is used to describe power states in which a display is not actively displaying video content but remains connected to main power and can be reactivated (for example, by a user action, an input signal, or a network request). For computer monitors, two host-controlled states are commonly encountered: a sleep-like state (D3hot) and a deeper off-like state (D3cold)

Our example includes the following Non-Active Mode limit levels without the application of any adders:

Table 89: MEPS for Non-Active Modes

Non-Active Mode	Required function	MEPS
D3cold [1]	Reactivation by power button or remote control	≤ 0.5 W (Computer monitors)
D3hot [1] [2]	Input signal reactivation	≤ 0.5 W (Computer monitors)
Standby [3]	Reactivation	≤ 0.5 W (All in-scope display classes except DVLED cabinets)

		≤ 4 W (DVLED cabinets) [6]
Networked Standby [3]	Network reactivation	≤ 1 W
Smart Standby [3] [4]	As many of the specified smart standby functions as possible [4]	≤ 1 W
Hands-free Wake [3] [5]	As many of the specified hands-free wake functions as possible	≤ 6 W

[1] For computer monitors only.
[2] When supported, computer monitors should be tested in the Non-Active Mode subtypes that include additional functions, using D3hot as the starting point. For example, if the monitor supports Smart Standby features, those features should be enabled when the monitor is in the D3hot power state, and the corresponding Non-Active Mode test (Smart Standby) should be performed.
[3] For TVs and DSDs where supported. For video walls, this limit applies at the LCD tile or DVLED cabinet level where applicable.
[4] The Smart Standby test is conducted in networked standby with additional Smart Wake features enabled. In this test, as many Smart Standby sub-functions as possible should be activated: reactivation, networked reactivation, wake-by-remote-control-app, wake-on-cast, wake-by-smart-speaker, and Bluetooth speaker link maintenance.
[5] In this test, as many hands-free wake sub-functions as possible should be enabled: voice activation, gesture recognition, presence detection, mobile-device proximity.
[6] In the case of DVLED cabinets, the reactivation function may be provided by an external control box.

The hands-free wake limit is intended to limit power to the best in-class levels (5 W–6 W) that were observed in recent TV research (Table 90).

Table 90: Television Standby power with hands-free wake enabled

Television Model	Standby Power with Hands-free Wake Enabled (W)
Hisense 55U6N	9
Fire TV Omni Series 4K43M600A	9
LG 42 OLED Flex[43]	6
Samsung QN55S95BAFXZA	5

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[43] Although this display is also marketed as a computer monitor and appears in PCL's study as such, it is also sold as a television and has an integrated TV tuner.

Due to insufficient data (as discussed in section DATASET ANALYSIS), a reliable regression model for Non-Active Mode power use could not be developed, and energy drivers with defensible power adders could not be identified. Additionally, for some monitor models that appeared in both PCL's laboratory testing and in the datasets reviewed, Non-Active Mode power values did not align, further reducing confidence in the existing data for adder development.

High Standby power values were observed during testing of some computer monitors, which suggests an energy savings opportunity may be available for this product class if test methods are refined and stronger data vetting is implemented. Based on prior experience with TV Standby policy, low power levels have been shown to be achievable even with Smart Standby features enabled. Therefore, conservative yet achievable power limits are recommended for most Non-Active Modes (as a feasibility led starting point rather than as regression derived values).

1.1.1.42.1 Special Considerations for Edge Cases

While not included in this example, an additional “Idle Mode” test could be considered to account for display modes such as “wallpaper,” “ambient,” or “gallery,” which display static images after pressing the display's off button. The test procedure could be specified with a higher—but still constrained—power limit, to encourage innovation while capping excessive energy use when the display is not in active use. Alternatively, these modes could also be addressed via an Annual Energy Consumption (AEC) requirement, with a different assumed duty cycle for displays that have these modes enabled by default.

Similarly, emerging modes that allow users to listen to music while the screen is off may warrant future policy coverage if uptake increases.

Additionally, one DVLED DSD was encountered (described in section 1.1.1.15.6: PIXEL-LEVEL DIMMING) that was designed without a true Non-Active Mode. This product lacked an off button and could only be turned off by unplugging it from the AC mains. Policymakers should consider how to address such designs and determine whether displays without user-accessible off functions should be discouraged, excluded, or addressed through an alternate requirement.

1.1.1.42.2 Existing Policy Approaches

Existing policies integrate Non-Active Mode requirements in different ways:

- **Ecodesign:** Tests off mode, passive standby, and networked standby, and specifies fixed standby power limits for each mode, with adders granted for certain functions (where present and enabled) such as:
    - Status display
    - Deactivation using room presence detection
    - Touch functionality, if used for activation
    - HiNA (high network availability) function

- **ENERGY STAR Displays 8.0:** Tests Non-Active Mode in Sleep Mode (by putting the monitor's host machine into sleep mode) and Off Mode (by turning off the monitor using its power switch). Only Sleep Mode measurements are used for compliance against the power limit function.
- **California Energy Commission (CEC):** Measures Sleep Mode and Off Mode in line with ENERGY STAR Displays 8.0, with a fixed power limit of 1.2 W for both modes.

Table 91 compares the proposed Non-Active Mode power limits with those from other policies, including any applicable power adders and the resulting total allowable power.

Table 91: Comparison of proposed and existing Non-Active Mode policies

Policy	Non-Active Mode	Base Limit (W)	Adders		Total Possible Limit (W)
			Adder	Amount (W)	
This Proposal	Standby	0.5	-		0.5
	D3hot				
	D3cold				
	Networked Standby	1			1
	Smart Standby				
	Hands-free wake	6			6
CEC Title 20	Off	1.2	-		1.2
	Standby				
Ecodesign	Off	0.3	-		0.3
	Standby	0.5	Status display	0.2	2.2
			Room presence detection deactivation	0.5	
			Reactivation via touchscreen	1	
	Networked Standby	2	Status display	0.2	7.7
			Room presence detection deactivation	0.5	
			Reactivation via touchscreen	1	
			HiNA	4	

The Ecodesign regulation includes several adders for features that may increase Non-Active Mode power consumption. In reviewing these adders, the following is noted:

The room presence detection deactivation adder applies only when the feature is enabled. However, it is understood that this feature is typically used to transition the display to an off state (rather than operating during Standby Mode), which suggests the adder may function more as an incentive rather than as a compensation for actual energy use in that state.

For reactivation via touchscreen, of nine monitors in the CEC dataset that supported this feature, none of them had recorded Sleep Mode levels at or above 1 W. This suggests that the energy cost of touchscreen wake-up capability may be negligible. However, the dataset does not specify how this feature was configured for testing, so it may not have been enabled.

No displays were identified in the datasets with status displays or HiNA functionality, so it was not possible to verify whether these features significantly impact Non-Active Mode power use. While the removal of these adders is not considered here, current datasets were insufficient to confirm whether they are needed or appropriately scaled.

Policymakers may still choose to consider some of the power adders proposed by Ecodesign, particularly if they have access to additional data to support their usage.

Discussion of Metrics, Limits and Sequence

In this section, with the concepts reviewed in section KEY CONCEPTS AND CORE PRINCIPLES, discussion of the key policy elements and alternative approaches related to each element is provided where applicable. A complex array of policy variables must be sorted through to arrive at a coherent policy approach. Several policy design decisions must be made before light-efficiency metrics can be applied consistently. These include: 1) where on the dimming line the display will be graded, 2) which PPSs will be subject to limits, 3) whether compliance is assessed per PPS or by using averaging, and 4) what form the limit line takes (efficiency-only, efficiency plus power cap, curved).

For Active Mode PCL recommends that the basic unit of measurement is the average power and average luminance over the 5-minute IEC broadcast test clip, rather than frame by frame or one-second interval measurements. As a reminder, filter-based camera photometers exhibit measurement uncertainty at short time intervals compared with their performance when averaging measurements over the entire test clip.

For Non-Active Mode, the basic unit of measurement is power measured in the relevant tests specified in IEC 62087-3, Edition 3:

- Standby
- Networked Standby
- Smart Wake Standby
- Hands-free Standby

For Active Mode, measurements are taken at different backlight/light source setting (LSS) levels to determine the performance of the display as a function of LSS level. This shows how display power use changes as brightness changes. This relationship matters because it describes the range of power and luminance outcomes available to manufacturers through default settings, and it also reflects how ABC adjusts the backlight/LSS automatically in response to ambient light. All displays scale power as LSS increases. In this report, the resulting relationship between power and luminance across LSS levels is referred to as a display's dimming line.

However, as noted in the key concepts review, basic LCDs typically do not reduce power when the video content is darker (i.e., they show limited power scaling with average picture level (APL), where white is 100% and black is 0%). This can be observed in power and luminance time-series plots. It is also reflected in the dimming line; displays with limited content-based power scaling tend to have a steeper slope (power rises more for a given increase in luminance), but also a lower y-intercept since local power scaling requires fixed compute and control power.

Once the dimming line concept is established, the team must determine the point on the dimming line where displays will be **graded**.

- **Fixed Luminance Level:** ENERGY STAR V8.0 grades all computer monitors at a fixed luminance setpoint of 200 cd/m^2. Applying this approach to TVs is impractical because some premium TVs have minimum luminance levels that exceed the maximum luminance achievable by some basic TVs. If a fixed setpoint were practical, it would simplify label design, energy reporting, and efficiency calculations. However, it might not be representative of real-world use. Larger, premium displays often default to higher luminance levels and are likely operate at higher luminance levels in the field. Industry sources also note that consumers prefer brighter displays, while basic display brightness is often constrained by cost rather than preference. As a result, grading at a luminance level that basic displays can reach may not be representative for premium displays.
- **Default LSS Level:** ANSI/CTA-2037-D grades efficiency at the factory default LSS level. This is generally the most representative approach for measuring power and evaluating efficiency under default operation.
- **All LSS Levels:** Limits could be applied at all tested LSS levels along the dimming line. However, this becomes problematic if a single limit line is used for both basic LCDs and displays with local power scaling and higher y-intercepts. For example, very low LSS test points are likely to fail for emissive displays because they often have higher baseline power (y-intercepts). In addition, few users watch content at these minimum LSS settings, so little benefit exists to including these test points as they are unlikely to improve policy outcomes for either MEPS or labels.

Once grading points are chosen, the team must also decide to **which PPSs the metrics will be applied**. Figure 103 illustrates the fact that a single display can exhibit many different energy efficiency performance levels across PPSs.

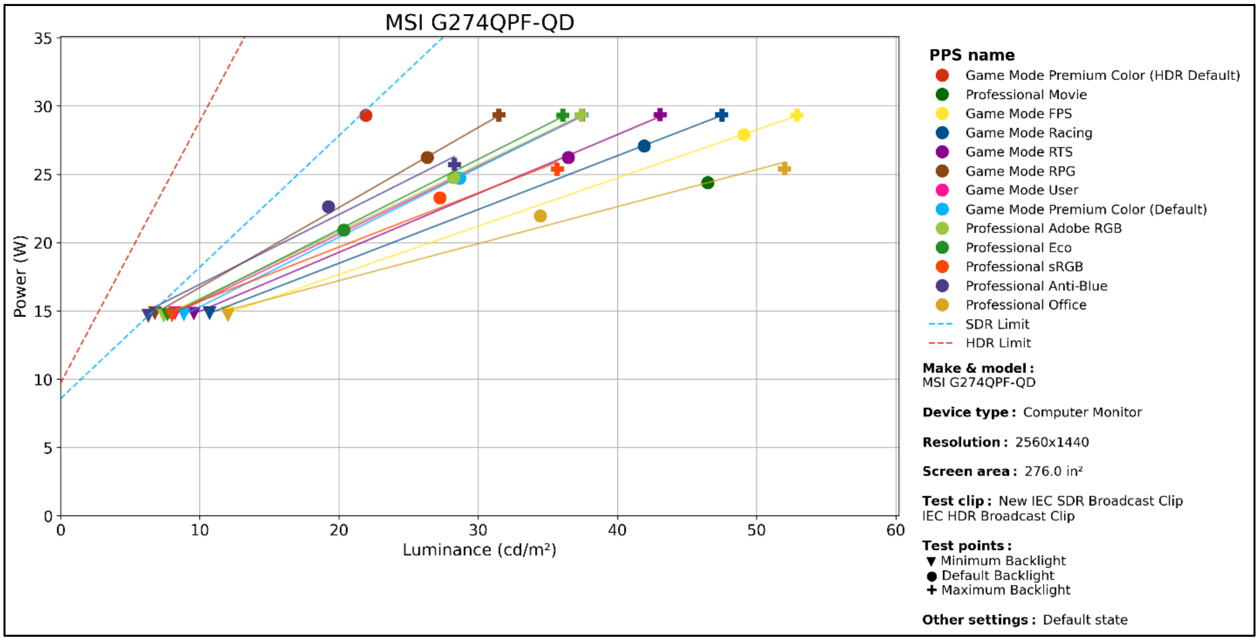

Figure 103: Impact of different PPSs on energy efficiency on the MSI G274QPF-QD monitor

Policymakers must also decide whether to apply MEPS limits to each **individual PPS** or whether compliance is assessed using an average across all PPSs. **Averaging** can create an incentive to increase the brightness of PPSs that appear efficient under the metric (for example, those with a lower slope) because doing so can significantly improve the overall average while shifting energy use upward in that PPS. This is a potentially harmful consequence of averaging that is avoided in the examples provided in this report.

If averaging is used, two approaches are commonly applied:

- **PPS-Level Limits with an Average Pass Requirement (used in ANSI/CTA-2047-D):** separate limit lines are applied to each tested PPS, but overall compliance is assessed "on average." In practice, this means the sum of the measured power levels must be less than or equal to the sum of the corresponding PPS limits.
- **Average-Only Limits:** limits are applied to an average power and average luminance value across PPSs, rather than to each PPS separately. This approach provides less visible guidance to manufacturer design teams, which receive very specific information from PPS-level limits.

MEPS or label **limit lines can take several forms**:

- **Linear Light Efficiency Limit Only:** compliance is determined solely by the relationship between power and luminance (i.e., light efficiency) without an additional power cap.
- **Linear Light Efficiency Limit Plus a Power Cap:** an additional upper bound is applied at higher luminance. However, compliance can be achieved by dimming the default brightness settings, so any estimated savings attributed to the power cap should be discounted if those settings are unlikely to persist in real-world use.

- **Curved Limit:** avoids a sharp transition point in the above limit, but makes it harder to separate the effects and associate confidence levels of the efficiency limit versus the power cap.

In all cases the primary parameters to consider are:

- Y-intercept (baseline power)
- Slope (power change per unit luminance)
- Curvature (how slope changes across the luminance range)

Figure 104 below illustrates linear versus curved limit line approaches against a set of dimming lines for a 65” 4K LCD (Brightest SDR PPS) from the CEC dataset. The gold line represents the basic proposed approach (as reflected in ENERGY STAR V9), where the light efficiency limit is defined with a slope and y-intercept that broadly match the displays that are near the compliance boundary. In effect, the limit line has been designed to run approximately parallel to the dimming lines in the vicinity of the limit. This minimizes the incentive to achieve compliance primarily by lowering brightness—a common risk in traditional policy approaches that use a simple watts/in2 power cap.

In this example, the line flattens (or caps) at a luminance level deemed sufficiently bright such that stakeholders agree that setting above that level should be discouraged by policy. Power caps are presented here as an option, but their appropriateness may depend on whether the policy instrument is a MEPS or a label, and whether it is voluntary or mandatory.

The blue line represents an alternative curved limit line approach. This avoids a single sharp transition point, which can sometimes lead to unintended consequences. For example, if the limit line switches abruptly from an efficiency slope to a power cap at a specific luminance, a manufacturer may simply tune the default picture mode so the display tests just below that luminance threshold to pass, rather than improving the hardware’s efficiency. However, a curved line also reduces the extent to which the limit line runs parallel to dimming lines near the compliance boundary—which is undesirable because when the limit line is not parallel to typical dimming lines near the pass/fail point, compliance can be improved mainly by shifting the graded brightness setting (e.g., lowering default LSS) rather than by improving the display’s underlying efficiency.

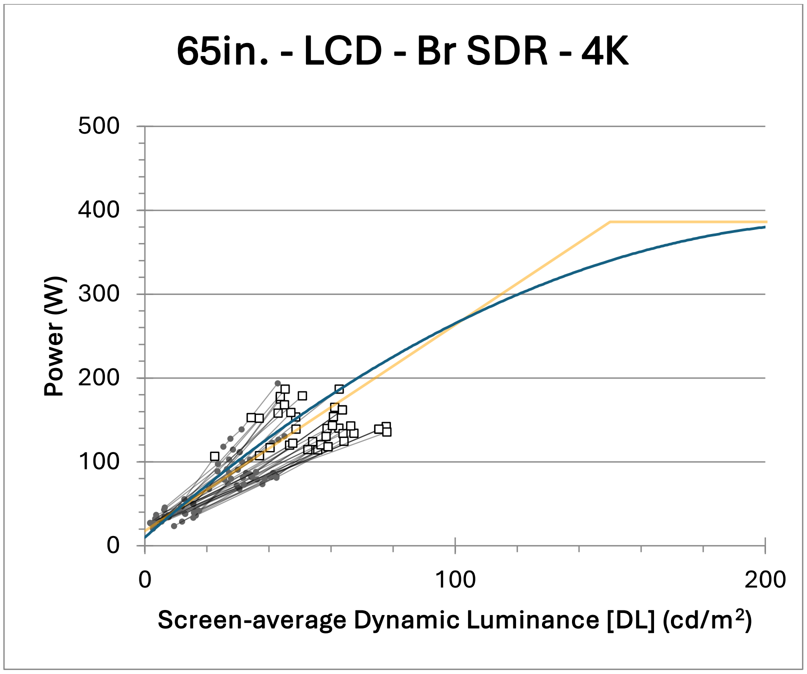

Figure 104: Linear versus curved reference line approaches

Note: The boxes represent default backlight settings used as the grading points in this example. A unit would pass the hypothetical limit if the box falls below the gold line.

If displays are graded by averaging the pass/fail margins (for example, averaging the number of watts above or below the limit across PPS), then the gold line can create a perverse incentive. For displays with Brightest PPS dimming lines that have a lower slope than the reference line, the largest compliance margin is likely to occur at the corner point (150 cd/m^2 in this case). This can incentivize manufacturers to tune the Brightest PPS luminance toward that corner, because a larger positive watt margin for the brightest PPS can offset poorer margins where other PPS dimming lines are above their respective PPS limits.

In the case of the blue curved reference line, a similar optimization incentive can exist. The PPS luminance may be tuned toward the point where the instantaneous slope of the curved blue line matches the display's dimming line slope, as that point can maximize the compliance margin under an averaging approach.

Developing labeling schemes is a complex undertaking. The labeling examples proposed are provided as illustrative "greenfield" options, recognizing that regional policy choices will be shaped by local regulatory objectives and constraints.

The test sequence (or clear rules for constructing the test sequence) should be explicitly specified. An example test sequence is provided in Table 93. IEC 62087-3, Edition 3 anticipates that regulators will define the test sequence required to support their policy approach. While IEC provides a default test sequence, that sequence only supports a limited range of policy options.

Determining the best method for calculating total energy consumption in any scenario will be challenging, given the limited information about which PPSs and standby functions are most used in practice. At present, insufficient data is available to develop an informed duty cycle.

A common concern with light efficiency metrics is that one display can use more power than another at default settings and still be rated as more efficient. This can occur because factory default settings often correspond to different luminance levels and therefore do not constitute a like-for-like basis for comparison. Under a light-efficiency metric, displays are effectively compared at the same luminance. A display that draws more power at its default setting may nonetheless draw less power than another display when both are set to the same luminance across the relevant range (Figure 105).

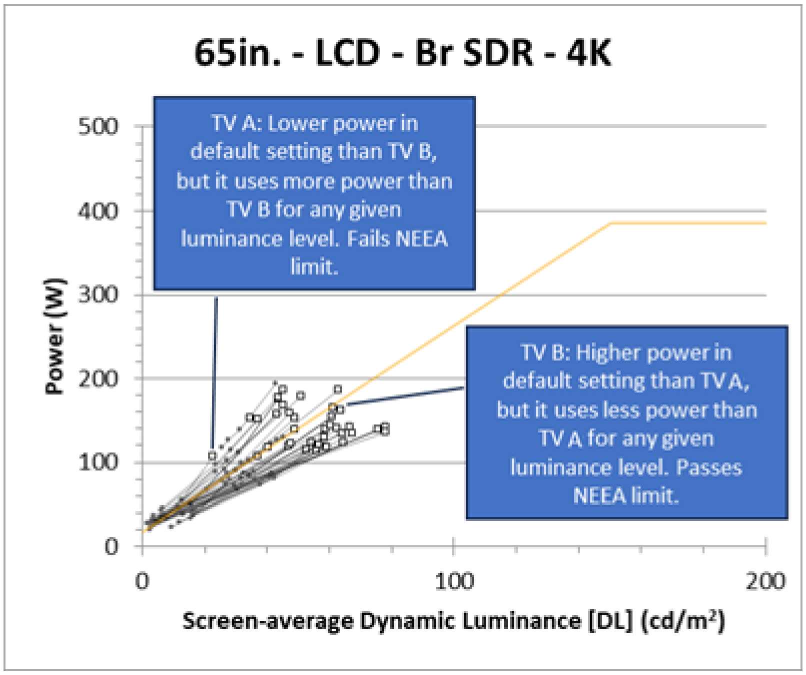

Figure 105: Comparison between different TV dimming lines

Different limit lines can be developed by technology type (e.g., LCDs vs. emissive displays). This approach has advantages and disadvantages:

Pros:

- The y-intercept and slope can be better matched by technology type, which can reduce incentives to raise or lower default LSS levels purely for compliance.

Cons:

- Technology-neutrality is reduced. This could be partly compensated for by setting comparable levels of stringency across technology types (for example, similar expected compliance rates).

Achieving an appropriate balance across market segments is challenging. Basic LCDs are typically the least efficient TV type at common luminance levels, but they are also very low-cost. Adding local power scaling capability could add tens of dollars to the bill of materials (BOM) cost, so broad penetration of local dimming in the budget segment is unlikely in the short to medium term. As a result, limits that apply reasonable pressure to budget displays may apply relatively little pressure to premium displays unless additional design choices are made. Notably, budget laptops have helped drive the development of advanced global dimming techniques that may be adaptable to wall-powered budget displays.

ABC enables TVs to automatically adjust screen brightness in response to ambient light levels, potentially saving energy in dim viewing conditions. However, ABC reduces energy use primarily by lowering the luminance, not by improving underlying display efficiency relative to light efficiency limits. In addition, even with the ABC test method improvements in ANSI/CTA-2037-D and IEC 62087-3, Ed. 2 (including use of an LED light source and a 45-degree angle of incidence), test conditions represent only one possible ambient lighting scenario and cannot capture the spectral and spatial diversity of real-world environments. For these reasons, core energy efficiency tests are recommended to be performed with ABC disabled. By contrast, ANSI/CTA-2037-D requires ABC to be enabled during core tests if enabled by default for the tested PPS.

ABC performance can still be evaluated separately. An adaptation of the current Ecodesign test method could be used by measuring screen-average luminance and power while playing the broadcast test clip in the Default SDR PPS, consistent with the default test sequence in IEC 620897-3, Edition 3. If ABC is verified to reduce power and luminance appropriately in response to ambient light, an incentive equivalent to 10%–15% power reduction could be applied for energy labeling purposes.

ABC illuminance (lux) levels for computer monitors and outdoor displays may differ from the TV-specific lux levels required in IEC 620897-3, Edition 3. Research into ABC for outdoor DSDs is documented in ANNEX I:

ABC POLICY RECOMMENDATIONS FOR Outdoor Displays.

Finally, certain settings and capabilities do not appear to warrant power adders; these are detailed in Table 92. As a reminder, this report distinguishes between a feature being **enabled** (its setting) and it being an inherent **capability** of a display (e.g., its maximum refresh rate capability).

Table 92: Proposed exclusions from energy efficiency policy implementation

Feature	Setting/Capability	Relevant sections
Color gamut [1]	Setting	1.1.1.13.7 COLOR GAMUT SETTING AND CAPABILITY
Viewing angle contrast ratio	Capability	1.1.1.13.9 VIEWING ANGLE CAPABILITY
Viewing angle color gamut	Capability	1.1.1.13.9 VIEWING ANGLE CAPABILITY
AI image processing	Setting	1.1.1.13.10 AI IMAGE PROCESSING SETTING
Supported duty cycle	Capability	1.1.1.15.11 DUTY CYCLE CAPABILITY
Response time	Setting	1.1.1.13.14 RESPONSE TIME SETTING
USB charging	Setting/Capability	1.1.1.13.17 USB CHARGING CAPABILITY AND SETTING
Screen curvature	Setting	1.1.1.13.18 SCREEN CURVATURE CAPABILITY AND SETTING
Support for outdoor use	Capability	1.1.1.15.14 OUTDOOR USE CAPABILITY
KVM switch	Setting/Capability	1.1.1.13.19 KVM SWITCH SETTING
Operating system	Setting/capability	1.1.1.15.13 OPERATING SYSTEM CAPABILITY AND SETTING

[1] If separate from a PPS setting

More details on the impact of each item on energy efficiency is available in Table 17 in section RESEARCH METHODOLOGY AND FINDINGS.

1.1.1.42.3 MEPS and Label Summary Table

Table 93 below summarizes the recommended test sequence and associated MEPS and energy label requirements. We organized to include test sequence next to metrics and limits because IEC 62087-3, Edition 3 is structured to standardize individual test procedures, not the sequence in which they are used, which is fundamentally left to policymakers.

Section TEST METHOD focuses on these procedures, and this section addresses metrics, limits, and test sequence.

Table 93: Summary of test sequence requirements and MEPS and energy label requirements

Mode	Test Procedure	Preset Picture Setting [6]	Test Clip	ABC	ABC Lux	Light Source Setting	Measure	MEPS [10]	Label [9]
Active	Broadcast	Default SDR PPS	IEC SDR Broadcast Test Clip	Off		Maximum [11]	Power and Screen-average Luminance		
						Default [1]		≤ SDR Limit 1 + Adders	Scaled Limit 1, Adders, Limit 2 Power Caps and ABC credit
						Minimum [11]			
		Other SDR PPSs [6]				Default		≤ SDR Limit 1 + Adders	Scaled Limit 1, Adders, Limit 2 Power Caps and ABC credit
		Default HDR PPS [2]	IEC HDR10 Broadcast Test Clip			Maximum [11]			
						Default [1]		≤ HDR Limit 1 + Adders	Scaled Limit 1, Adders, Limit 2 Power Caps and ABC credit
						Minimum [11]			
		Other HDR PPSs				Default		≤ HDR Limit 1 + Adders	Scaled Limit 1, Adders, Limit 2 Power Caps and ABC credit
		Default SDR PPS [3]	IEC SDR Broadcast Test Clip	On	141	Default			ABC credit is 10% for units that meet section 1.1.1.40 ABC ELIGIBILITY CRITERIA
					85				
					49				
					17				

Mode	Test Procedure	Preset Picture Setting [6]	Test Clip	ABC	ABC Lux	Light Source Setting	Measure	MEPS [10]	Label [9]
	Contrast Ratio	SDR Normal PPS	IEC 62977-2-1 Window Pattern	Off		Default	Screen-center luminance	Determines contrast ratio adder eligibility for computer monitor PPSs; used for information reporting in other display types	
		Other SDR PPSs							
	Color Gamut [11]	Default SDR PPS	IEC 62977-2-1 Window Pattern	Off		Default	Screen-center chromaticity	For information reporting only	
Non-Active	D3cold [7]						Power	≤ 0.5 W	
	D3hot [7]							≤ 0.5 W	
	Standby [8]							≤ 0.5 W	
	Networked standby [8]							≤ 1 W	
	Smart standby [4] [8]							≤ 1 W	
	Hands-free wake [5] [8]							≤ 6 W	

[1] If the default setting is within 10% of Maximum (e.g., the default light source setting is 91 out of 100), or if the setting is not represented as a numeric value, then add a test with light source set to midpoint between Maximum and Minimum.

[2] If HDR10 is not supported, then HDR tests shall not be performed.

[3] These four tests characterize SDR ABC performance for TVs that support ABC function.

[4] In this test, enable as many Smart Standby sub-functions as possible: reactivation, networked reactivation, wake-by-remote-control-app, wake-on-cast, wake-by-smart-speaker, and Bluetooth speaker link maintenance.

[5] In this test, enable as many hands-free wake sub-functions as possible: voice activation, gesture recognition, presence detection, mobile-device proximity.

[6] For any test sequence instructions, unless the word "Retail" is included in the PPS title (e.g., Retail Default SDR PPS), it shall be assumed that PPSs listed in any test sequence instructions are not associated with Retail configuration.

[7] For computer monitors only.

[8] For TVs and DSDs where supported.

[9] Label limits are discussed in section Energy Label. Each limit is graded individually. The overall score is the lowest of individual grades.

[10] All MEPS limits must be met individually (i.e., no averaging across PPSs) .

[11] This data point is collected for future limit development and is not proposed for current use for MEPS or labeling.

Test Method

This section proposes test procedures for evaluating the energy performance of computer monitors, DSDs, and televisions which is based on the test methods described in IEC 62087-3, Edition 3 (currently in committee draft) and IEC 62977-2, which is a normative reference in IEC 62087-3, Edition 3. Table 94 summarizes the test procedures included in PCL's example policy approach.

This table does not describe a test sequence (described in the previous section), but rather the fundamental methods used for testing each equipment under test (EUT).

Table 94: Summary of proposed tests

Test	Method	Product Classes
Active Mode		
Power and Luminance Testing	Measures power and screen-average luminance while playing a broadcast content test clip to assess the relationship between power and luminance across at least three light source settings, according to the method outlined in IEC 62087-3, Edition 3.	All
Color Gamut	Measures the EUT's color gamut in each tested PPS per the method outlined in IEC 62977-2.	All
Contrast Ratio	Measures the EUT's contrast ratio in each tested PPS per the method outlined in IEC 62977-2.	All
Non-Active Mode		
D3coldD3cold	Measures power after powering down the EUT to Standby from Active Mode using the power button or remote control, without LAN or WAN connection per IEC 62301, Edition 3.	Computer monitors
D3hotD3hot	Measures power after powering down the EUT to Standby from Active Mode by putting the connected PC to sleep, without LAN or WAN connection per IEC 62301, Edition 3.	Computer monitors
Standby	Measures power after powering down the EUT to Standby from Active Mode, without LAN or WAN connection per IEC 62301, Edition 3.	TVs DSDs
Networked Standby	Measures power after powering down the EUT to Standby from Active Mode, with LAN and WAN connections and a network reactivation function enabled per IEC 63474, Edition 2 (except WAN shall be connected).	Where applicable (typically not applicable to computer monitors)

Test	Method	Product Classes
Non-Active Mode (cont'd)		
Smart Standby	Measures power after powering down the EUT to Standby from Active Mode, with LAN or WAN connection and the following functions enabled where available: - Wake-on-Cast (e.g., Chromecast, Apple AirPlay) - Wake-by-Smart-Speaker (e.g., Amazon Alexa, Google Assistant) - Wake-by-Remote-Control-App - Bluetooth link persistence	Where applicable (typically limited to smart TVs)
Standby with Hands-free Wake	This test is only required if one or more hands-free wake functions listed below are supported by the EUT: - Voice activation - Gesture recognition - Presence detection - Mobile-device proximity Smart Standby functions shall be disabled. The EUT shall be configured to enable as many hands-free wake functions as possible to persist unless otherwise specified by the entity ordering the test. Hands-free wake triggers (e.g., presence or voice commands) shall be avoided during the duration of the test.	Where applicable (typically limited to smart TVs)

Test Set-up

PCL recommends that Equipment Under Test (EUT) be configured following the initial setup recommended by IEC 62087-3, Edition 3 committee draft. Unless otherwise required by the test procedure, the EUT should be kept in its default configuration during testing, while considering the following additional requirements:

- **Account sign-in:** If the EUT offers the option to log into an account to set it up, sign-in should not be completed unless it is necessary to perform certain tests.
- **Accessibility:** If an accessibility menu appears during set-up, accessibility features such as enhanced contrast and text-to-speech should remain disabled unless they are enabled by default.
- **Features that base product performance on past usage behavior:** These should be disabled unless they are enabled by default.
- **Other Considerations:**

  - If a feature setting is pre-selected (e.g., the option is highlighted), then the pre-selection should be accepted.
  - If multiple configuration choices are presented with no clearly indicated default/ pre-selection, the choice that provides the greatest functionality should be selected. If functionality cannot be reliably determined, a single consistent selection rule should be applied and documented (for example, selecting the option closest to the upper left corner of the screen).
  - If touchscreen capability is available and is marketed as a primary function of the display, touchscreen shall be enabled through standard user settings (even if this needs additional configuration or is disabled by default)
  - All configuration choices shall be documented.

The test distances defined in Table 95 below are recommended because they are a reasonable approximation of real-world viewing distances.[44]

Table 95: Distances used for testing

Display Type	Test Distance
Television	1.77 x width
Digital signage display	1.77 x width
Computer monitor	1.28 x width

For televisions and DSDs, the test distance matches that specified in the IEC TV test method: 62087-3, Edition 3. For computer monitors, shorter test distances are used to reflect typical desktop viewing. Policymakers may consider requiring that the shorter test distance be used for displays other than computer monitors if they are primarily intended for touchscreen interaction, as it more accurately reflects typical usage scenarios where viewers must be close enough to operate the screen by touch (e.g., checkout kiosks).

The environmental conditions specified in IEC 62087-3, Edition 3 should be confirmed prior to testing.

Active Mode

1.1.1.43 Basic Active Mode Test Configuration

Before Active Mode testing, the following camera procedures should be completed, per IEC 62087-3, Edition 3.

- **Dark Current Compensation:** The camera sensor's baseline signal (typically caused by thermal noise) should be measured by taking a sensor-average reading with the lens cap on and

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[44] A justification for the test distances can be found in the Close-Range Testing section of Annex D: Modifying the PCL Camera System. A more in-depth analysis of the 1.28 x width test distance for computer monitors is available in Annex E: Justifying a Measurement Distance for Computer Monitors.

subtracting it from all subsequent readings to ensure that reported values only captured actual luminance.

- **Screen Configuration:** The active screen area should be detected and a geometry correction applied to it, as described in ANNEX D: MODIFYING THE PCL CAMERA SYSTEM, to align the camera's measurement region with the display's active area.
- **Color Correction Factor (CCF):** A CCF calibration should be performed once for each EUT using the procedure detailed in this document. This step generates specific luminance correction coefficients for each display to account for differences in spectral power distribution (i.e., the mix of wavelengths emitted by the display).

1.1.1.44 Power and Luminance Testing

As noted above, it is assumed that a camera-based test method is used that simultaneously measures screen-average luminance and power, with both values averaged over the duration of an SDR or HDR broadcast test clip aligned with the relevant sections of the forthcoming IEC 62087-3 Edition 3 standard.

1.1.1.45 Resolution

Screen resolution should be confirmed by interrogating the display using software (either supplied with the electronic display, or through external tools). The vertical and horizontal resolution and the total pixel count (vertical resolution times horizontal resolution) should be recorded.

A range of native (included in the display) and external software tools can be used to obtain resolution data. Many require the display to be connected via an HDMI port. Examples include:

- Windows display settings
- EDID (Extended Display Identification Data) viewer tools (Windows and other operating systems), such as ViewSonic EDID Viewer, NVIDIA Control Panel, and MonitorInfoView (NirSoft)

1.1.1.46 Color Gamut

Color gamut should be tested in the Default SDR PPS using the measurement method described in section COLOR GAMUT, which is based on the procedure in IEC 62977-2-1. The *u′* and *v′* chromaticity coordinates for red, green, and blue should be measured and then converted into a percentage of the CIELUV color space to express the display's color gamut coverage.

Reporting requirements should include the CIELUV percentage value to inform the development of future policy.

1.1.1.47 Contrast Ratio

Contrast ratio should be measured for each PPS tested using a measurement method based on IEC 62977-2-1, as described in section 4.2.2.1.8: CONTRAST RATIO CAPABILITY

Contrast ratio results can vary significantly depending on the sensitivity of the measurement instrument, particularly at the lowest luminance ranges. An instrument with a luminance measurement range that begins at 0.001 cd/m^2 or lower is recommended (for example, the Konica Minolta LS-100).

Non-Active Mode

For Non-Active Mode testing across all display types, **Standby Mode** power should be measured in line with the definition in the IEC 62087-3 Edition 3 committee draft. The dataset indicates that Standby Mode power demand can exceed 9 W in modern computer monitors even if no additional functions (i.e., other than reactivation) are enabled. This suggests that standby mode should be explicitly covered in energy efficiency policy. Where standby requirements already exist, stronger data vetting and check-testing are recommended, as discrepancies were observed between PCL's test results and the values reported in the CEC MAEDbS.

1.1.1.48 DSDs and Televisions

DSDs and televisions should be tested in one of the following three **Standby Mode** subtypes. The subtype offering the greatest available functionality should be selected, using the hierarchy below (from least to most functionality):

- **Standby** (no internet connection)
- **Networked Standby**
- **Smart Standby**

Whenever available, a separate Standby test should be performed for **Standby with Hands-free Wake** (e.g., voice-activated or motion-triggered wake). In this test, the EUT should be configured with hands-free wake enabled and with other Smart Standby features disabled.

Laboratory measurements indicate that best-in-class televisions with hands-free wake functionality consume approximately 5 W. Separating this test category supports tighter limits for other Non-Active Modes, while still accommodating the higher energy demands of hands-free wake.

1.1.1.49 Computer Monitors

To better reflect real-world computer monitor operation, **D3hot and D3cold power states** should be measured as monitor-specific subsets of **Standby Mode.** These Advanced Configuration and Power Interface (ACPI)-defined states are more representative of how monitors are managed in modern computing environments. Tested should be conducted as follows:

- **D3hot:** Test by connecting the monitor to a host device that will send its peripherals to a D3hot power state when the host device (usually a computer) enters a sleep mode (as defined by ACPI).[45] This behavior can be verified using the host device's operating system documentation (for example, Windows' Device Power State documentation).
- **D3cold:** Test by turning off the monitor using its built-in off switch, or a remote control if available.

Whenever supported, monitors should also be tested in the Standby subtypes mentioned in the previous section, using D3hot as the starting point. For example, if the monitor supports Smart Standby features,

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[45] A sleep mode would usually be between S1–S3 per ACPI. However, as Modern Standby (S0 Low Power Idle) is becoming the standard in Windows operating systems, this report recommends its use for testing whenever available.

those features should be enabled when the monitor is in the D3hot power state, and the corresponding Standby test should be performed.

Power Measurements for Battery-Operated Displays

For battery-operated displays that offer no mains connection (can only operate on battery), power should be measured using the method detailed in Section 1.2.7 of the Ecodesign regulation. In summary, the battery is fully charged, and the display is disconnected from the external power source. After the fully charged state is verified, the display is placed in the required measurement mode, and screen-average luminance is measured while playing the dynamic test clip.

After the test clip finishes, the display is turned off and power is measured during a complete charging cycle. The average power input, measured from the beginning of this charging cycle to the point at which the battery is once more fully charged, is used to calculate the power value to be reported.

Testing Recommendations for Video Wall LCD Tiles or DVLED Cabinets

PCL recommends the following when testing LCD tiles or DVLED cabinets:

- If a single LCD video wall tile or DVLED cabinet cannot display the dynamic broadcast test clip, the video wall system shall be assembled in the minimum configuration capable of displaying the clip. The final configuration (e.g., 2 × 4, 2 × 3) shall be documented, along with the total power draw of the assembled configuration (excluding the video wall controller) and the calculated power draw per display unit. Per-unit power may be determined by measuring the total power of the assembled configuration and dividing by the number of tiles or cabinets.
- If an LCD video wall tile or DVLED cabinet cannot operate without a video wall controller or control box, then the unit shall be tested with a compatible controller. The controller’s power consumption shall be measured and reported separately from the display unit under test.
- If an LCD tile or DVLED cabinet cannot be tested using the Standby test methods for TVs or DSDs (see section 1.1.1.48: DSDS AND TELEVISIONS), Standby power shall be determined by dimming the display to zero, or minimum achievable light output with no active network connection. Networked Standby power shall be determined using the same display state, but with the network connection enabled where applicable. Typically, networked standby would not apply to a DVLED cabinet since the network function is provided by the controller, not the individual cabinets.

We acknowledge that assessing the energy efficiency of video wall control boxes is outside the scope of this research; however, initial reporting of their Active Mode power consumption may help inform policymakers about potential future energy savings opportunities.

Feature Reporting

In addition to the reporting requirements detailed in IEC 62087-3, Edition 3 committee draft Annex B, the following features should be reported:

- **For all display types:**

  - Screen curvature (expressed in radius)
  - Touchscreen
    - Capability
    - Default status (enabled/disabled by default)
    - Technology type (e.g., capacitive, infrared)
- For computer monitors:
  - Native refresh rate (Hz)
  - Maximum refresh rate capability (Hz)
  - Support for Variable Refresh Rate (VRR)
- For modular configuration testing:
  - How the individual tiles or cabinets are linked and how media is delivered (e.g., video wall management software, DisplayPort daisy chaining, video wall controller)

This additional information supports the application of the feature-based power adders outlined in section 1.1.1.41.2: ADDERS.

Glossary

A

ABC (Automatic Brightness Control): A display feature that automatically adjusts screen brightness based on ambient light levels detected by an integrated sensor. ABC can reduce power consumption by dimming the display in darker environments.

ABL (Automatic Brightness Limiting): A feature that reduces peak brightness to prevent overheating or excessive power draw, particularly in displays showing high-luminance content over extended periods.

ACPI (Advanced Configuration and Power Interface): An industry specification for power management in computing devices. Defines power states including D3hot (sleep/connected standby) and D3cold (off via device controls).

Active Mode: The operational state in which a display is powered on and actively rendering visual content.

ADS (Advanced Super Dimension Switch): A BOE-developed IPS-variant LCD panel technology offering competitive color reproduction and wide viewing angles at optimized cost.

AEC (Annual Energy Consumption): The total energy consumed by a display over a one-year period, typically calculated using assumed duty cycles for Active and Non-Active Modes.

B

Backlight: The light source behind an LCD panel that provides illumination. May be edge-lit (LEDs along the perimeter) or direct-lit (LEDs behind the entire panel).

BOM (Bill of Materials): The complete list of components required to manufacture a product, used to estimate manufacturing costs.

C

Cabinet: In DVLED systems, a modular assembly containing LED modules, receiving cards, power supplies, and structural housing that can be combined to create larger displays.

CCT (Correlated Color Temperature): A measure of light source color appearance, expressed in Kelvin (K). Higher values indicate cooler (bluer) light; lower values indicate warmer (yellower) light.

CEC (California Energy Commission): The state agency responsible for California's energy policy, including appliance efficiency standards under Title 20.

CIE (Commission Internationale de l'Éclairage): The International Commission on Illumination, the international authority on light, illumination, color, and color spaces.

CIELUV: A perceptually uniform color space defined by CIE, commonly used to express color gamut coverage as a percentage.

Color Gamut: The range of colors a display can reproduce, typically expressed as a percentage of a reference color space (e.g., sRGB, DCI-P3, Adobe RGB).

Contrast Ratio: The ratio between the brightest white and darkest black a display can produce, expressed as X:1. Higher ratios indicate better image depth and detail.

D

D3cold: An ACPI power state in which a display is in a deep off-like state, typically entered when the host device is shut down or the display is manually powered off.

D3hot: An ACPI power state in which a display is in a sleep-like state, typically entered when the host device enters sleep mode while maintaining the ability to reactivate quickly.

DCI-P3: A wide color gamut standard originally developed for digital cinema projection, now commonly used as a reference for HDR displays.

Dimming Line: A graphical representation showing the relationship between a display's power consumption and screen-average luminance across different light source settings.

Dimming Zone: A discrete area of a display's backlight that can be independently controlled to adjust brightness based on content.

Direct-Lit Backlight: An LCD backlight configuration where LEDs are positioned in an array directly behind the entire display panel, enabling more uniform lighting and potentially local dimming.

DL (Dynamic Luminance): Screen-average luminance measured throughout playback of a standardized broadcast test clip.

DOOH (Digital Out-of-Home): Digital advertising displays located in public spaces such as billboards, transit stations, and shopping centers.

DSD (Digital Signage Display): Commercial displays designed for public information, advertising, or wayfinding applications, typically featuring higher brightness, longer duty cycle ratings, and commercial-grade durability.

DVLED (Direct View LED): An emissive display technology using individual LED pixels (not backlit LCD), capable of very high brightness and scalable to large sizes through modular assembly.

Duty Cycle: The operational time pattern for which a display is rated, typically expressed as hours per day and days per week (e.g., 16/7, 24/7).

E

Ecodesign: The European Union's regulatory framework establishing minimum energy efficiency requirements for energy-related products.

Edge-Lit Backlight: An LCD backlight configuration where LEDs are positioned along the edges of the display, with a light guide plate distributing illumination across the panel.

EEI (Energy Efficiency Index): A metric used in EU Ecodesign regulations to compare a display's measured power consumption against a reference value based on screen area and resolution.

EMI shielding: the practice of reducing or blocking electromagnetic fields (EMF) and radio frequency interference (RFI) using conductive or magnetic barriers.

Emissive Display: A display technology in which each pixel generates its own light (e.g., OLED, DVLED), as opposed to modulating light from a separate backlight.

ENERGY STAR: A voluntary U.S. Environmental Protection Agency program that certifies energy-efficient products meeting specified performance criteria.

ePaper (Electronic Paper): A reflective display technology that mimics printed paper, consuming power only when the image changes. Suitable for static content but not video.

EPD (Enhanced Performance Display): A designation in ENERGY STAR and CEC policies for displays meeting specified color gamut and contrast ratio performance thresholds, qualifying for power adders.

Equipment Under Test (EUT): an electronic assembly undergoing testing, either at first manufacture or later during its life cycle as part of ongoing functional testing and calibration checks.

EU Energy Label: A mandatory label on products sold in the European Union indicating energy efficiency class (A through G) and annual energy consumption.

F

FALD (Full Array Local Dimming): An LCD backlight technology with LEDs arranged across the entire panel area, divided into independently controllable zones for improved contrast and efficiency.

FHD (Full High Definition): A display resolution of 1920 × 1080 pixels.

FRC (Frame Rate Control): A technique that simulates higher color bit depth by rapidly alternating between adjacent color values, creating the perception of intermediate shades.

FSC (Field Sequential Color): An LCD technology using sequential red, green, and blue LED illumination instead of color filters, potentially offering improved energy efficiency.

G

Gamma: A value describing the nonlinear relationship between input signal values and displayed luminance. Higher gamma values (e.g., 2.4) produce darker midtones suitable for dim viewing environments; lower values (e.g., 2.0) produce brighter midtones for bright environments.

GF (Grading Factor): A multiplier applied to efficiency limit calculations to establish different energy label grades (A through G).

Global Dimming: A dynamic backlight control technique that adjusts the entire backlight as a single zone based on overall image brightness.

G-SYNC: NVIDIA's proprietary variable refresh rate technology requiring dedicated hardware in the display.

H

HDR (High Dynamic Range): Content and display technology supporting an expanded range of brightness levels and colors compared to standard dynamic range (SDR), enabling brighter highlights and deeper blacks.

HDR10: An open HDR standard using static metadata, 10-bit color depth, and the Rec. 2020 color space.

H-K Effect (Helmholtz-Kohlrausch Effect): A perceptual phenomenon where more saturated colors appear brighter than less saturated colors of equal measured luminance.

I

IEC (International Electrotechnical Commission): An international standards organization for electrical and electronic technologies, responsible for display test method standards including IEC 62087.

IPS (In-Plane Switching): An LCD panel technology offering excellent color accuracy and wide viewing angles, widely used in professional and general-purpose monitors.

K

KVM (Keyboard, Video, Mouse) Switch: A device or integrated function allowing a single keyboard, video display, and mouse to control multiple computers or source devices.

L

LCD (Liquid Crystal Display): A display technology using liquid crystals to modulate light from a backlight, with color filters creating red, green, and blue subpixels.

LED (Light-Emitting Diode): A semiconductor device that emits light when current flows through it. Used in display backlights and as the pixel elements in DVLED displays.

Light Source Setting (LSS): The user-adjustable control that determines the overall brightness of a display's light source (backlight for LCDs, pixel drive level for emissive displays).

Local Dimming: A backlight control technique dividing the backlight into multiple independently controllable zones, enabling different areas of the screen to operate at different brightness levels based on content.

Luminance: The intensity of light emitted from a surface, measured in candelas per square meter (cd/m^2) or nits.

LUT (lookup table): a color grading and mapping tool that transforms RGB colors. Can be either 3D or 1D.

M

MAEDbS (Modernized Appliance Efficiency Database System): California Energy Commission's database of certified appliance models meeting Title 20 efficiency standards.

MEPS (Minimum Energy Performance Standards): Mandatory regulatory requirements establishing the minimum energy efficiency levels that products must meet to be sold in a market.

Micro-LED: An advanced emissive display technology using microscopic inorganic LEDs as individual pixel elements, offering high brightness, contrast, and longevity.

Mini-LED: An LCD backlight technology using very small LEDs (typically <300 µm) enabling high-density local dimming with hundreds to thousands of zones.

N

NEEA (Northwest Energy Efficiency Alliance): A nonprofit organization working to accelerate energy efficiency in the Pacific Northwest United States.

Non-Active Mode: Power states in which a display is not actively rendering content but remains connected to power, including standby, sleep, and networked standby modes.

O

OLED (Organic Light-Emitting Diode): An emissive display technology using organic compounds that emit light at the pixel level, enabling perfect blacks, wide viewing angles, and fast response times.

OPS (Open Pluggable Specification): A standardized slot in commercial displays allowing installation of dedicated computing modules for content playback and management.

P

PCAP (Projected Capacitive): A touchscreen technology using a grid of conductive elements to detect touch location, typically reducing display luminance by approximately 20%.

PCL (Pacific Crest Labs): A US-based consulting firm specializing in display energy efficiency research and policy development.

Pixel Density: The number of pixels per unit area, typically expressed as pixels per square inch (pixels/in^2) or pixels per square centimeter (pixels/cm^2).

Pixel Pitch: The distance between the centers of adjacent pixels, typically expressed in millimeters. Smaller pitch indicates higher resolution.

PLS (Plane-to-Line Switching): A Samsung-developed IPS-variant LCD panel technology offering comparable viewing angles and color performance with improved brightness and efficiency.

Power/ Reference: A metric expressing a display's measured power consumption as a percentage of its calculated power reference line, used to compare relative efficiency across different display sizes and resolutions.

PPS (Preset Picture Setting): A predefined combination of picture quality parameters (brightness, contrast, color settings, etc.) that users can select, such as "Standard," "Movie," "Vivid," or "Game."

PR (Pixel Resolution): The total number of physical pixels across a display screen, calculated as horizontal pixels × vertical pixels.

Q

QD-OLED (Quantum Dot OLED): A display technology combining OLED's self-emissive properties with quantum dot color conversion for improved color gamut and brightness.

QHD (Quad High Definition): A display resolution of 2560 × 1440 pixels.

Quantum Dot: Nanoscale semiconductor particles that emit specific colors of light when illuminated, used to enhance color gamut in LCD and OLED displays.

R

Rec. 709 (ITU-R BT.709): The standard color space for high-definition television, covering approximately 35.9% of the CIE 1931 color space.

Rec. 2020 (ITU-R BT.2020): A wide color gamut standard for ultra-high-definition television, covering approximately 75.8% of the CIE 1931 color space.

Refresh Rate: The number of times per second a display updates its image, measured in hertz (Hz). Higher rates provide smoother motion rendering.

Response Time: The time required for a pixel to transition between states, typically measured in milliseconds. Faster response times reduce motion blur.

S

Screen Area (A): The viewable display surface, typically expressed in square inches (in^2) or square decimeters (dm^2).

SDR (Standard Dynamic Range): Conventional video content and display technology with a limited brightness and contrast range compared to HDR.

SF (Scaling Factor): A multiplier applied to efficiency limit calculations to adjust overall stringency and achieve desired pass rates.

Signal-to-Light Mapping: The relationship between input video signal values and the corresponding light output produced by a display, influenced by gamma curves and picture processing.

sRGB: A standard color space for consumer displays and the internet, covering approximately 35.9% of the CIE 1931 color space.

T

TCON (Timing Controller): The circuit board in a display that manages timing and control signals for the panel, including coordination of local dimming zones.

TEC (Total Energy Consumption): See AEC (Annual Energy Consumption).

TFT (Thin-Film Transistor): The transistor technology used in active-matrix LCD panels to control individual pixels.

Title 20: California's appliance efficiency regulations administered by the California Energy Commission (CEC).

TN (Twisted Nematic): The oldest and typically most affordable LCD panel technology, known for fast response times but limited viewing angles.

T-OLED (Transparent OLED): An OLED display technology using transparent substrates and electrodes, allowing visibility through the panel when inactive.

U

UEC (Unit Energy Consumption): The calculated annual energy consumption of an individual display unit based on measured power levels and assumed duty cycles.

UNB (Ultra Narrow Bezel): LCD video wall panels with bezels less than 5 mm wide.

UST (Ultra short throw): a specialized projector designed to sit just inches away from a wall or screen, yet produce a large, high-definition image

V

VA (Vertical Alignment): An LCD panel technology offering high contrast ratios and good viewing angles, but typically slower response times than TN or IPS.

VESA (Video Electronics Standards Association): An industry organization developing display interface and performance standards.

Video Wall: A large display created by combining multiple display panels or modules, including tiled LCD, DVLED cabinet, and rear-projection configurations.

VRR (Variable Refresh Rate): A display technology that dynamically adjusts refresh rate to match content frame rate, reducing screen tearing and stuttering. Implementations include AMD FreeSync and NVIDIA G-SYNC.

X

XNB (Extreme Narrow Bezel): LCD video wall panels with bezels less than 3 mm wide.

Y

Y-intercept: In dimming line analysis, the power level at which the dimming line crosses the vertical axis (zero luminance), representing the baseline power consumption of display electronics independent of light output.

UNITS OF MEASUREMENT

cd/m² (candela per square meter): The SI unit of luminance, also called a "nit."

dm² (square decimeter): A metric unit of area equal to 0.01 square meters or approximately 15.5 square inches.

Hz (hertz): The unit of frequency, representing cycles per second. Used to express display refresh rates.

in² (square inch): An imperial unit of area.

kWh (kilowatt-hour): A unit of energy equal to one kilowatt of power sustained for one hour.

lux (lx): The SI unit of illuminance, measuring incident light on a surface. One lux equals one lumen per square meter.

TWh (terawatt-hour): A unit of energy equal to one trillion watt-hours, used to express large-scale energy consumption.

W (watt): The SI unit of power, representing one joule of energy per second.

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Annex A: Methodology

Laboratory Testing

This section describes the core measurement procedures used throughout PCL's laboratory testing. Details on any additional tests performed on select display models (for example, refresh rate comparisons) are provided in sections 0: COMPUTER MONITOR FINDINGS AND DISCUSSION and 0: DIGITAL SIGNAGE DISPLAYS FINDINGS AND Discussion.

Unless otherwise noted, testing procedures generally followed the requirements outlined in the IEC 62087 series, including specifications for test equipment.[46] In addition, elements of the US federal test method were incorporated, which is based on ANSI/CTA-2037-D. For each test, its subsection indicates which methodology was followed or adapted.

The following test equipment for all testing was used, which complies with the requirements in IEC 62087-1 Edition 2 committee draft unless otherwise noted:

- **PCL Gen 3 camera photometer:** to measure screen-average luminance and screen-center (also known as peak) luminance.
- **SpectraScan PR-655 and PR-650 spectroradiometers:** to measure screen-center luminance for contrast ratio tests, to determine chromaticity coordinates for color gamut tests, and to obtain color correction factor coefficients for each display.
- **Konica Minolta LS-100 luminance meter:** to measure screen-center luminance for contrast ratio tests.[47]
- **Yokogawa WT210 power meter:** to measure power levels.
- **Chroma 61602 AC source:** to provide stable power to the unit under test at 115 V/60 Hz during testing.

Table 96 shows the test clips used in testing, along with which policies (if any) reference them.

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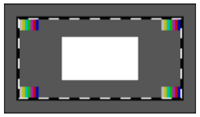
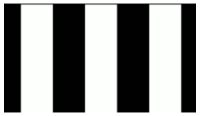
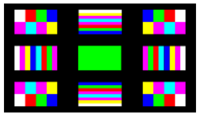
[46] This refers to the IEC 62087 series currently in development, which has an expected release of 2026 for Edition 2 of part 1, and Edition 3 of parts 2 and 3.

[47] The PR-655 was used to perform all contrast ratio tests in computer monitors. The PR-655 was unavailable during PCL's DSD testing, the PR-650 was used for white screen measurements and the LS-100 for black screen measurements as the PR-650 did not have enough sensitivity at low light levels to measure black screens.
The LS-100 does not meet the requirements of the IEC 62087-1 Edition 2 committee draft.

Table 96: Overview of test clips used in testing

Test Clip	Clip Name	Policies	Usage	File Name	File Location
	L10-L80 box-and-outline patterns	Ecodesign EU Energy Label	Screen-center luminance	IEC_L20PeakLumMotion_HD_5994p_SDR_HEVC_AAC_v1-0.MP4	Available on Google Drive
	VESA FPDM2 L80	ENERGY STAR Displays 8.0 CEC Title 20	Screen-center luminance	L80_1920x1080.PNG	Available at PCL's Google Drive
	IEC three-bar video signal	ENERGY STAR Displays 8.0 CEC Title 20	Screen-center luminance	IEC_ThreeBar_HD_5994p_SDR_HEVC_AAC.MP4	Available at IEC's TC 100
	IEC SDR 10-minute test clip	Ecodesign EU Energy Label ENERGY STAR Displays 8.0 CEC Title 20 US Federal test method	Screen-average luminance and power (US Federal test method) Power (all other policies)	IEC_Broadcast_HD_5994_SDR_HEVC_AAC.MP4	Available at IEC's TC 100
	IEC HDR10 5-minute broadcast test clip	Ecodesign EU Energy Label US Federal test method	Screen-average luminance and power (US Federal test method) Power (Ecodesign, EU Energy Label)	IEC_Broadcast_HD_5994p_HDR10_HEVC_AAC_v1-0.MP4	Available at IEC's TC 100
	New IEC SDR 5-minute broadcast test clip	-	Screen-average luminance and power	IEC_Broadcast_HD_5994p_SDR_HEVC_AAC_v2-0.MP4	Draft version available at PCL's Google Drive

Test Clip	Clip Name	Policies	Usage	File Name	File Location
	Gray pattern	-	Screen uniformity testing	Lum.mp4	Available at PCL's Google Drive
	CCF pattern	-	Color correction factor measurements	CCF_v6_HD_5sec.mp4	Available at PCL's Google Drive
	IEC 62977-2-1 window pattern	-	Color gamut, contrast ratio, and viewing angle testing	IEC Contrast Ratio and Color Gamut Clip 27Sep2024.MP4	Version created by PCL based on IEC 62977 available at PCL's Google Drive

Active Mode

Sample Configuration

Each EUT was configured according to the setup procedure described in ANSI/CTA-2037-D section 9, which includes connecting the EUT to the internet (if supported) and enabling any available Smart Standby features. Per ANSI/CTA-2037-D, these features remain enabled during both Active Mode and Non-Active Mode testing.

Internet connectivity and Smart Standby features were generally not applicable to most of the displays in PCL's sample plan. Only two computer monitors (the LG 42 OLED Flex and the Samsung Smart Monitor M8) included operating systems that supported internet connectivity, and only the LG model supported a form of Smart Standby (via Apple AirPlay). While the DSDs more commonly supported internet connections, none of them featured the Smart Standby functionalities defined in ANSI/CTA-2037-D as these are more common in consumer use cases. DSDs are more commonly designed with wake-on-signal (which wakes the display when a source is connected, generally for use cases like a conference room) and sometimes wake-on-LAN.

Basic Active Mode Test Configuration

Before conducting each Active Mode test, the following procedures were completed to prepare the camera photometer for accurate luminance measurement:

- **Dark Current Compensation:** Measures the sensor's baseline signal (typically caused by thermal noise) by taking a sensor-average reading with the lens cap on and subtracts it from all subsequent readings to ensure only actual luminance is captured.
- **Screen Configuration:** Detects the screen area and applies geometry correction, as described in ANNEX D: MODIFYING THE PCL CAMERA SYSTEM, to align the camera's measurement region with the display's active area.
- **Color Correction Factor (CCF):** A CCF calibration was performed once per EUT using the procedure detailed in this document. This step generates custom luminance correction coefficients for each display to account for differences in spectral power distribution.

Power and Luminance Testing

To evaluate and compare the proposed testing methodology with that of existing policy approaches, two primary types of tests were conducted: screen-average dynamic broadcast clip testing using a camera photometer (which includes luminance and power measurements) and screen-center luminance testing (without power measurements). Screen-center luminance-based policies measure screen-center luminance with a test pattern and measure power separately with a broadcast test clip.

Dynamic Broadcast Clip

To test dynamic broadcast clip power and screen-average luminance in SDR, the new IEC SDR broadcast clip specified on the IEC 62087-2 Edition 3 committee draft was used (developed by PCL based on the existing IEC 62087-2, Edition 2 HDR10 test clip). HDR testing was conducted using this IEC 62087-2 Edition 2 HDR10 broadcast clip.

While broadcast content may be less representative for computer monitors and DSDs, it is the most appropriate standardized content currently available. This research does not attempt to characterize representative test content for computer monitors and DSDs.

When Automatic Brightness Control (ABC) was off by default, testing was conducted with this feature off. When it was on by default, testing was conducted with it on (at different lux levels) and off (at the default light source setting for ABC off).

When testing with ABC off, measurements at the following light source settings were taken:

- Default
- Maximum
- Minimum

If the Default light source setting was the same as the Maximum light source setting offered by the display (i.e., if the light source went from 0-100 and Default was 100), the Midpoint ("Mid" light source setting) between the Maximum (Default) and Minimum levels was also tested.

When testing with ABC on, measurements were taken at the lux levels specified in the IEC 62087-3 Edition 3 committee draft, with the ABC lamp placed at a 45-degree angle from the ABC sensor. The lux levels used are highlighted in orange on Table 97.

Table 97: Lux level requirements per IEC 62087-3 Edition 3 committee draft

Allowed Lamp Angle +/- 2 degrees	Required Illuminance Meter Angle +/- 2 degrees	Required Lux Levels per Lamp Angle ± 5%			
-30	30	115	69	40	14
-35	35	122	73	43	15
-40	40	131	78	46	16
-45	**45**	**141**	**85**	**49**	**17**
-50	50	156	93	54	19
-55	55	174	105	61	21
-60	60	200	120	70	24

Figure 106 shows the placement of the ABC lamp relative to the EUT and camera photometer.

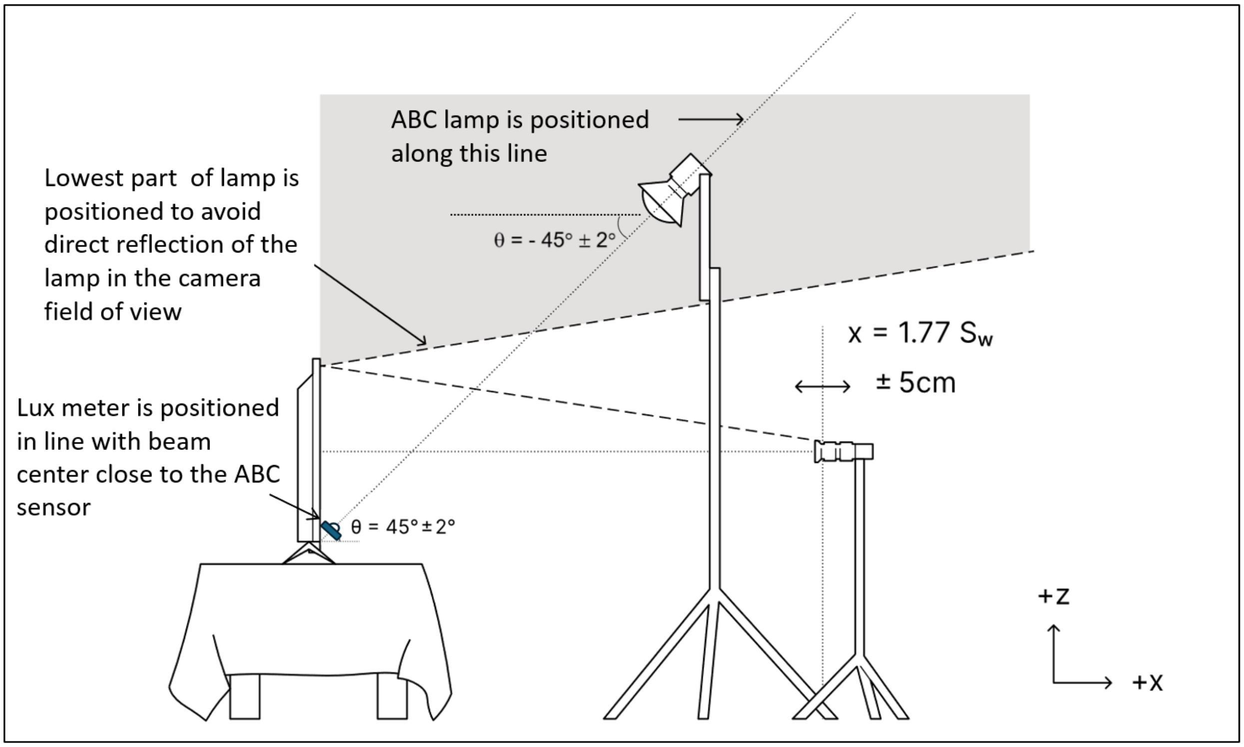


Figure 106: ABC lamp placement during testing

Whether testing was conducted with ABC on or off, those test points were used to produce dimming lines and determine Power/Reference as defined in section ENERGY EFFICIENCY DETERMINATION.

For PCL's laboratory testing, the grading point at which energy efficiency is determined was the Default light source setting (also known as ABC off) test point. ANNEX C: DIMMING LINES FOR ALL DISPLAYS Tested shows dimming lines and performance against the limit for all PPSs of each display tested.

Screen-Center Pattern

To compare PCL's approach to that of existing test pattern-based display policies, luminance testing was completed following their methodologies. These policies rely on screen-center measurements to characterize luminance. The policies reviewed, test clips used (introduced in Table 96), and measurement methods followed (as detailed by each policy) are detailed in Table 98.

Table 98: Screen-center luminance measurements from policies reviewed

Policies	Test Clip	Measurement Method
ENERGY STAR Displays 8.0 CEC Title 20	IEC three-bar video signal	The pattern is displayed for at least 10 minutes, or until the luminance reading stabilizes within 2% for over 60 seconds. Screen-center luminance is then measured in the default PPS, with default light source setting and ABC off.
ENERGY STAR Displays 8.0 CEC Title 20	VESA FPDM2 L80	Same method as the IEC three-Bar pattern. This pattern is used only if the three-bar signal is not supported by the display.
Ecodesign EU Energy Label	L10-L80 box-and-outline patterns	A dynamic test pattern is selected from the L10–L80 box-and-outline pattern set based on screen size: • For displays between 6" and 12", the L40 pattern is used • For displays 12" or larger, the L20 pattern is used Screen-center luminance is measured after 30 seconds, allowing the display to stabilize. Measurements are taken in the "normal configuration" (default PPS, default light source setting).[48] Although the test may be conducted with ABC enabled if it is on by default, for simplicity, all tests were conducted with ABC disabled.

Uniformity

Screen uniformity was assessed to confirm that screen-center luminance measurements are not representative of screen-average luminance. To do so, spot luminance measurements were conducted with the gray pattern on Table 96 and compared them to the screen-average luminance when displaying the same pattern. The uniformity ratio was calculated as the ratio of the screen center to the screen-average, as shown in Figure 107.

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[48] In EU policy, "normal configuration" refers to "a display setting which is recommended to the end-user by the manufacturer from the initial set up menu or the factory setting that the electronic display has for the intended product use."

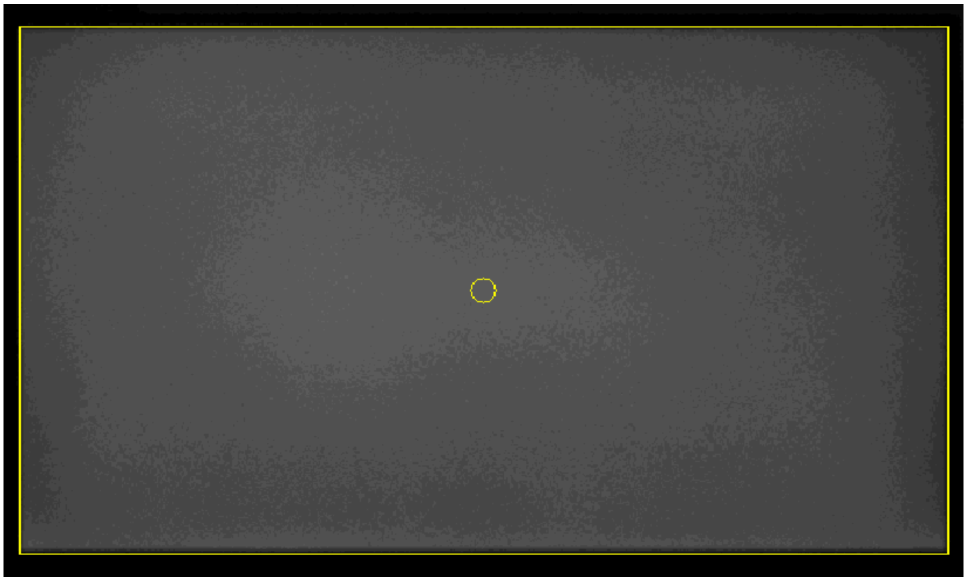


Figure 107: Screenshot from the uniformity test in TV EASY

Note: The yellow circle represents the screen-center measurement area, while the yellow square represents the screen-average measurement area (including the yellow circle).

The screen-center measurement area was sized to be approximately the same size as the measurement area of PCL's PR-655 spectroradiometer. The NEEA TV EASY software supports changing the size of this measurement area so testers can update it to match their photometer's.

These measurements were completed using the default PPS at default light source setting and ABC off.

PCL's camera should not be used as a spot photometer with high-contrast patterns due to stray light affecting spot measurement accuracy. ANNEX D: MODIFYING THE PCL CAMERA SYSTEM goes into detail about this phenomenon.

Color Gamut

Color gamut was measured using a PR-655 spectroradiometer. The method described in IEC 62977-2-1, Section 7.8 "Chromaticity/color gamut area." This method uses a tiled window pattern (Figure 108), where the center square is sequentially set to red, green, and blue, and measurements are taken at the screen center.

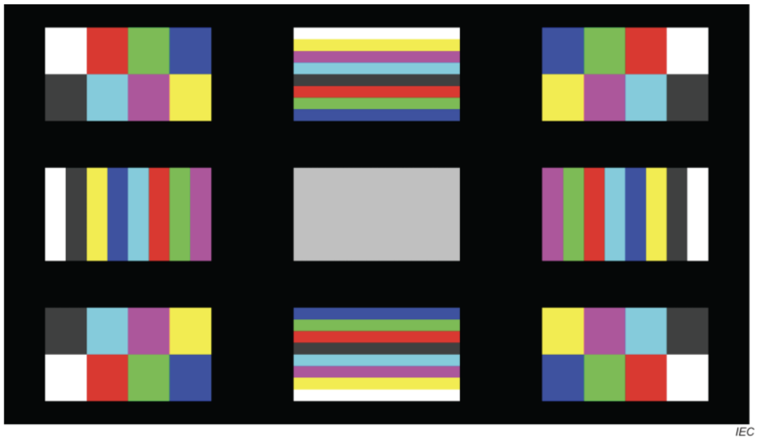


Figure 108: The center square color to the measured color in the IEC 62977-2-1 window pattern

IEC 62977-2-1 offers multiple approaches for measuring color gamut. We selected the method outlined in IEC 62977-2-1: Section 7 because the color distribution of the window pattern is designed to more closely approximate real-world viewing conditions than the single-color patterns also available in this standard. As a result, the measured color gamut better reflects how the display will be perceived by end-users in typical usage scenarios. Additionally, the color boxes that surround the center pattern must be adjusted to maintain a consistent average picture level (APL) of ~25%.

Using this method, chromaticity coordinates are obtained (u′ and v′ values) for each primary color. While IEC 62977-2-1 also includes a method for calculating color gamut volume—a more comprehensive metric that accounts for variations in lightness and chroma—the chromaticity-based color gamut area was opted for. This approach enables more direct comparison with existing datasets, which typically use chromaticity-based measurements.

The measurements were converted into a percentage area of CIELUV following the equation outlined in Section 5.18 of IDMS v1.03 (Equation 10).

Equation 10: How to obtain CIELUV area (A) from IDMS v1.03

$$A = 256.1\ |(u'_R - u'_B)(v'_G - v'_B) - (u'_G - u'_B)(v'_R - v'_B)\ (in\, percent).$$

Note: The color gamut area (A) is determined by the chromaticity coordinates of red (R), green (G), and blue (B)

Since testing was conducted using the default PPS (with default light source setting and ABC off), the resulting measurements reflect the color gamut of the display’s default configuration, not the panel’s full color gamut capability. Sometimes, different picture settings yield different color gamut measurements.

Contrast Ratio

We followed the contrast ratio measurement method described in section 7.4 "Darkroom contrast ratio" of IEC 62977-2-1. This method uses the same window test pattern used for PCL's color gamut measurements (Figure 108).

To measure, the pattern with a center white box was rendered (at maximum input signal) and then with a center black box (at the lowest grey level), taking screen-center luminance measurements in both cases. The contrast ratio was then calculated as the white luminance divided by black luminance at the center.

This approach more closely reflects real-world broadcast or content viewing scenarios than a full-screen black or white pattern. The surrounding colored boxes help maintain electro-optical loading similar to that of typical video content. This prevents measurement anomalies such as overestimation of contrast that can occur with simple full-screen patterns due to display compensation algorithms or dimming behavior that would not occur under real usage. This leads to the contrast ratio measured to be representative of realistic display behavior under dynamic content conditions.

Because this testing was conducted using the display's default PPS and light source setting, the measured contrast ratios reflect the performance of the default configuration rather than of the panel's maximum contrast ratio capability.

Our contrast ratio measurements are intended for comparison purposes only, as computer monitor contrast ratio tests were completed with the PR-655 SpectraScan®, which has reduced accuracy below 0.68 cd/m^2 and is not well-suited for determining the true contrast ratio of a display. Our DSD contrast ratio testing was completed using the Konica Minolta LS-100, which can measure luminance as low as 0.001 cd/m^2 with a ±2% accuracy (±1% accuracy at 1 cd/m^2 or higher).

According to display industry expert Marques Girardelli, contrast ratio tends to correlate with common LCD panel types, as Table 99 shows.

Table 99: Typical contrast ratio for LCD panels

Panel Type	Typical Contrast Ratio
IPS	1,500:1 or less
VA	At least 3,000:1
LCD with Local Dimming Enabled	Over 10,000:1

Viewing Angle

We repeated the contrast ratio and color gamut measurements at horizontal viewing angles of 45° and 85° (with 0° being perpendicular to the screen surface).

ENERGY STAR Displays 8.0 measures contrast ratio at a viewing angle of 85° for its Enhanced Performance Display classification, which is why it was included. PCL added a measurement at 45° to see if the impact of viewing angle on energy efficiency changed across angles. IEC 62977-2-1, which provides PCL's contrast ratio measurement method, does not recommend specific viewing angles at which to test..

As with the previous color gamut and contrast ratio measurements, these tests were completed using the display's default PPS and light source setting.

Non-Active Mode

Below Non-Active Mode measurement methods for computer monitors and DSDs are described. While this research mostly tries to align with the Non-Active Mode terminology defined in IEC 62087 (with the exception of the computer monitors power states described in the following section), certain policies use alternative Non-Active Mode definitions. PCL notes whenever definitions do not align with the core definitions informed by IEC 62087.

For both computer monitors and DSDs, the tester waited for the screen to emit no light and for power levels to remain generally stable for 15 minutes (i.e., if the power plot showed the display consumed more power for the first 10 minutes of being shut off, the tester waited for the power to drop before measuring) before recording power measurements for 15 minutes.

Computer Monitors

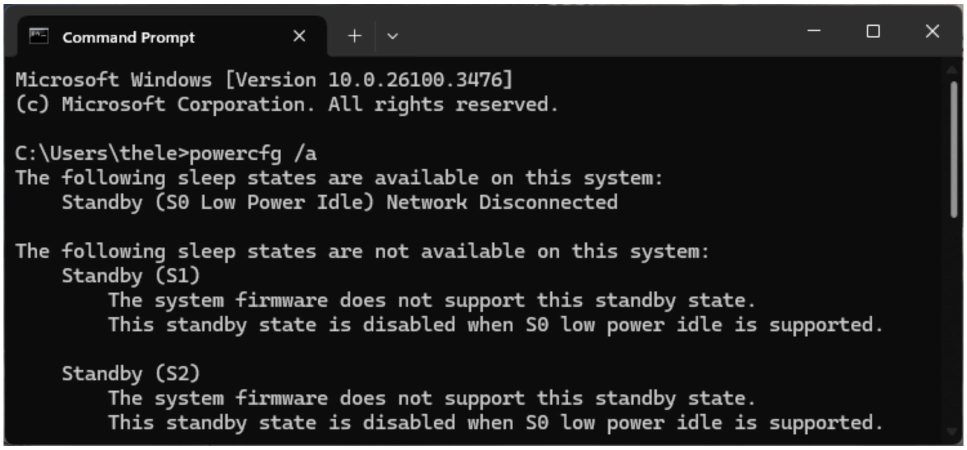
In computer monitors, D3cold and D3hot power states per ACPI specifications were measured. D3hot is a device power state where the monitor is mostly off but still receives minimal power to retain some state or enable wake-up logic, such as responding to a signal from the host system. In D3cold, by contrast, the monitor cannot retain state or respond to any input until it is fully re-initialized.

While this testing shows that both of these modes could be considered Standby (see below for special considerations on D3cold), it was chosen to include both in testing as they are more representative of actual usage.

These modes were using the methods below:

- **D3hot:** Power was measured while the display was connected to a Windows computer that entered Modern Standby Network Connected sleep state (S0 Low Power Idle), which leads to the computer powering down the monitor. Modern Standby enables the system to stay connected to the network while in a low power mode. We picked this mode because it is the most widely available on modern computers, although some of them still offer other sleep modes. Policies reviewed that test computer monitors in D3hot (referred to as Sleep Mode in ENERGY STAR Displays 8.0 and CEC Title 20) do not reference the sleep state in which the host computer should be.

  We confirmed the laptop's sleep state setting by running the *powercfg /a* command, which confirmed the sleep states available on this device (Figure 109). When the computer goes into its sleep state, it instructs the monitor to enter D3hot state (assuming the monitor has not been manually powered down by the user.)



```
Microsoft Windows [Version 10.0.26100.3476]
(c) Microsoft Corporation. All rights reserved.

C:\Users\thele>powercfg /a
The following sleep states are available on this system:
    Standby (S0 Low Power Idle) Network Disconnected

The following sleep states are not available on this system:
    Standby (S1)
        The system firmware does not support this standby state.
        This standby state is disabled when S0 low power idle is supported.

    Standby (S2)
        The system firmware does not support this standby state.
        This standby state is disabled when S0 low power idle is supported.
```

Figure 109: S0 Low Power Idle is the only available sleep state on this computer

- **D3cold:** Power was measured after the display was turned off using its built-in power button. This state largely correlates with Off Mode per its IEC 62087-3 definition. However, in some cases computer monitors retained secondary functions such as decorative lighting while in D3cold state, which would make D3cold a Standby Mode.

Digital Signage Displays

In DSDs, Standby power measurements were set up by using the method described in ANSI/CTA-2037-D. Power was measured after connecting the display to the internet (if available). Since none of the samples tested had Smart Standby features, the equivalent of ANSI/CTA-2037-D Standby with Internet Connection tests were conducted.

Regression Methodology

The goal of the regression analysis is to identify key energy drivers that may impact energy efficiency. Energy efficiency is represented by the Power/Reference metric (defined in section ENERGY EFFICIENCY DETERMINATION) at the grading point given by each dataset. This metric relies on screen-average dynamic broadcast clip luminance, which PCL estimates as dataset luminance information is limited to screen-center, static pattern measurements.

We performed dataset analysis using Python, specifically Pandas for processing data frames, scikit-learn for running the regression analysis, and matplotlib for graphing.

To prepare the data for the regression, Boolean (true or false) variables were mapped to binary 0/1 values. Categorical features were one-hot encoded. One-hot encoding refers to the process of converting a single categorical column into multiple binary columns, where each new column represents one possible category value. PCL also excluded any features (columns) with fewer than ten valid value entries.

In the case of panel subtype data, any LCD models classified as simply TFT were removed as this is an overarching LCD technology and does not represent actual panel subtype.

For columns where a single entry could have multiple attribute tags separated by commas, each tag was treated as an independent feature. The column was split into its individual components, and a new binary column was created for each unique value.

Missing values in numeric features (e.g., refresh rate columns, measured in hertz) were imputed using the column's mean numerical value to ensure completeness across all predictors.

Refresh rate fields were rescaled from hertz to hundreds of hertz to make the coefficient magnitudes easier to read. We also considered only refresh rates over 60 Hz in the regression, which is the de facto standard refresh rate for computer monitors in the US.

While brand and manufacturer variables were include in this regression analysis, this study does not intend to draw conclusions on the inherent energy efficiency impact of a brand or manufacturer. Rather, certain manufacturers may tend to design products with given features (such as additional computing capabilities) that increase energy consumption but are not otherwise captured by existing regression variables. Including brand and manufacturer variables helps isolate the influence of such features, enabling a more accurate assessment of other variables' effects.

As a reminder, the main regression outputs are the explicit linear formulas to predict Power/Reference, listing the intercept and coefficients for each feature to be applied per Equation 11 below.

Equation 11: How to predict dependent variables from regression analysis coefficients

$$Dependent\ Variable = Intercept + Coefficient\ Value * Independent\ Variable$$

Where:

- **Dependent Variable** is the expected Power/Reference value
- **Intercept** is the constant value to which coefficients are applied
- **Coefficient Value** is the effect a given feature is predicted to have on Power/Reference
- **Independent Value** indicates the presence or lack thereof of a given feature

Regression model performance was evaluated using the R^2 statistic, which indicates how well the model explains the variability in the target outcome. Higher R^2 values suggest a better fit.

CEC MAEDbS Dataset

We performed regression analysis on computer monitors using data from the CEC MAEDbS database. This database includes a variety of reporting fields for computer monitors (such as variable refresh rate capability, color gamut coverage, and screen curvature) used as coefficients for this regression analysis. In comparison, DSDs had far fewer reporting requirements and were historically mixed with television data through 2024. This lack of reporting requirements led to fewer variables that could be included in this regression, leading to the decision to exclude this data from dataset analysis.

For monitor data, the analysis was limited to models from 2021 onward to reduce the dataset size and focus on more recent products. PCL also removed a small number of outliers to not pollute the regression analysis, such as rare backlight technologies (like CCFL) or brands that had only a single sample each. Our final dataset included 753 computer monitors.

We added or completed existing columns with panel technology, native refresh rate, and maximum refresh rate using Gemini Deep Research. The resulting datasets are available in the GitHub repository for this project.

The MAEDbS dataset provides only screen-center luminance measurements, based on the three-bar test pattern. However, the established efficiency metrics require screen-average luminance to understand energy efficiency relative to Limit 1. To bridge this gap, a flat conversion ratio of 20%—the average value (dynamic broadcast clip screen-average luminance/three-bar clip screen-center luminance) from PCL's own testing— was applied by comparing screen-center luminance for the three-bar pattern used by this policy to screen-average dynamic luminance using the new IEC SDR broadcast clip. Figure 110 shows both sets of readings against PCL's conversion ratio for the computer monitors tested.

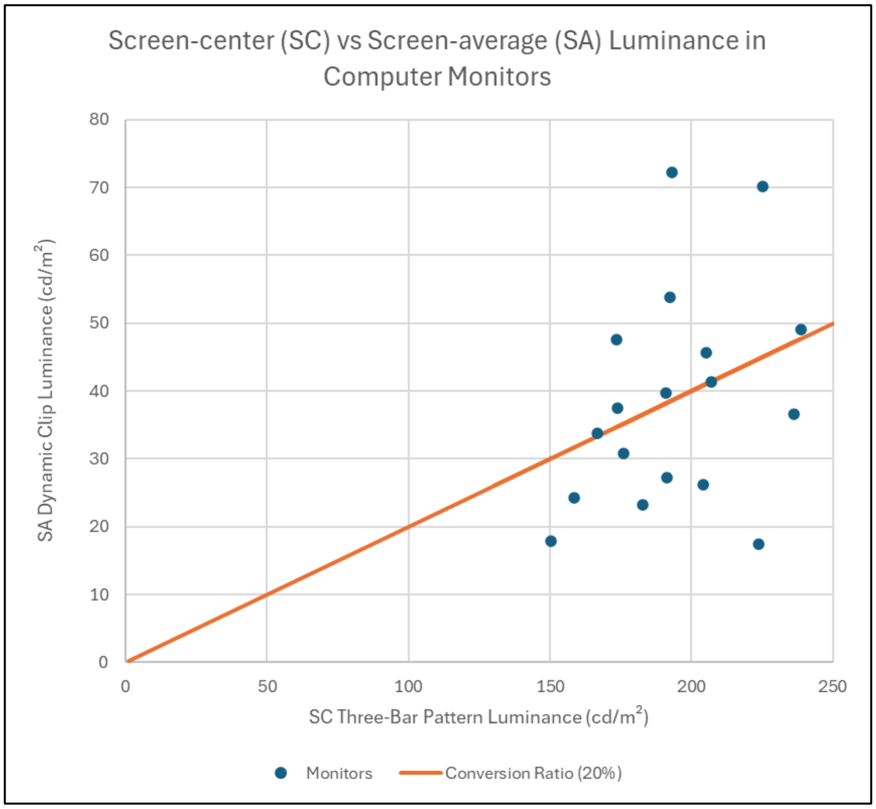


Figure 110: Screen-center, three-bar pattern versus screen-average, broadcast clip luminance

OLED panels tend to have more uniform luminance, meaning their screen-average and screen-center values are sometimes closer than in other panel types. Because of this, a different conversion rate of 30% for this panel type, based on existing TV data.

Since luminance and power measurements were taken after getting the screen-center luminance as close to 200 cd/m^2 as possible, this means that energy efficiency for these displays is graded at about 40 cd/m^2 (screen-average, dynamic broadcast clip luminance) given PCL's 20% conversion rate (or about 60 cd/m^2 for OLED panel types).[49]

We used this data to complete linear regression analysis and to understand the impact of different attributes on energy efficiency. We go further into the impact of each attribute in sections 0 and 0.

ENERGY STAR Displays 8.0 Dataset

Since the 2020 ENERGY STAR Displays 8.0 dataset includes enough data for both computer monitors and DSDs, PCL used it in the regression analysis of both display types. After removing a small number of outliers to enhance predictive power, the final dataset included 797 computer monitors and 176 DSDs.

For computer monitors, the dataset was enriched with native and maximum refresh rate data using Gemini Deep Research.

As the brand and manufacturer fields for both computer monitors and DSDs exhibited an almost complete overlap, only the brand field was included in the regression analysis.

The dataset includes contrast ratio measurements for each display. Because contrast ratio numerators are typically reported in the thousands (e.g., 3000:1), these values were divided by 1000 to improve visualization of their relationship to energy efficiency.

The dataset also includes panel type information. Although subtypes of IPS panels (such as AAS, ADS, and PLS) are labeled as such, all were categorized under the general IPS label for the purposes of regression analysis. This simplification avoids potential misclassification, as other displays labeled as IPS may belong to one of these subtypes, which could otherwise introduce noise into the regression results.

As the ENERGY STAR Displays 8.0 dataset does not have screen-average, dynamic broadcast clip luminance results, the "As-Tested Luminance" values were used to estimate screen-average luminance measurements. "As-Tested Luminance" values are screen-center luminance readings taken using the three-bar pattern (referenced on Table 96) after adjusting the display's light source to get as close as possible to 200 cd/m^2 for computer monitors (with other settings set to their default values). In the case of DSDs, luminance was set to a value greater than or equal to 65% of the manufacturer-reported maximum luminance. If the DSD tested was a tiled or modular configuration, luminance was measured for each tile and the average of all tiles was reported.

To convert screen-center luminance values to estimated screen-average luminance, conversion rates of 20% for monitors (the same rate used for the 2025 CEC MAEDbS dataset) and 15% for DSDs (30% for OLEDs in either product class) were used. PCL determined the 15% conversion rate for DSDs based on PCL's test data. Figure 111 shows screen-center versus screen-average luminance for DSDs.

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[49] While screen-center measurements were taken following CEC's methodology, it was decided to instead use a conversion rate to simulate screen-average, dynamic luminance given the Power/Reference metric used in PCL's analysis was developed based on screen-average, dynamic luminance data.

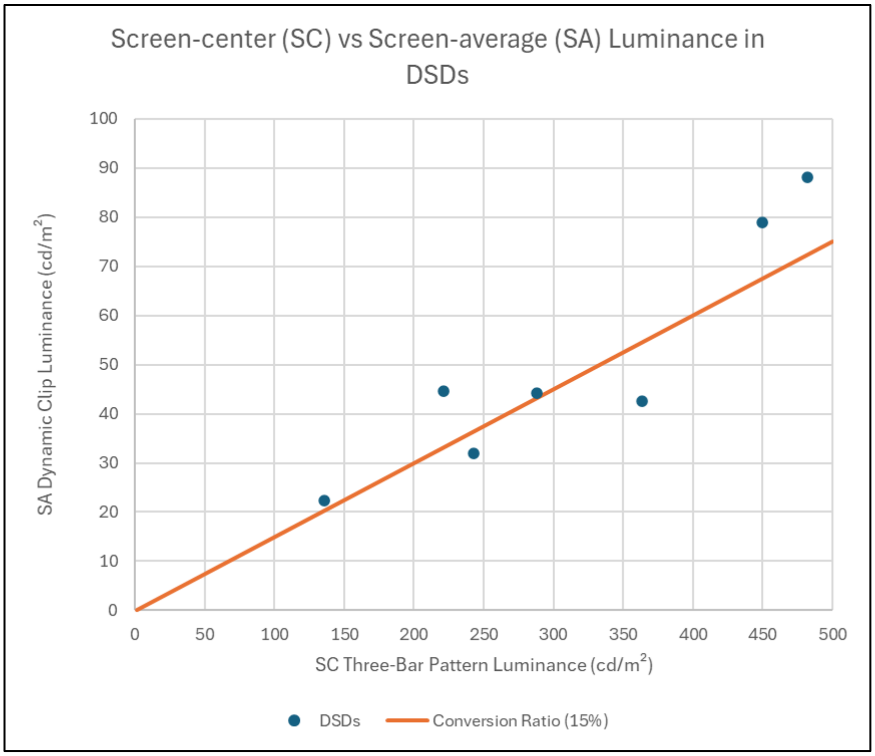


Figure 111: Screen-center, three-bar pattern versus screen-average, broadcast clip luminance

Power values in this dataset were taken by measuring power after the display was set to its "As-Tested Luminance." Power is measured while playing the IEC SDR 10-minute test clip (also referenced in Table 96.)

Annex B: Sample Plan

Table 100 summarizes the displays included in PCL's laboratory testing sample plan. The following subsections expand on the reasoning for choosing these models.

The GitHub repository for this project includes a database with expanded model information.

Table 100: List of displays included in PCL's sample plan

Make	Model	Display Type	Display Technology	Light Source Type	LCD Type	Width (in)	Height (in)	Pixel Columns	Pixel Rows	Aspect Ratio
Acer	AOPEN 16PM6QT	Computer Monitor	LCD	Edge-lit	IPS	13.5	7.5	1920	1080	16:9
Acer	AOPEN 20E0Q	Computer Monitor	LCD	Edge-lit	TN	17.4	9.8	1600	900	16:9
Lenovo	L22e-40	Computer Monitor	LCD	Edge-lit	VA	19.2	10.8	1920	1080	16:9
ASUS	ROG Swift Pro PG248QP	Computer Monitor	LCD	Edge-lit	TN	21	11.75	1920	1080	16:9
Dell	P2423D	Computer Monitor	LCD	Edge-lit	IPS	24	14	2560	1440	16:9
HP	524SH	Computer Monitor	LCD	Edge-lit	IPS	20.75	10.5	1920	1080	16:9
Lenovo	ThinkVision T24T-20	Computer Monitor	LCD	Edge-lit	IPS	20.75	11.5	1920	1080	16:9
MSI	G274QPF-QD	Computer Monitor	LCD	Edge-lit	IPS	24	11.5	2560	1440	16:9
Acer	B277	Computer Monitor	LCD	Edge-lit	IPS	23.5	13.2	1920	1080	16:9
Acer	Nitro XV275U P3biipx	Computer Monitor	LCD	Direct-lit	IPS	23.5	13.2	3840	2160	16:9
AOC	Q27G3XMN	Computer Monitor	LCD	Direct-lit	VA	23.5	13.2	2560	1440	16:9
Apple	Studio Display	Computer Monitor	LCD	Edge-lit	IPS	23.5	13.2	5120	2880	16:9
ASUS	ProArt Display PA279CRV	Computer Monitor	LCD	Edge-lit	IPS	23.75	13.25	3840	2160	16:9

Make	Model	Display Type	Display Technology	Light Source Type	LCD Type	Width (in)	Height (in)	Pixel Columns	Pixel Rows	Aspect Ratio
INNOCN	27M2V	Computer Monitor	LCD	Direct-lit	IPS	23.5	13.2	3840	2160	16:9
Samsung	Smart Monitor M8 M80C S32CM80	Computer Monitor	LCD	Edge-lit	VA	27.9	15.7	3840	2160	16:9
LG	34WQ73A-B	Computer Monitor	LCD	Edge-lit	IPS	31.4	13.2	3440	1440	21:9
MSI	MEG 342C QD-OLED	Computer Monitor	Emissive	OLED	-	31.4	13.2	3440	1440	21:9
Dell	U4021QW	Computer Monitor	LCD	Edge-lit	IPS	37	15.75	5120	2160	21:9
LG	42 OLED Flex 42LX3QPUA	Computer Monitor	Emissive	OLED	-	36.7	20.6	3840	2160	16:9
Samsung	Odyssey Neo G9 G95NA S49AG95	Computer Monitor	LCD	Direct-lit	VA	47.4	13.2	5120	1440	32:9
MicroTouch	SK-190P-A1	DSD	LCD	Edge-lit	Unconfirmed	14.5	11.5	1280	1024	5:4
LG	43UM340E	DSD	LCD	Unknown	IPS	37	21	3840	2160	16:9
LG	50UL3J-M	DSD	LCD	Unknown	IPS	43	24.3	3840	2160	16:9
Samsung	SH37C	DSD	LCD	Edge-lit	Unconfirmed	35.5	10	1920	540	32:9
Sharp	AQUOS 4P-B65EJ2U	DSD	LCD	Unknown	Unconfirmed	65	36.5	3840	2160	16:9
SZ CHANHONGRUN	D16	DSD	Emissive	Direct View LED	-	37.5	15	160	64	5:2
Samsung	OH55A-S	DSD	LCD	Edge-lit	Unconfirmed	47	26.5	1920	1080	16:9
LG	75TR3DK-B	DSD	LCD	Unknown	IPS	64.5	36.5	3840	2160	16:9
Samsung	VH55R-R	DSD	LCD	Unknown	IPS	53.5	47.5	1920	1080	16:9

The following sections summarize how the samples are distributed across the categories defined for each product type.

Since PCL's study focuses on the most mainstream display technologies used in computer monitors and DSDs, emerging or niche technologies such as dual-layer LCD, micro-LED, and transparent OLED were exclude from laboratory testing.

Computer Monitors

PCL designed PCL's computer monitor sample plan to reflect the diversity of panel technologies outlined in section DISPLAY TECHNOLOGIES. Table 101 and Table 102 below summarize the distribution of panel types included in the sample.

Table 101: Distribution of panel technologies in monitor samples

Panel Technology	Monitor Count
Emissive	**2**
OLED	2
LCD	**18**
Direct-lit	4
Edge-lit	14

Table 102: Distribution of panel subtypes in monitor samples

Panel Subtype	Monitor Count
Emissive	**2**
WOLED	1
QD-OLED	1
LCD	**18**
IPS	12
TN	2
VA	4

Table 103 shows the distribution of computer monitors across the segments in this market.

Table 103: Distribution of market segments in monitor samples

Monitor Market Segment	Count
Consumer	7
Gaming	7
Business/Enterprise	4
Professional/Creative	2

Several of PCL's samples were selected based on their specific features whose energy consumption this research sought to evaluate. The list below summarizes some of the features tested and the computer monitors that included them.

- Local Dimming
    - Acer Nitro XV275U P3biipx
    - AOC Q27G3XMN
    - ASUS ProArt Display PA279CRV
    - INNOCN 27M2V
    - MSI MEG 342C QD-OLED
    - LG 42 OLED Flex 42LX3QPUA
    - Samsung Odyssey Neo G9 G95NA S49AG95
- Variable Refresh Rate (VRR)
    - Lenovo L22e-40
    - ASUS ROG Swift Pro PG248QP
    - MSI G274QPF-QD
    - Acer Nitro XV275U P3biipx
    - AOC Q27G3XMN
    - ASUS ProArt Display PA279CRV
    - INNOCN 27M2V
    - MSI MEG 342C QD-OLED
    - LG 42 OLED Flex 42LX3QPUA
    - Samsung Odyssey Neo G9 G95NA S49AG95
- Touchscreen
    - Acer AOPEN 16PM6QT
    - Lenovo ThinkVision T24T-20
- Screen Curvature
    - LG 34WQ73A-B
    - MSI MEG 342C QD-OLED
    - Dell U4021QW
    - LG 42 OLED Flex 42LX3QPUA
- KVM Switch

- LG 34WQ73A-B
- MSI MEG 342C QD-OLED
- Dell U4021QW

DSDs

PCL's sampling focused on obtaining models representative of a range of common use cases, including retail, education, and conference-room applications.

Table 104 and

Table 105 present the distribution of panel technologies across the DSDs tested.

Table 104: Distribution of panel technologies in DSD samples

Panel Technology	Monitor Count
Emissive	**1**
DVLED	1
LCD	**8**
Edge-lit	3
Unknown	5

Table 105: Distribution of panel subtypes in DSD samples

Panel Subtype	Monitor Count
Emissive	**1**
DVLED	1
LCD	**8**
IPS	4
Unknown	4

Table 106 shows the breakdown the LCD panel subtype is assumed based on the contrast ratio measurements taken (as described in APPENDIX A: CONTRAST RATIO).

Table 106: Distribution of DSD panel subtypes with contrast ratio assumptions

Panel Subtype	Monitor Count
Emissive	1
DVLED	1
LCD	8
IPS	7
VA	1

Table 107 provides a high-level breakdown of DSDs by market segment.

Table 107: Distribution of market segments in DSD samples

DSD Market Segment	Count
Commercial Monitor and Digital Signs	7
Video Wall —DVLED	1
Video Wall—Tiled LCD	1

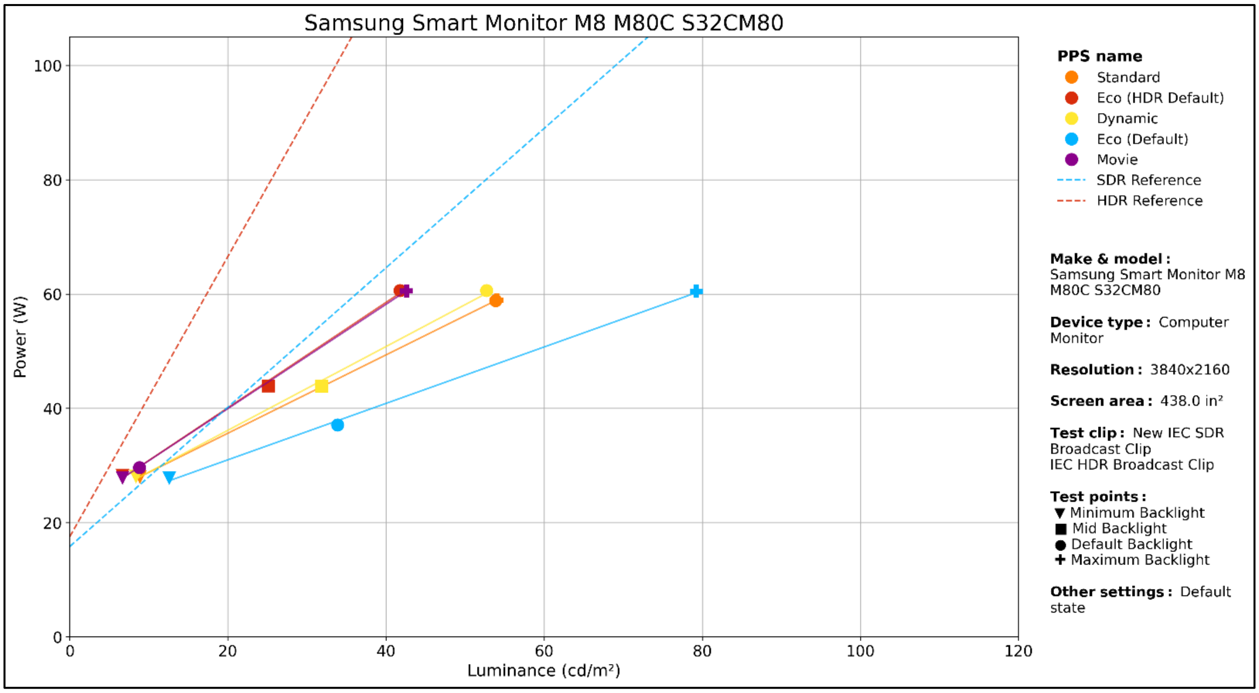
As with computer monitors, certain DSDs were chosen because this report would ascertain the impact on energy efficiency of specific features they offered:

- Modular Panels
    - Samsung VH55R-R
- Touchscreen
    - MicroTouch SK-190P-A1
    - LG 75TR3DK-B
- Outdoor Displays
    - MicroTouch SK-190P-A1
    - SZ CHANHONGRUN D16
    - Samsung OH55A-S
- Operating System
    - LG 50UL3J-M
    - Samsung SH37C
    - Samsung OH55A-S
    - Samsung VH55R-R
    - LG 75TR3DK-B

Annex C: Dimming Lines for All Displays Tested

The plots in each subsection are set to have the same scale for easier comparison across models.

Computer Monitors



Make & model : Samsung Smart Monitor M8 M80C S32CM80

Device type : Computer Monitor

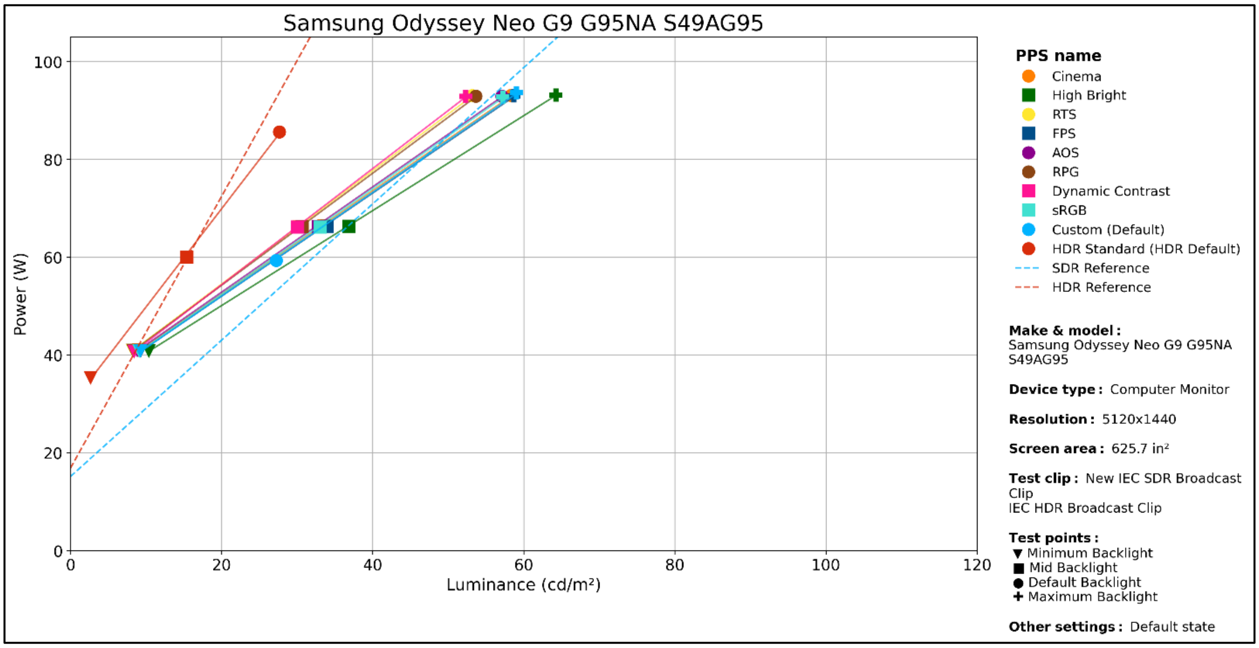
Resolution : 3840x2160

Screen area : 438.0 in²

Test clip : New IEC SDR Broadcast Clip
IEC HDR Broadcast Clip

Test points :
▼ Minimum Backlight
■ Mid Backlight
● Default Backlight
✚ Maximum Backlight

Other settings : Default state



Make & model : Samsung Odyssey Neo G9 G95NA S49AG95

Device type : Computer Monitor

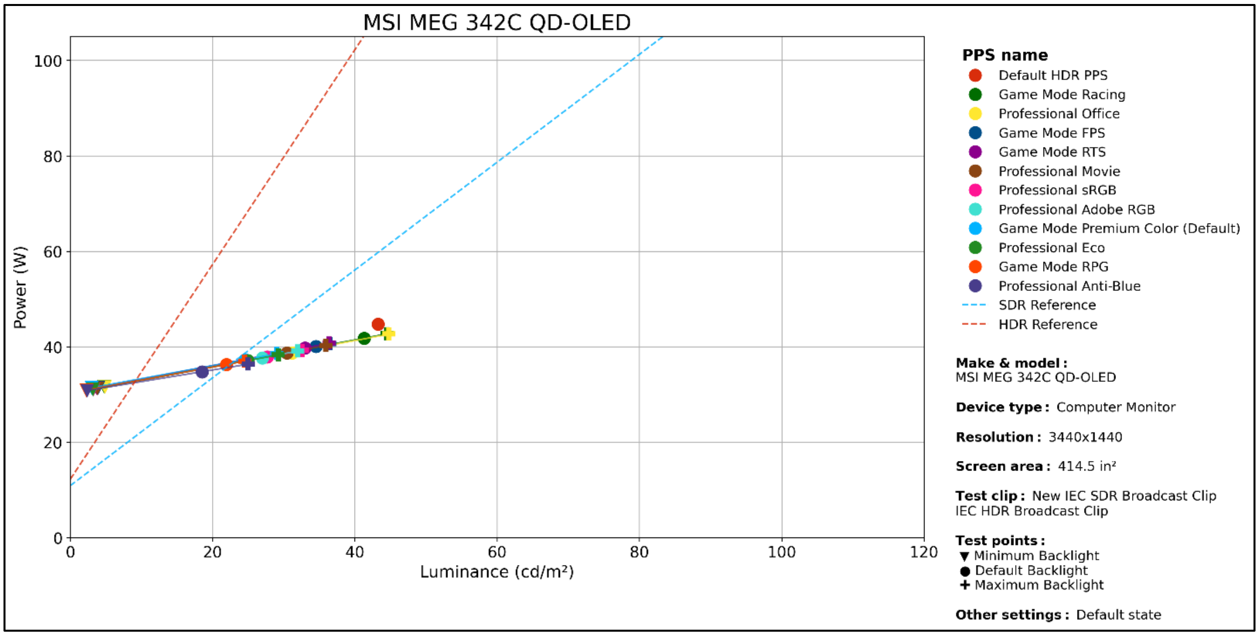
Resolution : 5120x1440

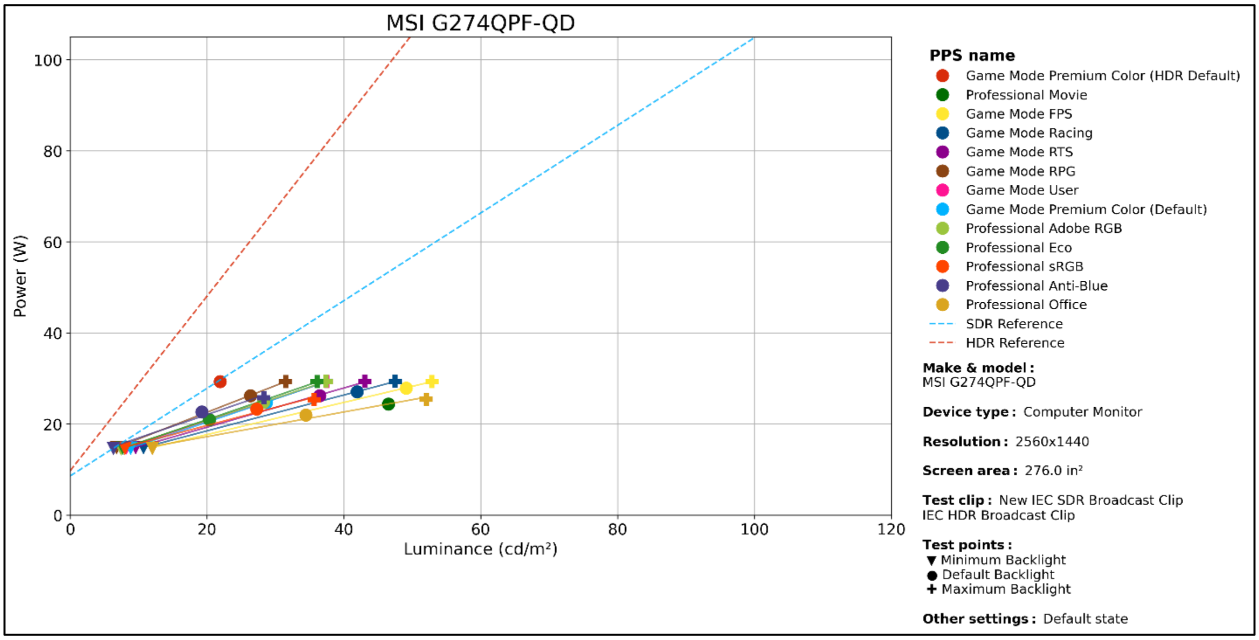
Screen area : 625.7 in²

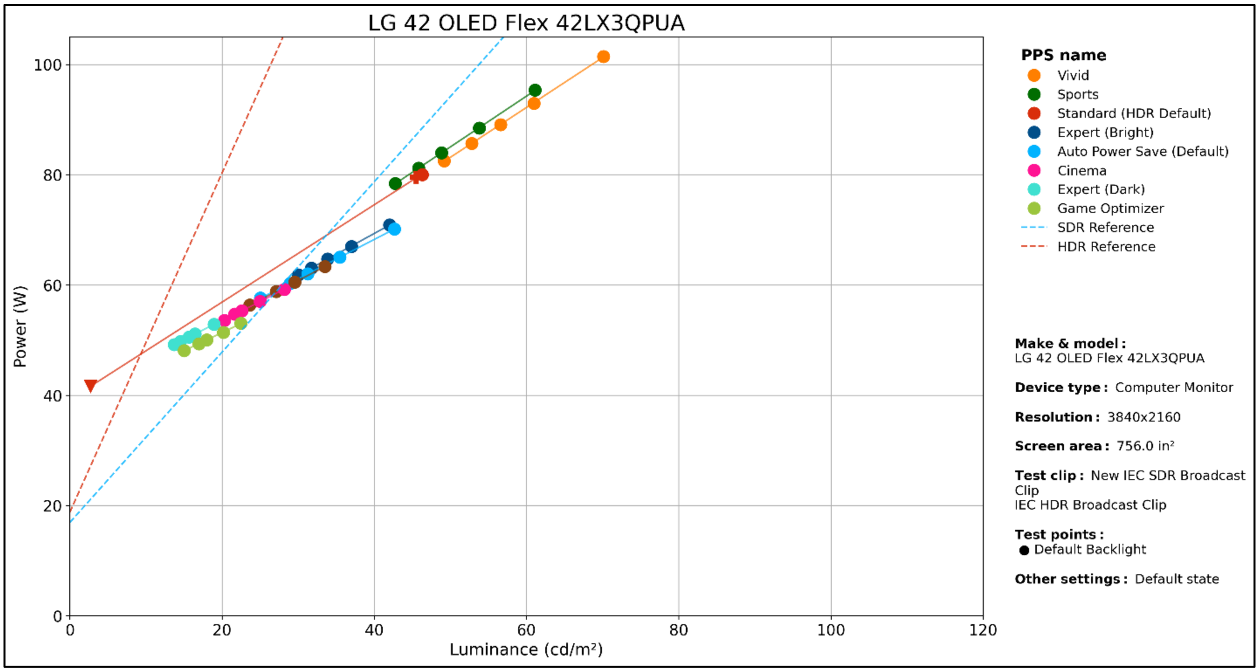
Test clip : New IEC SDR Broadcast Clip
IEC HDR Broadcast Clip

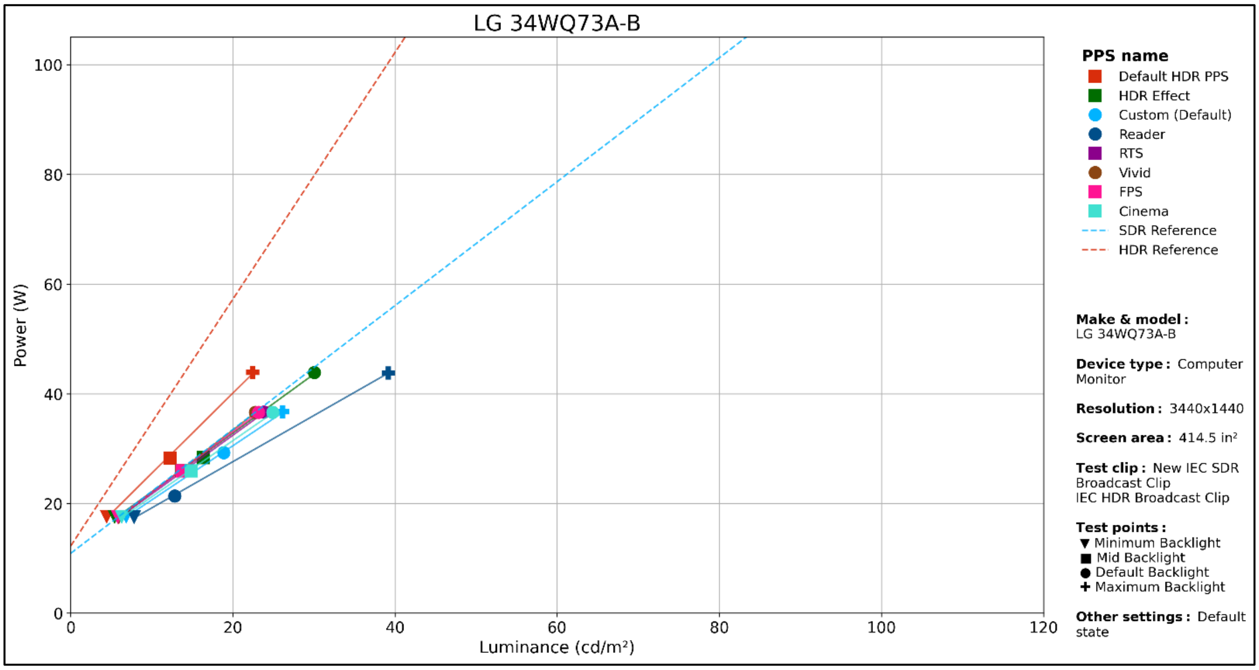
Test points :
▼ Minimum Backlight
■ Mid Backlight
● Default Backlight
✚ Maximum Backlight

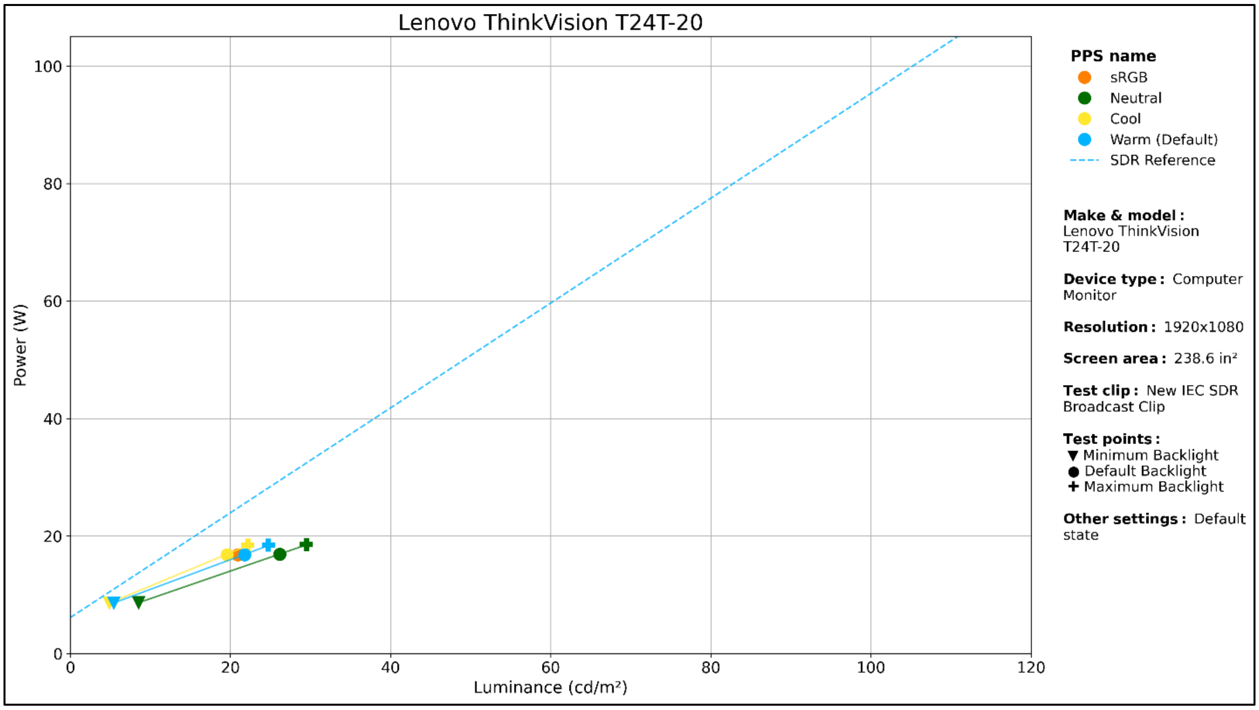
Other settings : Default state

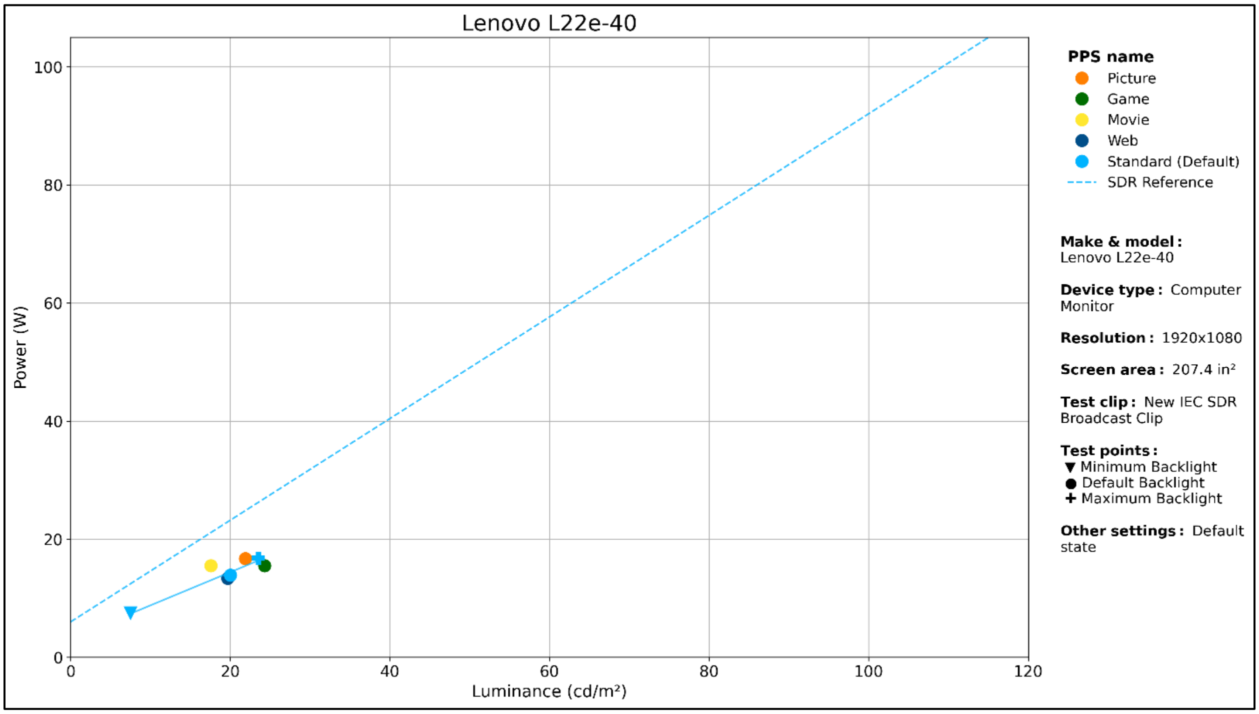

MSI MEG 342C QD-OLED
Power (W)
Luminance (cd/m²)
0
20
40
60
80
100
120
PPS name
Default HDR PPS
Game Mode Racing
Professional Office
Game Mode FPS
Game Mode RTS
Professional Movie
Professional sRGB
Professional Adobe RGB
Game Mode Premium Color (Default)
Professional Eco
Game Mode RPG
Professional Anti-Blue
SDR Reference
HDR Reference
Make & model : MSI MEG 342C QD-OLED
Device type : Computer Monitor
Resolution : 3440x1440
Screen area : 414.5 in²
Test clip : New IEC SDR Broadcast Clip
IEC HDR Broadcast Clip
Test points :
▼ Minimum Backlight
● Default Backlight
✚ Maximum Backlight
Other settings : Default state

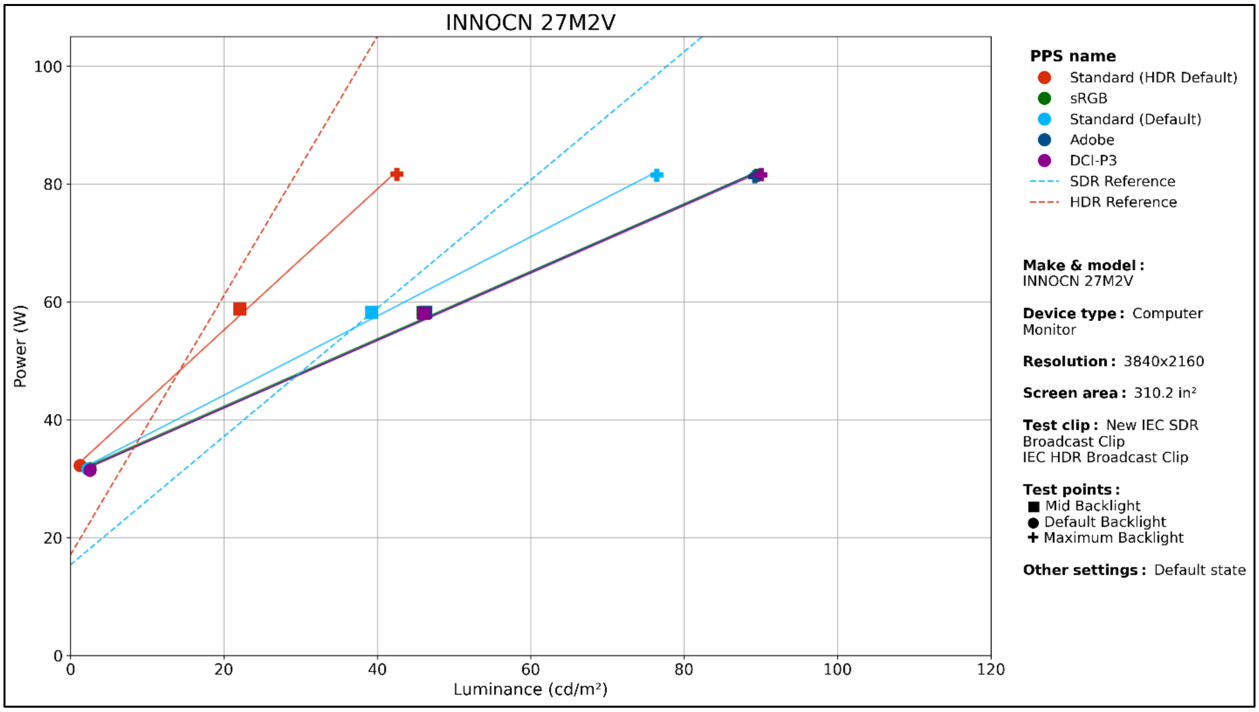

MSI G274QPF-QD
Power (W)
Luminance (cd/m²)
0
20
40
60
80
100
120
PPS name
Game Mode Premium Color (HDR Default)
Professional Movie
Game Mode FPS
Game Mode Racing
Game Mode RTS
Game Mode RPG
Game Mode User
Game Mode Premium Color (Default)
Professional Adobe RGB
Professional Eco
Professional sRGB
Professional Anti-Blue
Professional Office
SDR Reference
HDR Reference
Make & model : MSI G274QPF-QD
Device type : Computer Monitor
Resolution : 2560x1440
Screen area : 276.0 in²
Test clip : New IEC SDR Broadcast Clip
IEC HDR Broadcast Clip
Test points :
▼ Minimum Backlight
● Default Backlight
✚ Maximum Backlight
Other settings : Default state

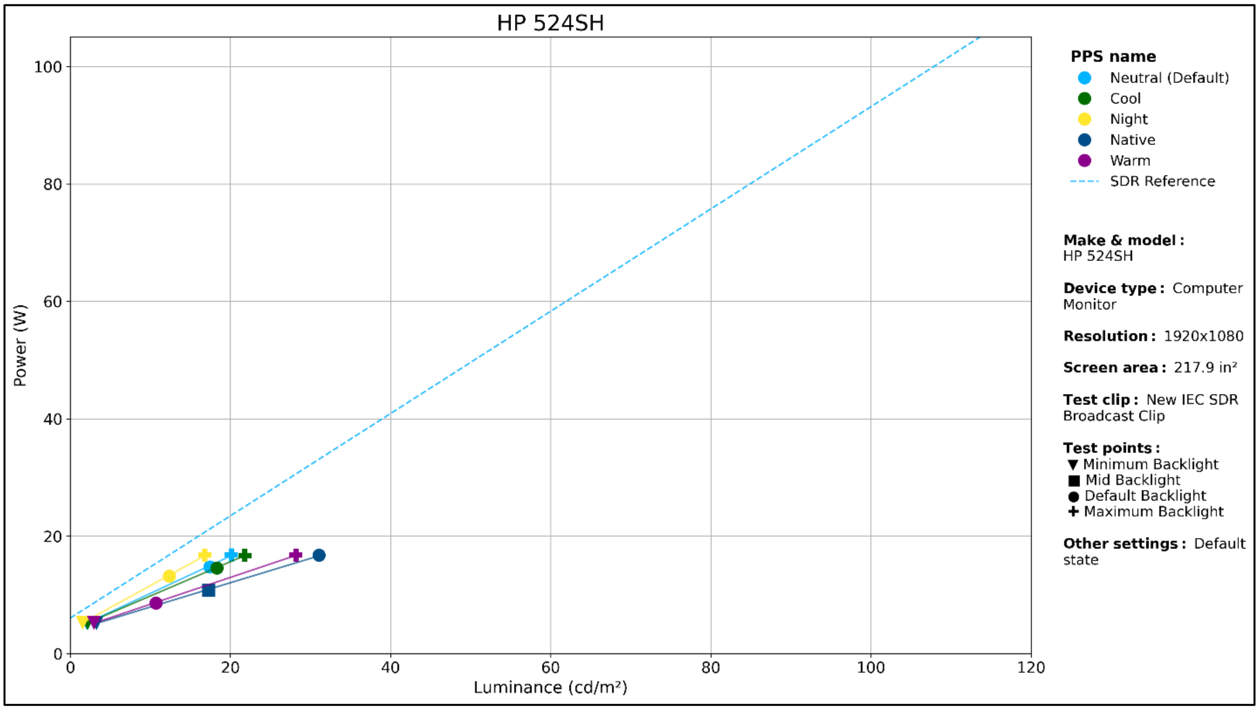

LG 42 OLED Flex 42LX3QPUA
Power (W)
Luminance (cd/m²)
0
20
40
60
80
100
120
PPS name
Vivid
Sports
Standard (HDR Default)
Expert (Bright)
Auto Power Save (Default)
Cinema
Expert (Dark)
Game Optimizer
SDR Reference
HDR Reference
Make & model : LG 42 OLED Flex 42LX3QPUA
Device type : Computer Monitor
Resolution : 3840x2160
Screen area : 756.0 in²
Test clip : New IEC SDR Broadcast Clip
IEC HDR Broadcast Clip
Test points :
● Default Backlight
Other settings : Default state

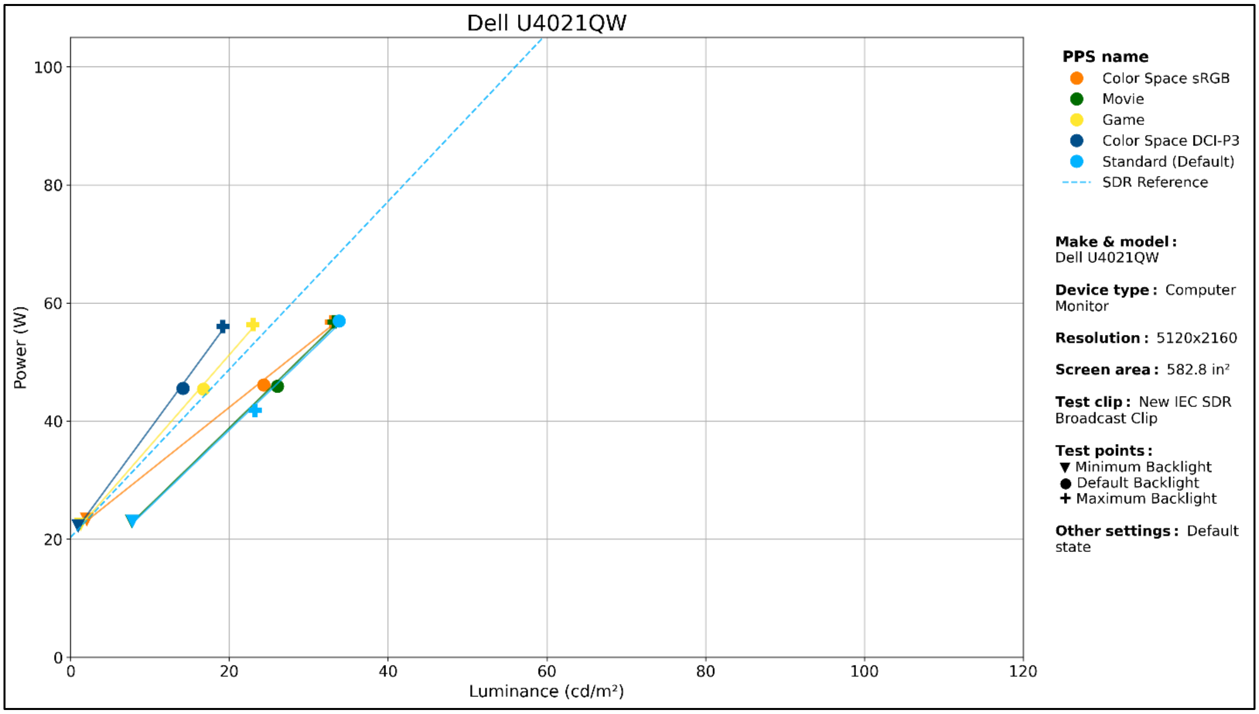

LG 34WQ73A-B
Power (W)
Luminance (cd/m²)
0
20
40
60
80
100
120
PPS name
Default HDR PPS
HDR Effect
Custom (Default)
Reader
RTS
Vivid
FPS
Cinema
SDR Reference
HDR Reference
Make & model : LG 34WQ73A-B
Device type : Computer Monitor
Resolution : 3440x1440
Screen area : 414.5 in²
Test clip : New IEC SDR Broadcast Clip
IEC HDR Broadcast Clip
Test points :
▼ Minimum Backlight
■ Mid Backlight
● Default Backlight
✚ Maximum Backlight
Other settings : Default state

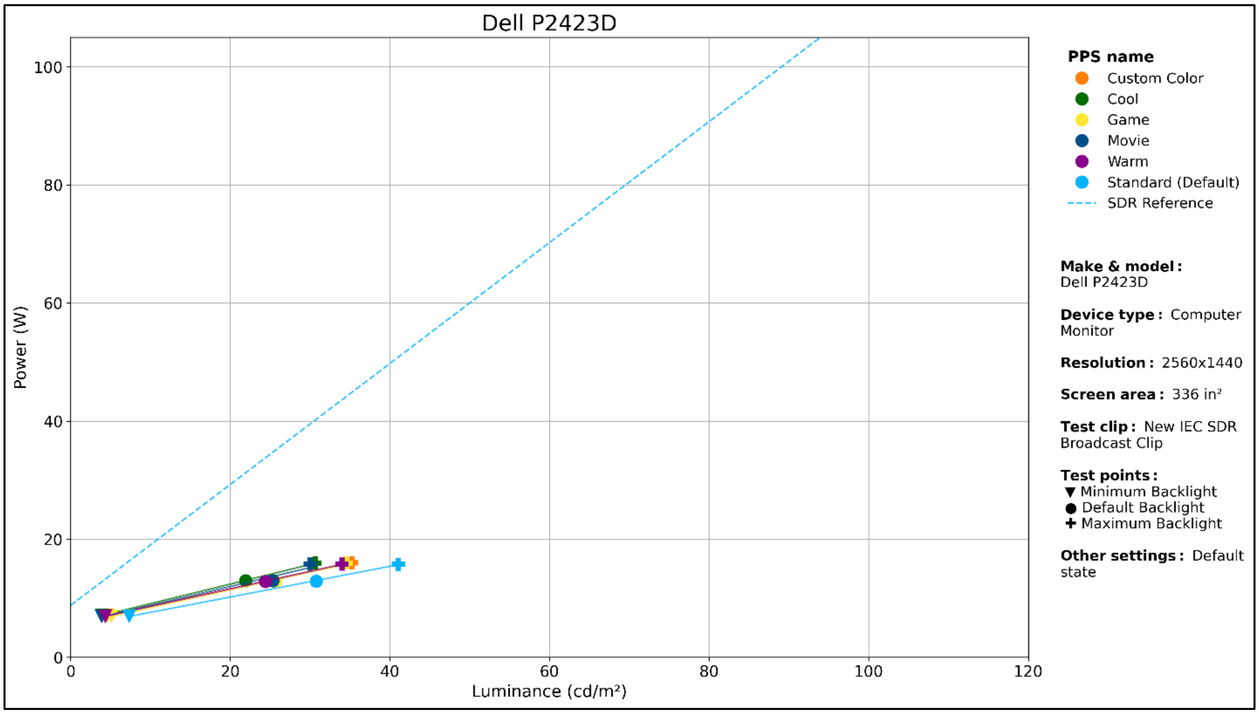

Lenovo ThinkVision T24T-20
Power (W)
Luminance (cd/m²)
0
20
40
60
80
100
120
PPS name
sRGB
Neutral
Cool
Warm (Default)
SDR Reference
Make & model : Lenovo ThinkVision T24T-20
Device type : Computer Monitor
Resolution : 1920x1080
Screen area : 238.6 in²
Test clip : New IEC SDR Broadcast Clip
Test points :
▼ Minimum Backlight
● Default Backlight
✚ Maximum Backlight
Other settings : Default state

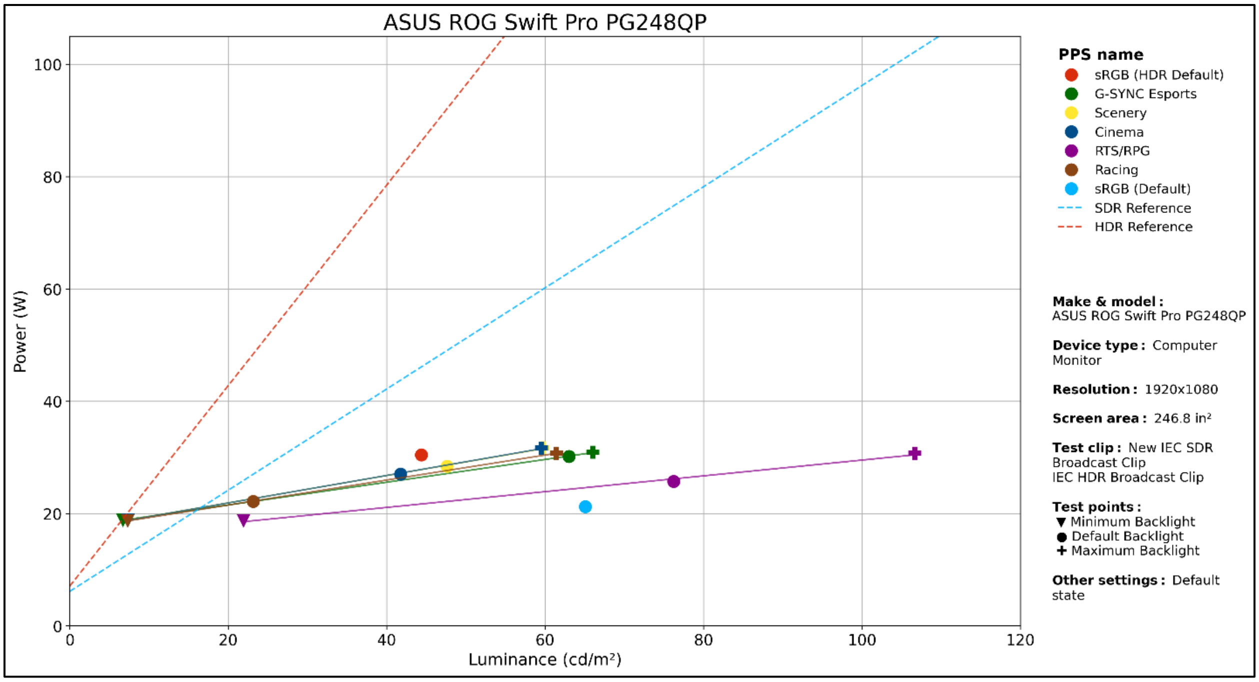

Lenovo L22e-40
Power (W)
Luminance (cd/m²)
0
20
40
60
80
100
120
PPS name
Picture
Game
Movie
Web
Standard (Default)
SDR Reference
Make & model : Lenovo L22e-40
Device type : Computer Monitor
Resolution : 1920x1080
Screen area : 207.4 in²
Test clip : New IEC SDR Broadcast Clip
Test points :
▼ Minimum Backlight
● Default Backlight
✚ Maximum Backlight
Other settings : Default state

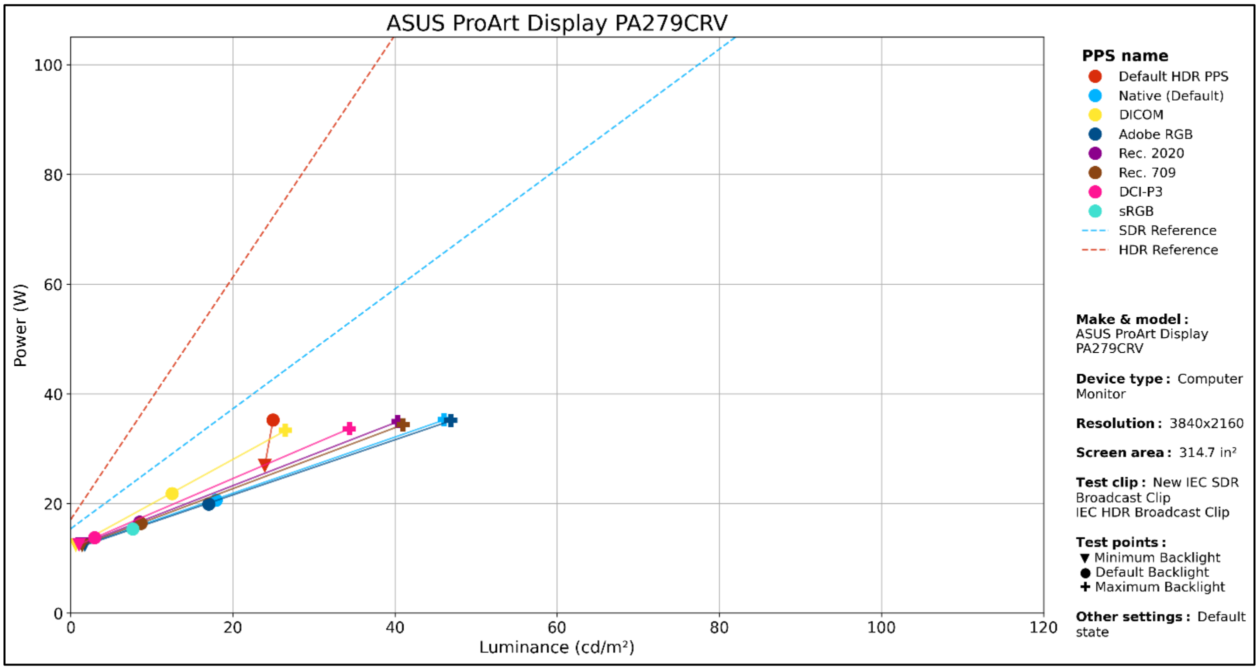

INNOCN 27M2V
Power (W)
Luminance (cd/m²)
0
20
40
60
80
100
120
PPS name
Standard (HDR Default)
sRGB
Standard (Default)
Adobe
DCI-P3
SDR Reference
HDR Reference
Make & model : INNOCN 27M2V
Device type : Computer Monitor
Resolution : 3840x2160
Screen area : 310.2 in²
Test clip : New IEC SDR Broadcast Clip
IEC HDR Broadcast Clip
Test points :
■ Mid Backlight
● Default Backlight
✚ Maximum Backlight
Other settings : Default state

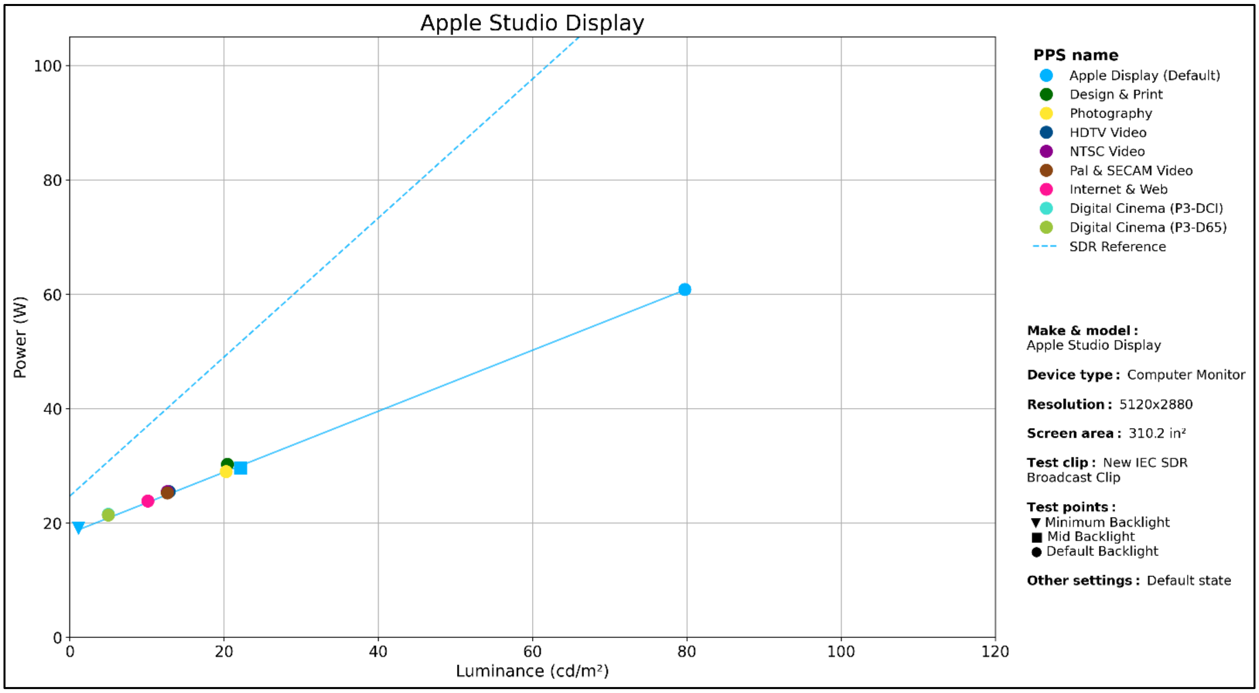

HP 524SH
Power (W)
Luminance (cd/m²)
0
20
40
60
80
100
120
PPS name
Neutral (Default)
Cool
Night
Native
Warm
SDR Reference
Make & model : HP 524SH
Device type : Computer Monitor
Resolution : 1920x1080
Screen area : 217.9 in²
Test clip : New IEC SDR Broadcast Clip
Test points :
▼ Minimum Backlight
■ Mid Backlight
● Default Backlight
✚ Maximum Backlight
Other settings : Default state

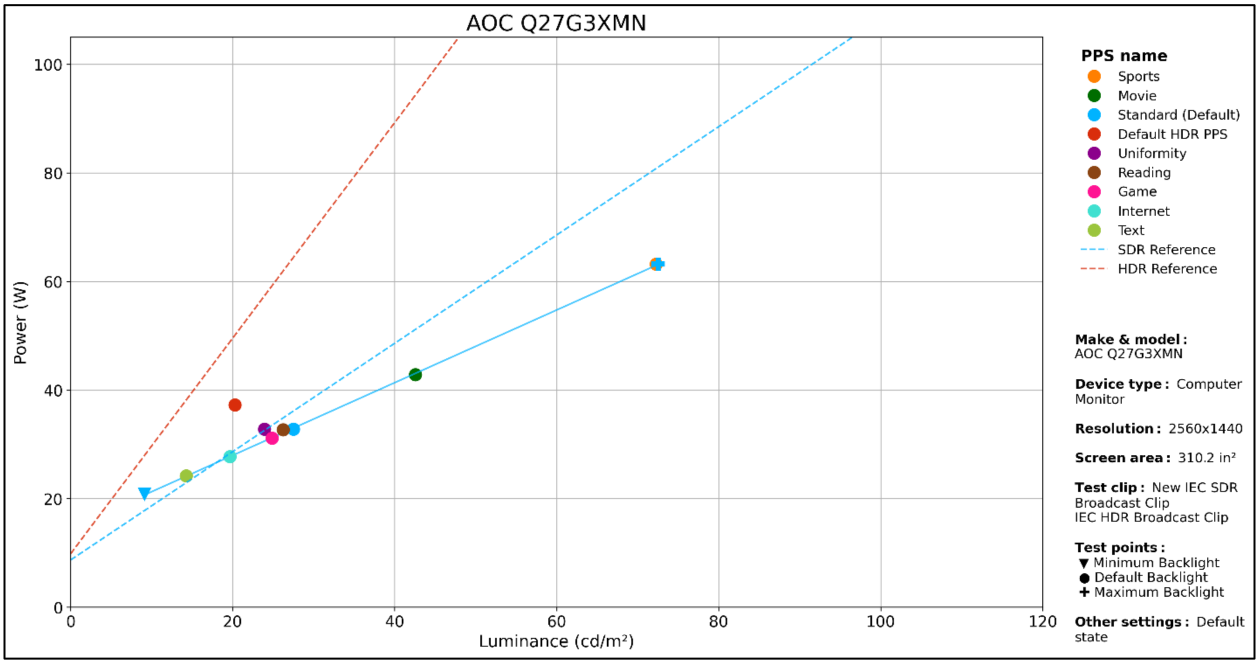

Dell U4021QW
Power (W)
Luminance (cd/m²)
0
20
40
60
80
100
120
PPS name
Color Space sRGB
Movie
Game
Color Space DCI-P3
Standard (Default)
SDR Reference
Make & model: Dell U4021QW
Device type: Computer Monitor
Resolution: 5120x2160
Screen area: 582.8 in²
Test clip: New IEC SDR Broadcast Clip
Test points:
▼ Minimum Backlight
● Default Backlight
✚ Maximum Backlight
Other settings: Default state

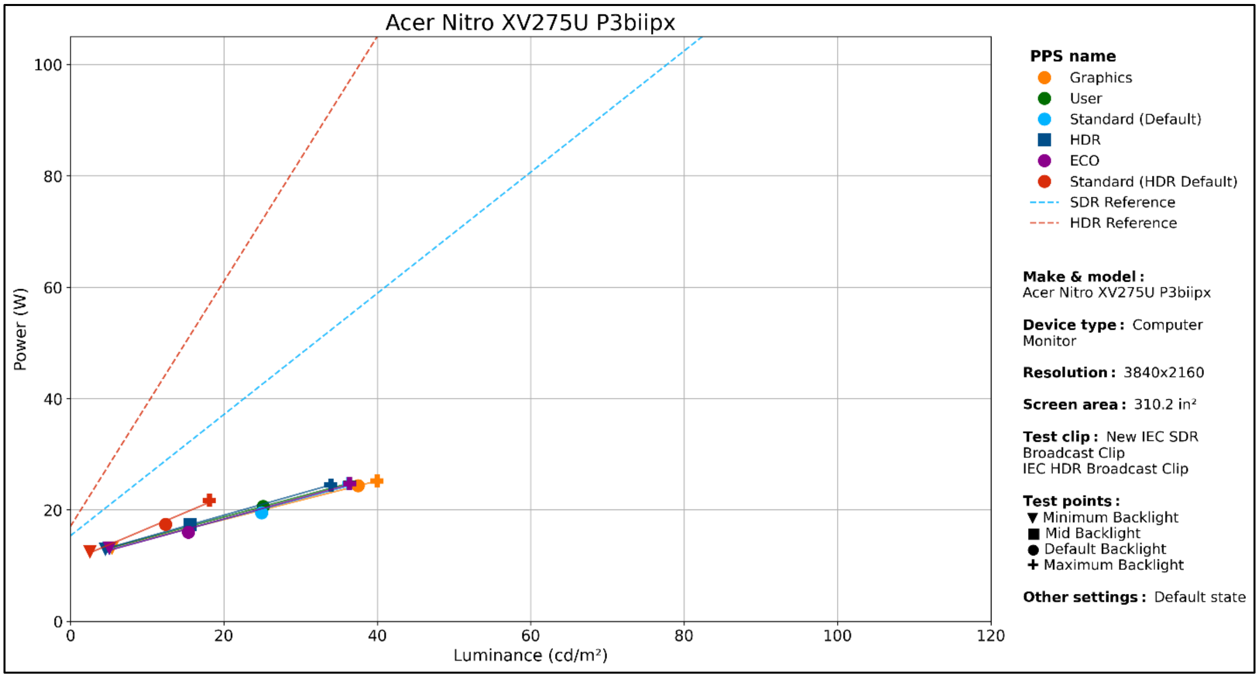

Dell P2423D
Power (W)
Luminance (cd/m²)
0
20
40
60
80
100
120
PPS name
Custom Color
Cool
Game
Movie
Warm
Standard (Default)
SDR Reference
Make & model: Dell P2423D
Device type: Computer Monitor
Resolution: 2560x1440
Screen area: 336 in²
Test clip: New IEC SDR Broadcast Clip
Test points:
▼ Minimum Backlight
● Default Backlight
✚ Maximum Backlight
Other settings: Default state


ASUS ROG Swift Pro PG248QP
Power (W)
Luminance (cd/m²)
0
20
40
60
80
100
0
20
40
60
80
100
120
PPS name
● sRGB (HDR Default)
● G-SYNC Esports
● Scenery
● Cinema
● RTS/RPG
● Racing
● sRGB (Default)
SDR Reference
HDR Reference
Make & model: ASUS ROG Swift Pro PG248QP
Device type: Computer Monitor
Resolution: 1920x1080
Screen area: 246.8 in²
Test clip: New IEC SDR Broadcast Clip
IEC HDR Broadcast Clip
Test points:
▼ Minimum Backlight
● Default Backlight
✚ Maximum Backlight
Other settings: Default state


ASUS ProArt Display PA279CRV
Power (W)
Luminance (cd/m²)
0
20
40
60
80
100
0
20
40
60
80
100
120
PPS name
● Default HDR PPS
● Native (Default)
● DICOM
● Adobe RGB
● Rec. 2020
● Rec. 709
● DCI-P3
● sRGB
SDR Reference
HDR Reference
Make & model: ASUS ProArt Display PA279CRV
Device type: Computer Monitor
Resolution: 3840x2160
Screen area: 314.7 in²
Test clip: New IEC SDR Broadcast Clip
IEC HDR Broadcast Clip
Test points:
▼ Minimum Backlight
● Default Backlight
✚ Maximum Backlight
Other settings: Default state


Apple Studio Display
Power (W)
Luminance (cd/m²)
0
20
40
60
80
100
120
PPS name
Apple Display (Default)
Design & Print
Photography
HDTV Video
NTSC Video
Pal & SECAM Video
Internet & Web
Digital Cinema (P3-DCI)
Digital Cinema (P3-D65)
SDR Reference
Make & model : Apple Studio Display
Device type : Computer Monitor
Resolution : 5120x2880
Screen area : 310.2 in²
Test clip : New IEC SDR Broadcast Clip
Test points :
▼ Minimum Backlight
■ Mid Backlight
● Default Backlight
Other settings : Default state


AOC Q27G3XMN
Power (W)
Luminance (cd/m²)
0
20
40
60
80
100
120
PPS name
Sports
Movie
Standard (Default)
Default HDR PPS
Uniformity
Reading
Game
Internet
Text
SDR Reference
HDR Reference
Make & model : AOC Q27G3XMN
Device type : Computer Monitor
Resolution : 2560x1440
Screen area : 310.2 in²
Test clip : New IEC SDR Broadcast Clip
IEC HDR Broadcast Clip
Test points :
▼ Minimum Backlight
● Default Backlight
✚ Maximum Backlight
Other settings : Default state



Make & model : Acer Nitro XV275U P3biipx

Device type : Computer Monitor

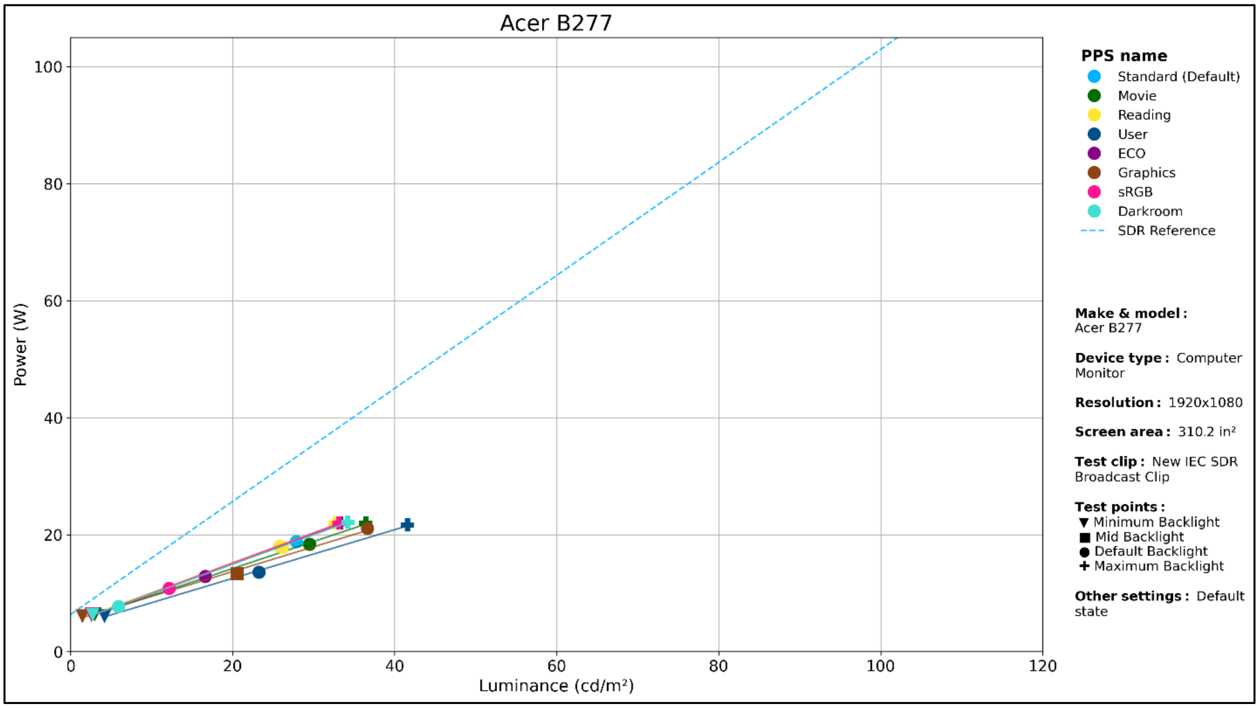
Resolution : 3840x2160

Screen area : 310.2 in²

Test clip : New IEC SDR Broadcast Clip
IEC HDR Broadcast Clip

Test points :
▼ Minimum Backlight
■ Mid Backlight
● Default Backlight
✚ Maximum Backlight

Other settings : Default state



Make & model : Acer B277

Device type : Computer Monitor

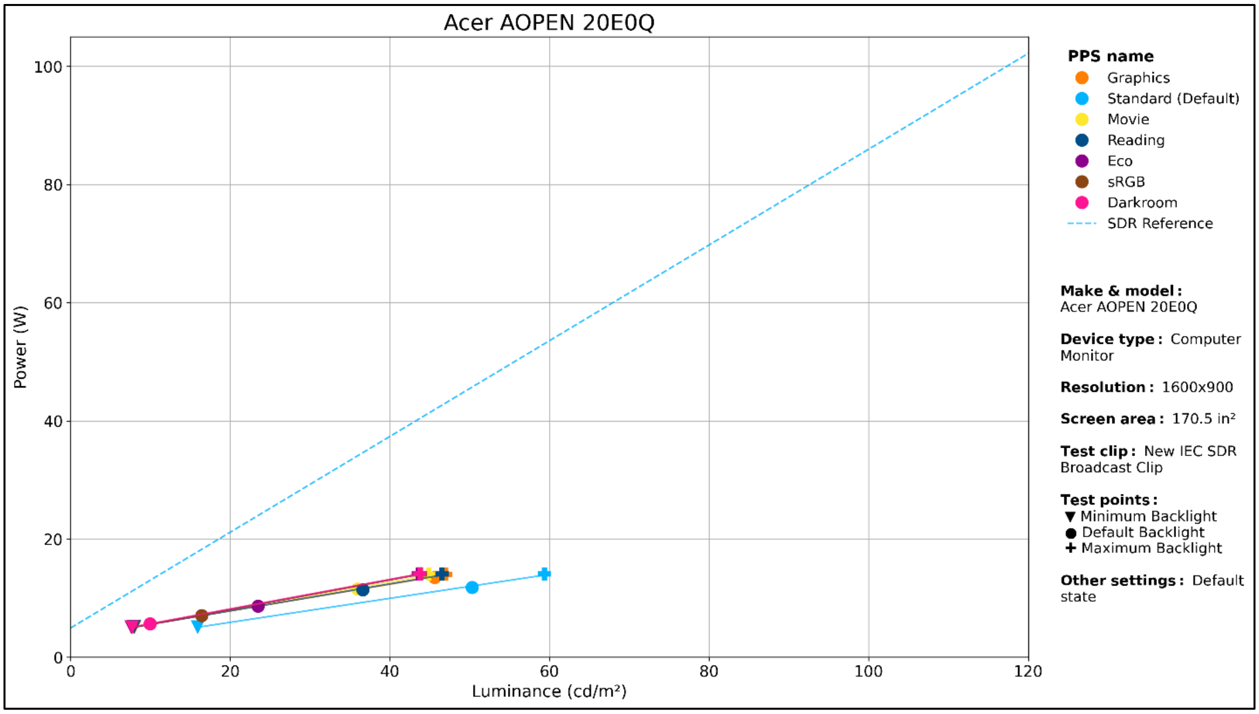
Resolution : 1920x1080

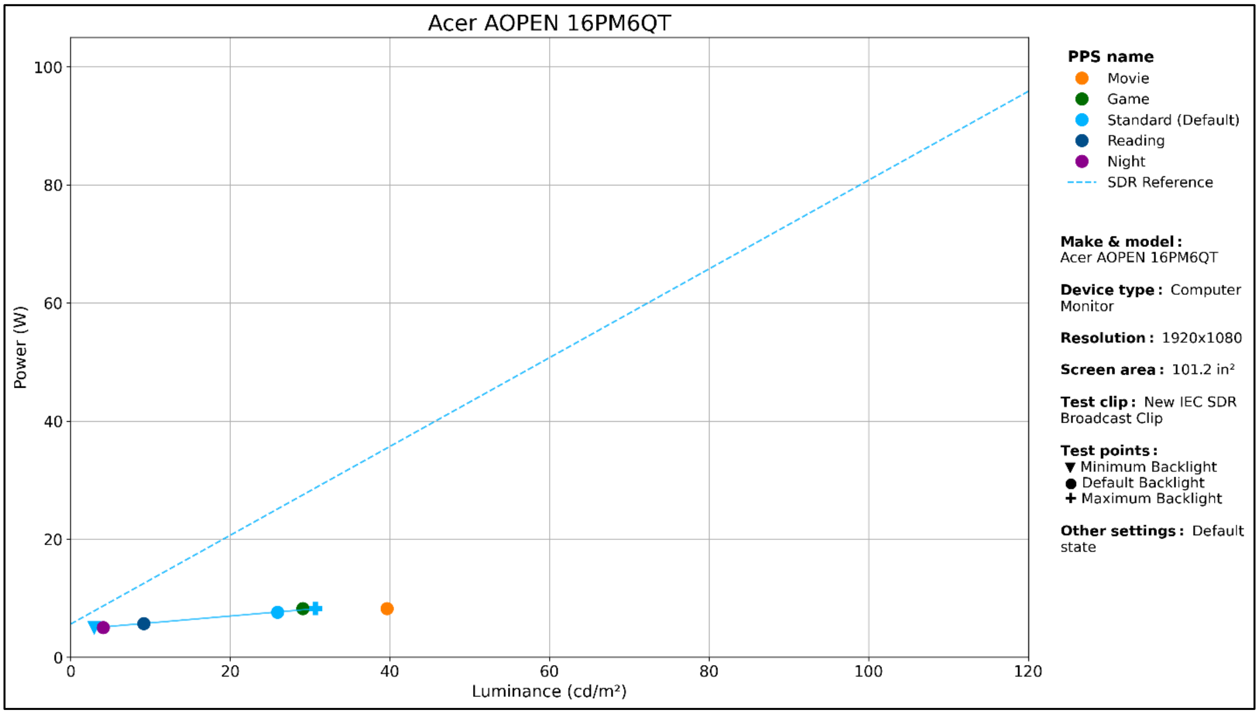
Screen area : 310.2 in²

Test clip : New IEC SDR Broadcast Clip

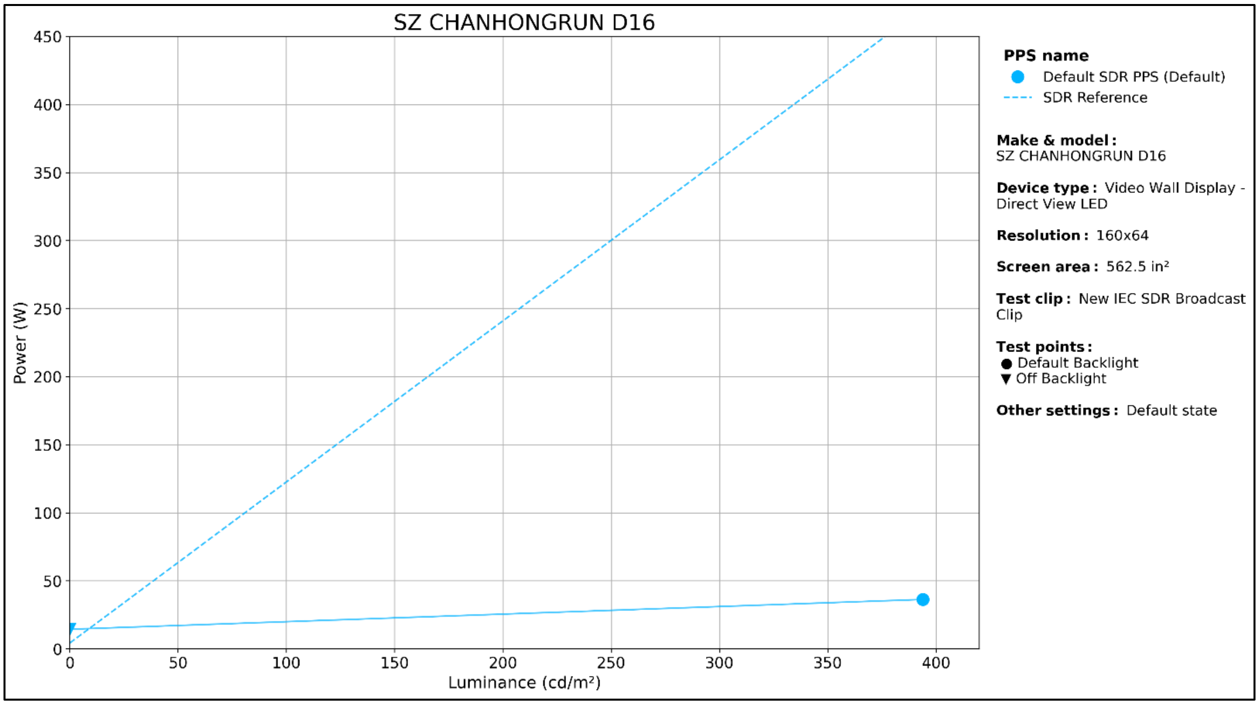
Test points :
▼ Minimum Backlight
■ Mid Backlight
● Default Backlight
✚ Maximum Backlight

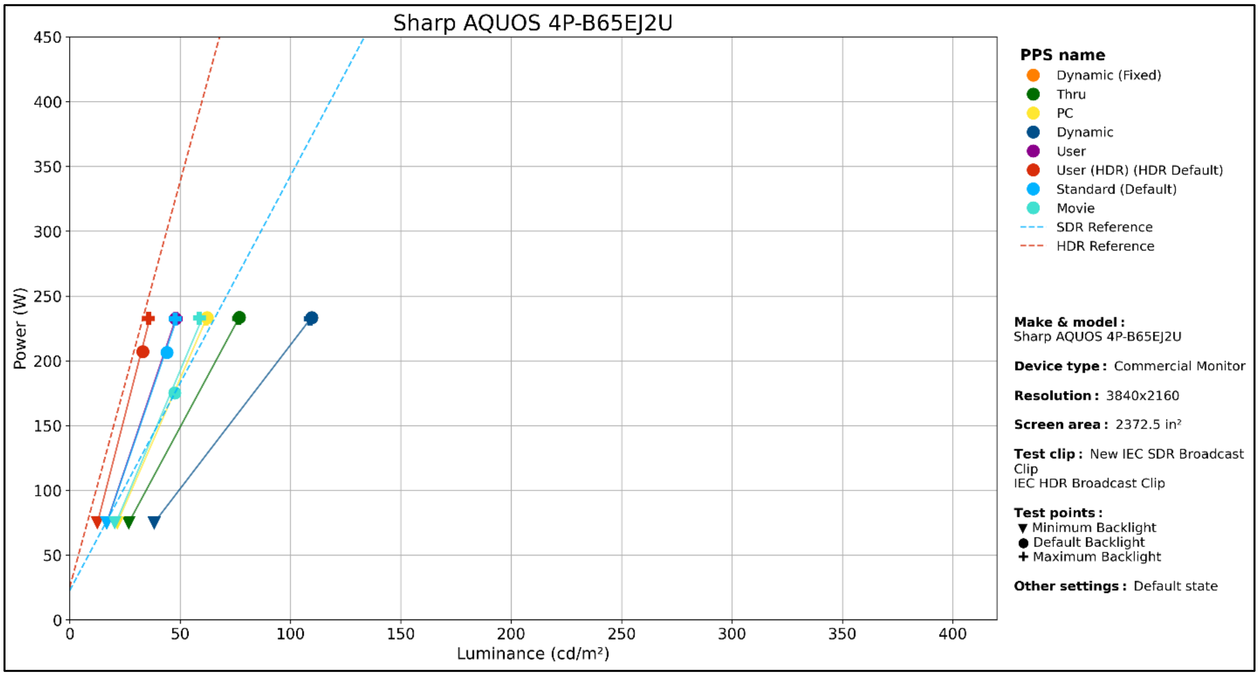
Other settings : Default state

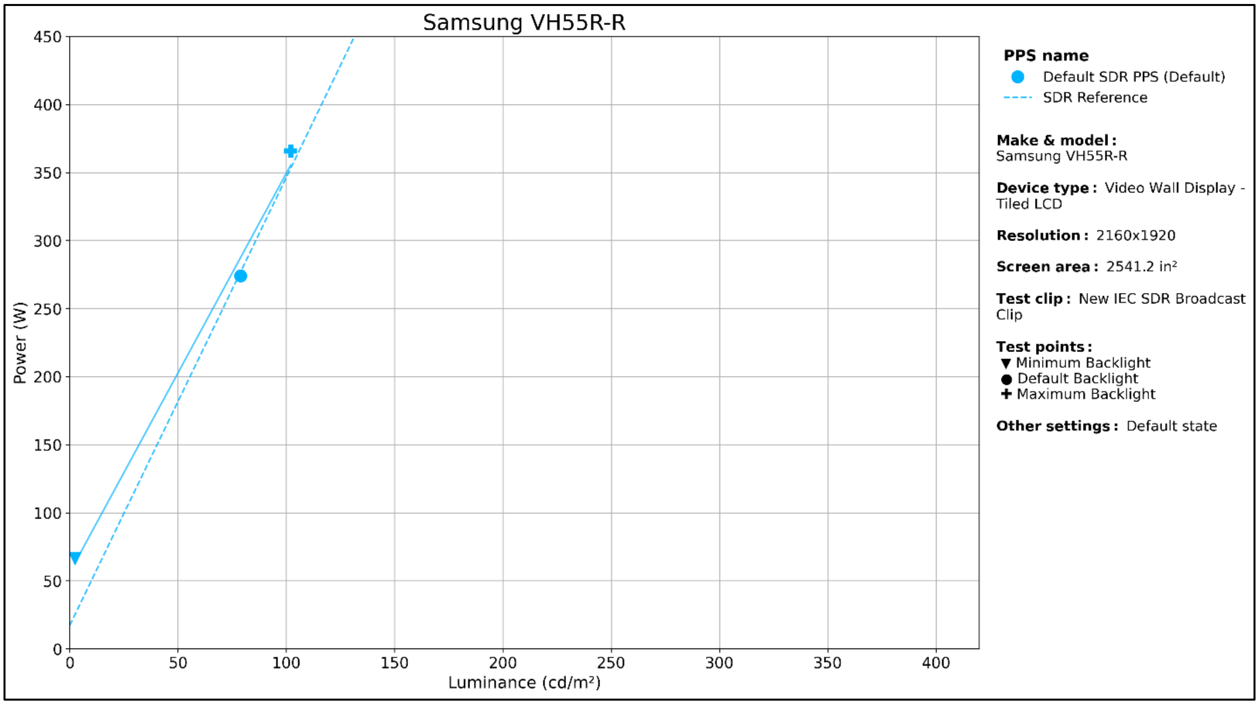

Acer AOPEN 20E0Q
Power (W)
Luminance (cd/m²)
0
20
40
60
80
100
120
PPS name
Graphics
Standard (Default)
Movie
Reading
Eco
sRGB
Darkroom
SDR Reference
Make & model: Acer AOPEN 20E0Q
Device type: Computer Monitor
Resolution: 1600x900
Screen area: 170.5 in²
Test clip: New IEC SDR Broadcast Clip
Test points:
▼ Minimum Backlight
● Default Backlight
✚ Maximum Backlight
Other settings: Default state

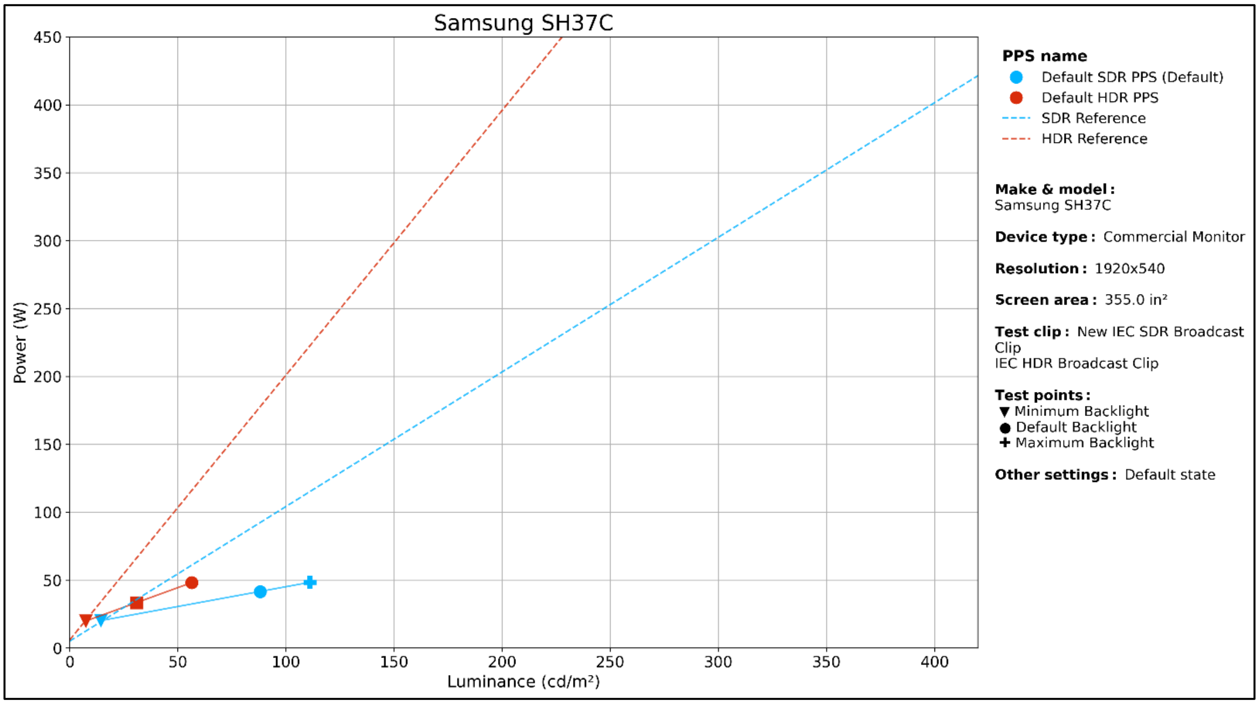

Acer AOPEN 16PM6QT
Power (W)
Luminance (cd/m²)
0
20
40
60
80
100
120
PPS name
Movie
Game
Standard (Default)
Reading
Night
SDR Reference
Make & model: Acer AOPEN 16PM6QT
Device type: Computer Monitor
Resolution: 1920x1080
Screen area: 101.2 in²
Test clip: New IEC SDR Broadcast Clip
Test points:
▼ Minimum Backlight
● Default Backlight
✚ Maximum Backlight
Other settings: Default state

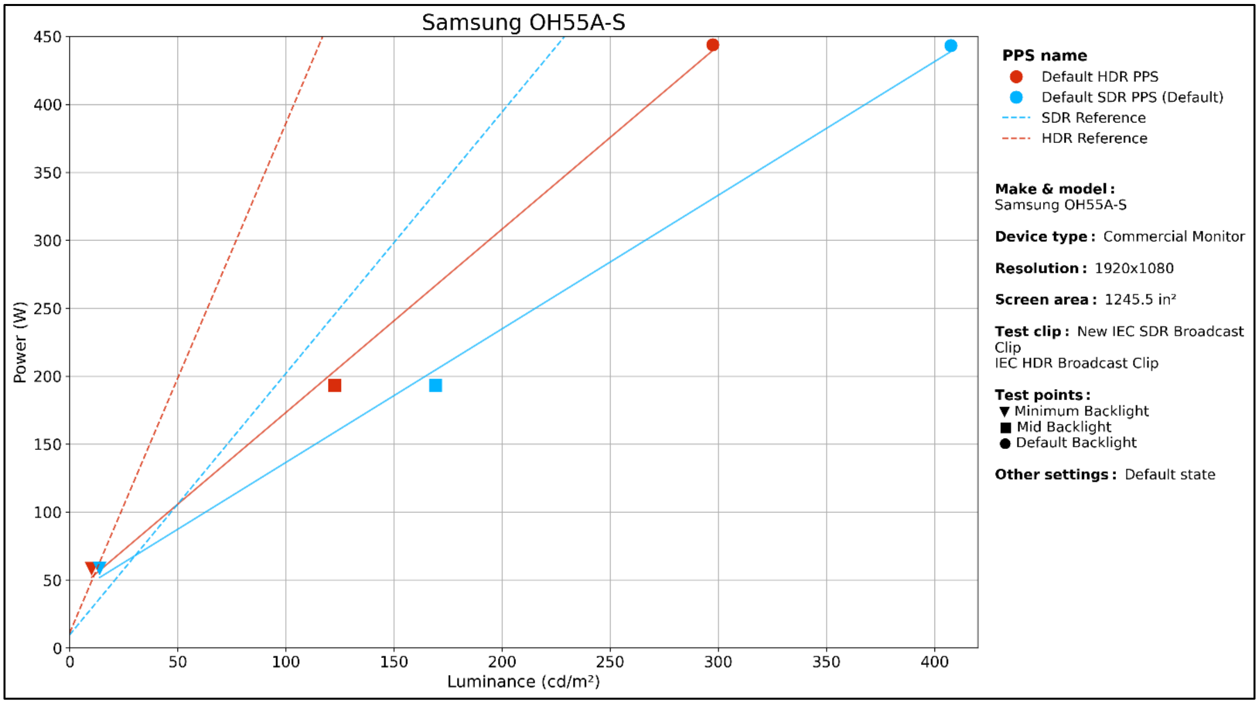
Digital Signage Displays

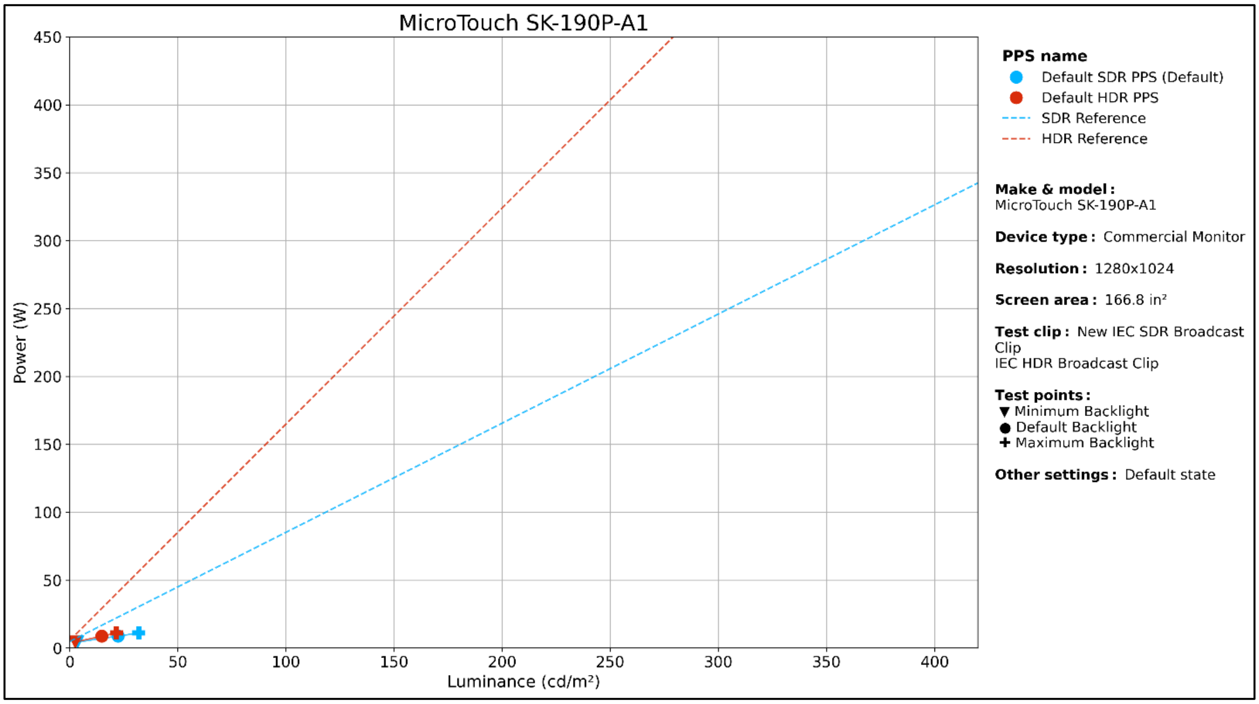


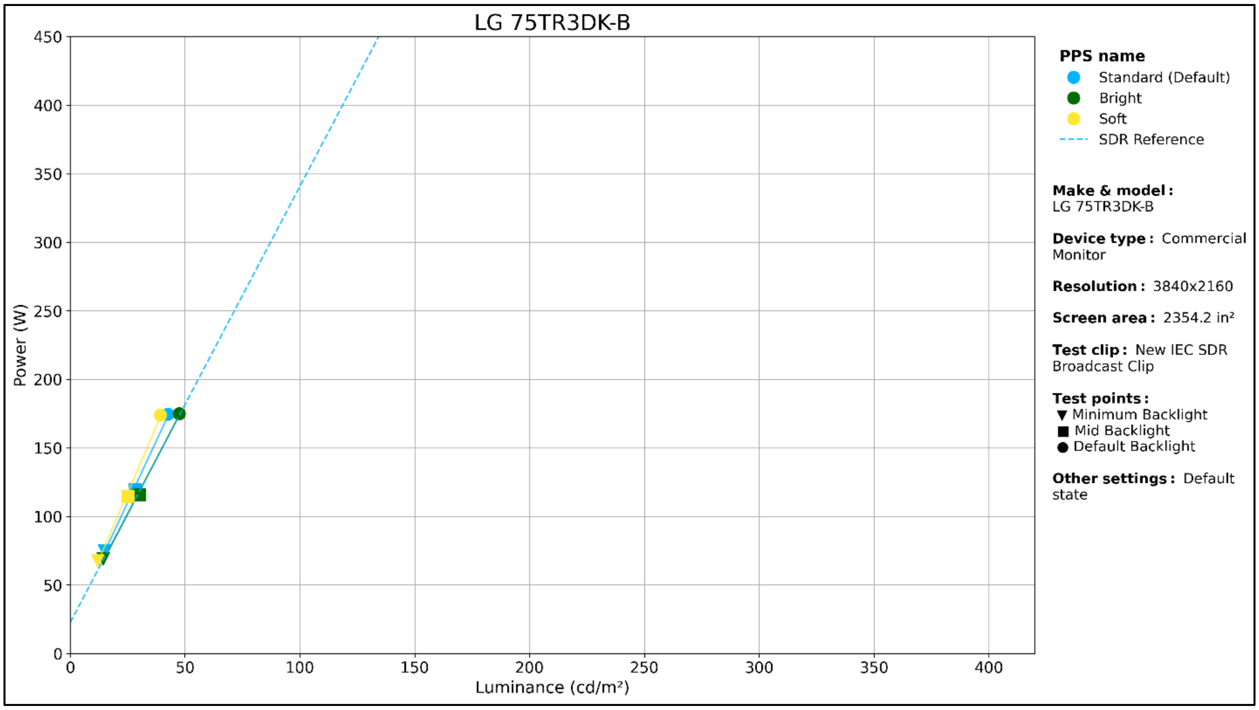


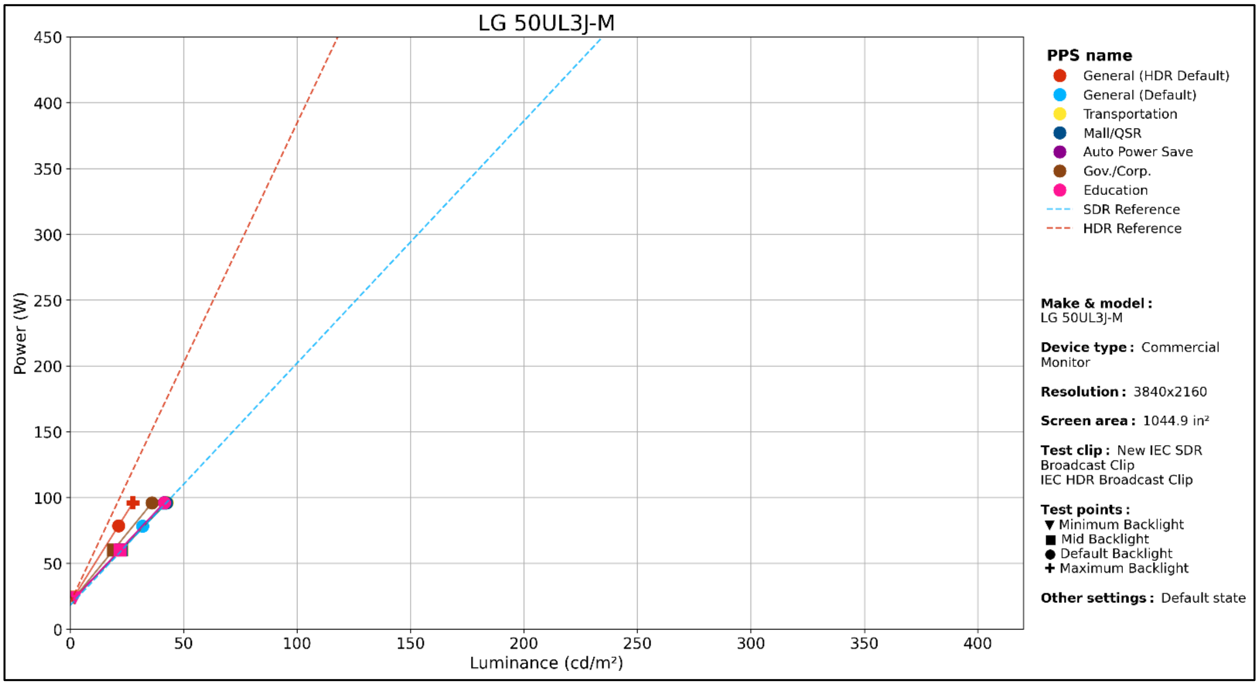

Samsung VH55R-R
Power (W)
Luminance (cd/m²)
0
50
100
150
200
250
300
350
400
450
PPS name
● Default SDR PPS (Default)
SDR Reference
Make & model : Samsung VH55R-R
Device type : Video Wall Display - Tiled LCD
Resolution : 2160x1920
Screen area : 2541.2 in²
Test clip : New IEC SDR Broadcast Clip
Test points :
▼ Minimum Backlight
● Default Backlight
✚ Maximum Backlight
Other settings : Default state

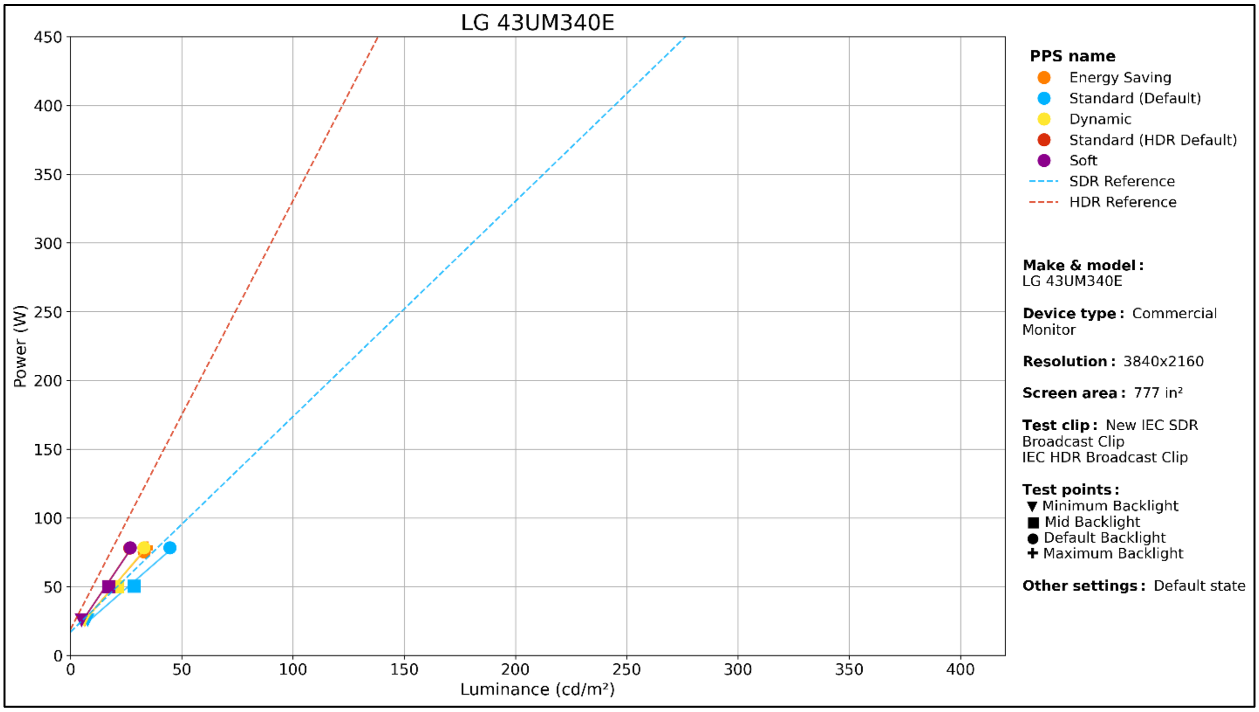

Samsung SH37C
Power (W)
Luminance (cd/m²)
0
50
100
150
200
250
300
350
400
450
PPS name
● Default SDR PPS (Default)
● Default HDR PPS
SDR Reference
HDR Reference
Make & model : Samsung SH37C
Device type : Commercial Monitor
Resolution : 1920x540
Screen area : 355.0 in²
Test clip : New IEC SDR Broadcast Clip
IEC HDR Broadcast Clip
Test points :
▼ Minimum Backlight
● Default Backlight
✚ Maximum Backlight
Other settings : Default state


Samsung OH55A-S
Power (W)
Luminance (cd/m²)
0
50
100
150
200
250
300
350
400
450
PPS name
Default HDR PPS
Default SDR PPS (Default)
SDR Reference
HDR Reference
Make & model: Samsung OH55A-S
Device type: Commercial Monitor
Resolution: 1920x1080
Screen area: 1245.5 in²
Test clip: New IEC SDR Broadcast Clip
IEC HDR Broadcast Clip
Test points:
▼ Minimum Backlight
■ Mid Backlight
● Default Backlight
Other settings: Default state


MicroTouch SK-190P-A1
Power (W)
Luminance (cd/m²)
0
50
100
150
200
250
300
350
400
450
PPS name
Default SDR PPS (Default)
Default HDR PPS
SDR Reference
HDR Reference
Make & model: MicroTouch SK-190P-A1
Device type: Commercial Monitor
Resolution: 1280x1024
Screen area: 166.8 in²
Test clip: New IEC SDR Broadcast Clip
IEC HDR Broadcast Clip
Test points:
▼ Minimum Backlight
● Default Backlight
✚ Maximum Backlight
Other settings: Default state


LG 75TR3DK-B
Power (W)
Luminance (cd/m²)
0
50
100
150
200
250
300
350
400
450
PPS name
Standard (Default)
Bright
Soft
SDR Reference
Make & model: LG 75TR3DK-B
Device type: Commercial Monitor
Resolution: 3840x2160
Screen area: 2354.2 in²
Test clip: New IEC SDR Broadcast Clip
Test points:
▼ Minimum Backlight
■ Mid Backlight
● Default Backlight
Other settings: Default state


LG 50UL3J-M
Power (W)
Luminance (cd/m²)
0
50
100
150
200
250
300
350
400
450
PPS name
General (HDR Default)
General (Default)
Transportation
Mall/QSR
Auto Power Save
Gov./Corp.
Education
SDR Reference
HDR Reference
Make & model: LG 50UL3J-M
Device type: Commercial Monitor
Resolution: 3840x2160
Screen area: 1044.9 in²
Test clip: New IEC SDR Broadcast Clip
IEC HDR Broadcast Clip
Test points:
▼ Minimum Backlight
■ Mid Backlight
● Default Backlight
✚ Maximum Backlight
Other settings: Default state


LG 43UM340E
Power (W)
Luminance (cd/m²)
0
50
100
150
200
250
300
350
400
450
PPS name
Energy Saving
Standard (Default)
Dynamic
Standard (HDR Default)
Soft
SDR Reference
HDR Reference
Make & model: LG 43UM340E
Device type: Commercial Monitor
Resolution: 3840x2160
Screen area: 777 in²
Test clip: New IEC SDR Broadcast Clip
IEC HDR Broadcast Clip
Test points:
▼ Minimum Backlight
■ Mid Backlight
● Default Backlight
✚ Maximum Backlight
Other settings: Default state

Annex D: Modifying the PCL Camera System

Computer monitors and DSDs come in a wider variety of sizes, curvatures, panel types, brightness levels, and aspect ratios than do TVs. With this in mind, PCL's camera hardware and NEEA TV EASY's image processing software were adjusted to encompass as many potential test cases as possible so that the suggested policy product scope would not be constrained by camera limitations. As noted above, PCL plans to share learnings with other camera vendors to foster a robust test equipment vendor base.

PCL's camera system consists of the camera itself and the NEEA TV EASY software to control it.[50] The changes implemented widen the possible use cases for PCL's camera system while preserving the measurement accuracy and uncertainty levels established in the previous version.

Based on an initial assessment of the computer monitor and DSD markets (discussed in section MARKETS AND TECHNOLOGIES), system capabilities were expanded to include:

- **Close-range testing:** Testing at closer viewing distances that are more representative of actual usage for computer monitors
- **High luminance measurements:** Extending the camera's luminance range from 2,000 to 10,000 cd/m^2 to support testing outdoor and semi-outdoor DSDs, which can have peak luminance of up to 10,000 cd/m^2
- **Curved and ultrawide displays:** Improving screen area detection and geometry correction for computer monitors and DSDs with different aspect ratios and curvatures
- **Low pixel density:** Enabling screen area detection and geometry correction for DSDs with low pixel densities
- **Improved calibration method:** Improving luminance calibration to reduce measurement error with twisted nematic displays in particular

The following sections detail the specific adjustments made to achieve these improvements via hardware (changing the camera lens, neutral density (ND) filter, and aperture setting) and software changes.

Close-Range Testing

To maintain consistency with the proposed policy approach, which places the camera photometer at a representative viewing distance, typical viewing distance for computer monitors and DSDs were researched. For computer monitors, research indicates that 1.28 x screen width is the best practical balance between representative viewing distances and the practical constraints of camera photometry per discussion in ANNEX E: JUSTIFYING A MEASUREMENT DISTANCE FOR COMPUTER Monitors. Because this distance is shorter than the TV test distance used in current camera systems on the market, it drives the need for wider field of view (FOV) camera system, which can be achieved with a shift from common 8.6 mm C-mount lens to 6mm.

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[50] While the NEEA TV EASY software will support computer monitors and DSDs as well as TVs, the current software name (TV EASY) will stay as-is.

PCL recommends maintaining the current TV test distance for DSDs (1.77x the display width as detailed in the ANSI/CTA-2037-D standard).[51] While DSDs have varied viewing distances, from close-range kiosks to outdoor displays, the TV testing distance aligns with one common scenario of DSDs with form factors (size and aspect ratio) and viewing distances similar to televisions. We believe this distance can also accommodate all DSDs that PCL recommends including in the product scope (section PRODUCT SCOPE).

The TV test distance for DSDs is an achievable choice for laboratory testing, as it fits within the spatial constraints of most lab setups without requiring excessive space. Since this is the same test distance used for televisions, laboratories 96+already equipped for TV testing can easily accommodate DSDs that are within the size range of commercially available TVs. Of course, larger lab spaces may be necessary for test labs that want to cover larger DSDs. We provided additional discussion on product scope based on screen area in section 1.1.1.33: SCREEN AREA.

Table 108 shows the recommended test distance for different display types as represented by a scaling factor of their width.

Table 108: Viewing distances for different display types

Display Type	Test Distance
Television	1.77x width
Digital signage display	1.77x width
Monitor	1.28x width

Figure 112 illustrates how much of the camera sensor a 16x9 monitor would fill (left) compared to a TV or DSD (right) in a camera system that uses a 6 mm lens like ours.

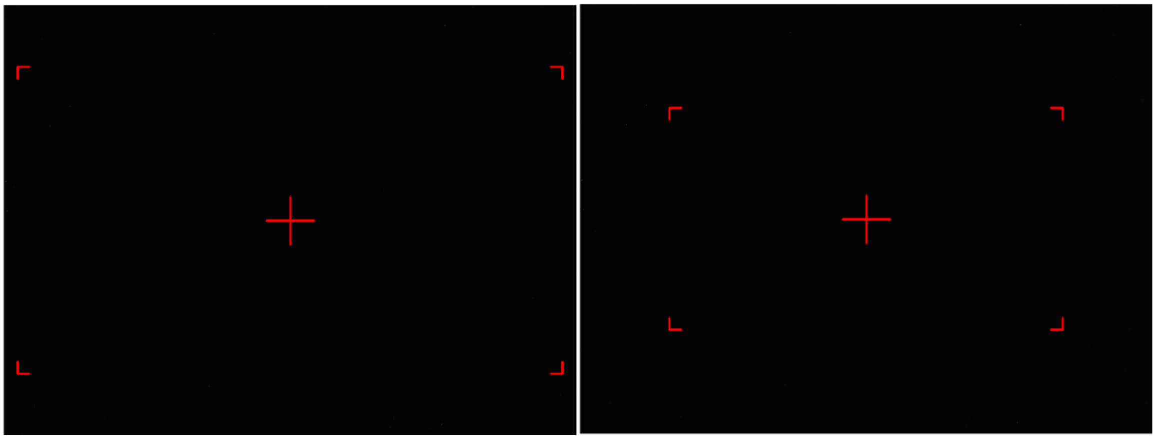

Figure 112: TV EASY's screen guides

Note: These guides are used to help position the camera at the appropriate test distance. On the left are the screen guides for testing a computer monitor, and on the right the screen guides for TVs and DSDs. TVs and DSDs look smaller in the camera feed due to the longer test distance.

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[51] The TV test distance comes from ANSI/CTA-2037-D, which is included by reference in the US federal test method. A justification (based on the diagonal size for TVs) for this test distance is found in PCL's camera technical white paper, appendix D.

In all cases, PCL recommends that displays be tested in landscape orientation, even if they are typically used in portrait mode. This orientation allows the camera photometer—which has a 4:3 or 16:9 landscape aspect ratio across all known vendors—to be positioned closer to the display without cropping the top of the screen. While other camera systems may use different aspect ratios, most are also wider than they are tall, so this approach is likely to be compatible with the majority of camera photometers. As a result, the captured image achieves higher digital resolution over the measured screen area, improving the overall accuracy of luminance measurements.

Current Camera – Gen 2

The second generation of PCL's camera photometer (Gen 2) is deployed worldwide for TV testing.[52] This configuration uses the Basler C23-0816-2M f8 mm lens[53] (Figure 113).

Figure 113: The Gen 2 lens, Basler C23-0816-2M f8mm

Per Figure 114, this lens can accommodate the required test distances for both TV and DSD testing. It can capture the full screen from as close as 1.6x the width of a display, which provides enough flexibility to position the camera slightly farther back and meet the 1.77x width viewing distance target.

---

[52] PCL plans to offer low- or no-cost Gen 2 to Gen 3 camera upgrades to existing kit owners.

[53] Basler's listing title for the C23-0816-2M f8 mm lens suggests it is an f8 mm lens. However, the lens's actual focal length is 8.6mm.

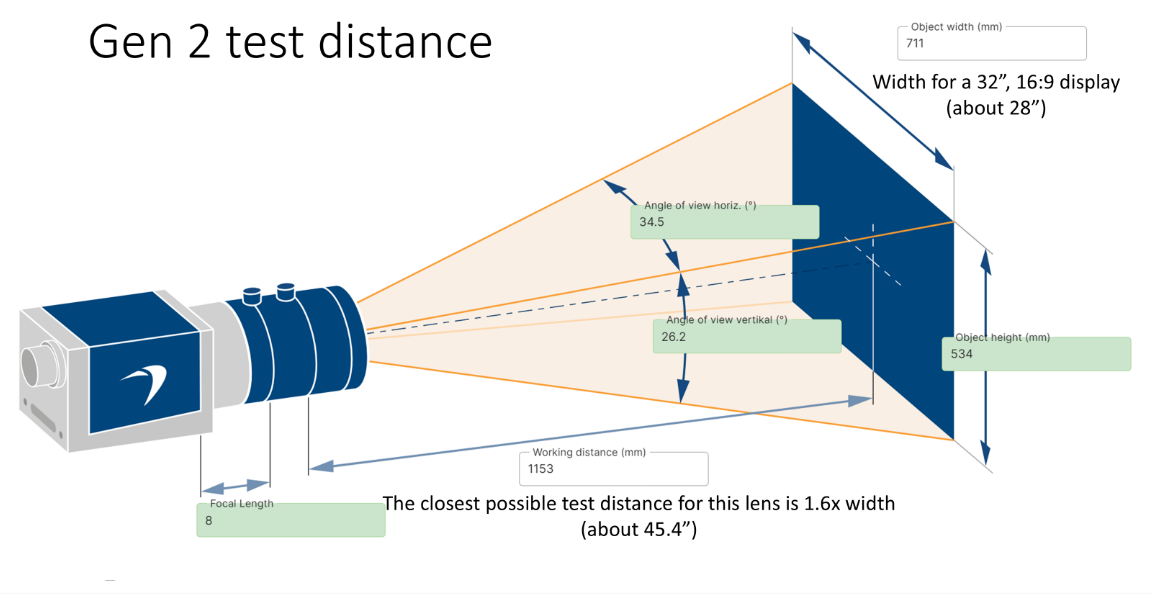


Figure 114: The closest possible test distance for the Gen 2 lens

Updated Camera – Gen 3

PCL's Gen 3 camera photometer uses the Basler C125-0618-5M f6 mm (Figure 3), which has a wider field of view. As shown in Figure 116, this lens can accommodate the proposed test distance for computer monitors.

Figure 115: New lens, Basler C125-0618-5M f6mm

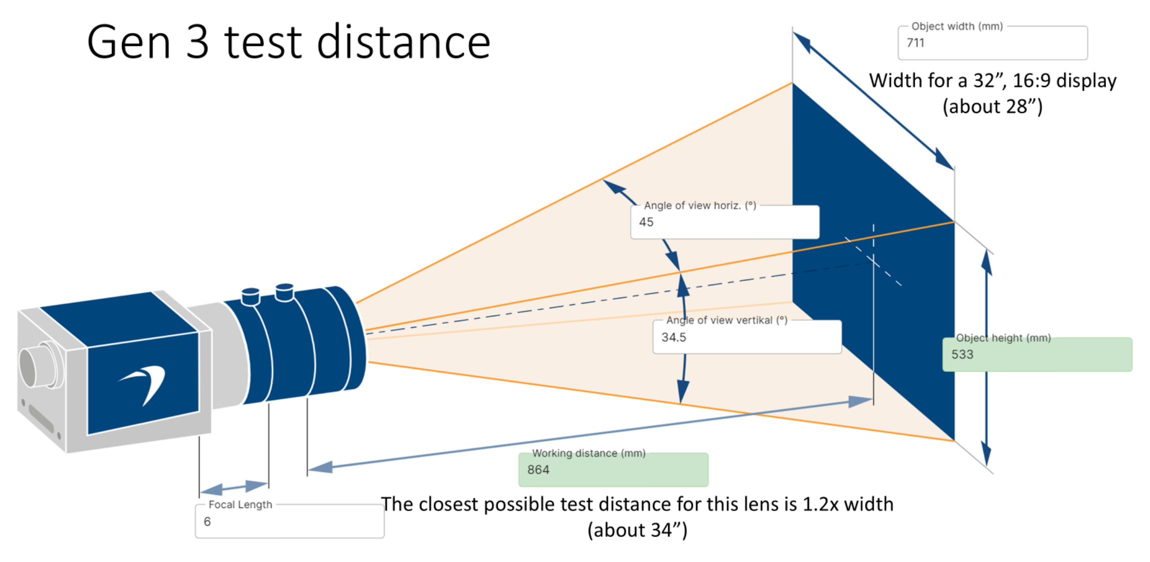


Figure 116: Working distance for the new lens

We collaborated with an experienced manufacturer of precision optical filters and coatings to develop a new version of the ND filter used in PCL's Gen 2 camera that accommodates the wider angle lens used in the Gen 3 camera. While the form factor was modified to ensure compatibility with the new lens, the filter maintains the same optical performance as the Gen 2 camera.

High Luminance Measurements

Our new Gen3 camera can measure peak brightness up to 10,000cd/m^2 while maintaining measurement precision. This increase allows testing digital signage displays (DSDs) that can reach significantly higher luminance levels than televisions.

For comparison, the Gen 2 camera system has a luminance measurement range of 0-2,000 cd/m^2 at the pixel level (meaning pixels receiving over 2,000 cd/m^2 are clipped at 2,000 cd/m^2). Although this is sufficient for testing computer monitors and televisions, it falls short for certain DSDs. Some outdoor and semi-outdoor or "window" DSDs on the market now have peak brightness levels of up to 10,000 cd/m^2.

To accurately measure bright DSDs without overexposing the camera sensor, the amount of incoming light was limited by reducing the iris aperture from *f*/4 to *f*/9.15. The image below illustrates how the f-stop number correlates with the camera's aperture size.

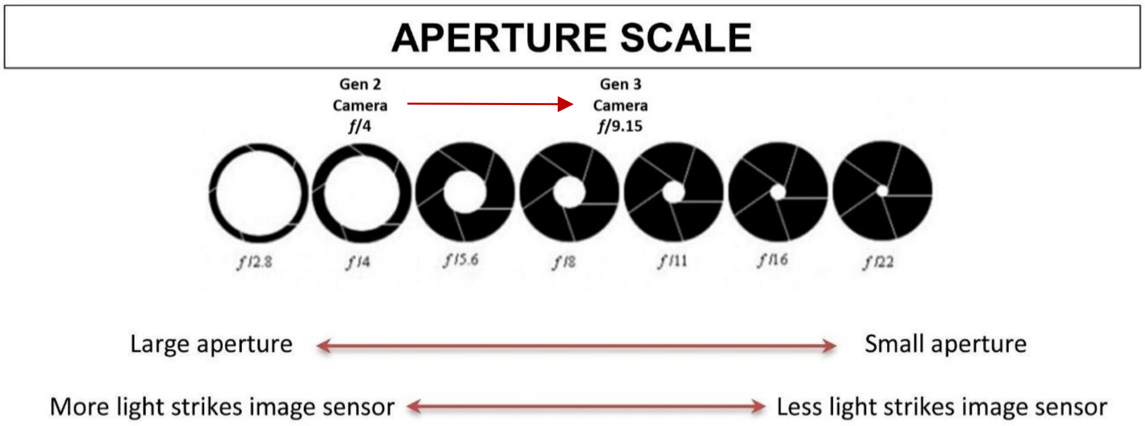


Figure 117: Aperture scale chart from photographer.org

Note: Annotation shows the move from f/4 to f/9.15

This adjustment expands PCL's maximum measurable luminance to 10,000 cd/m^2, ensuring that PCL's system can effectively capture and analyze high-luminance DSDs while maintaining measurement precision. Table 109 summarizes the light reduction components for each camera and the maximum luminance the camera can measure.

Table 109: Comparison between light reduction and camera signal in both camera configurations

	Light Reduction					Camera Signal		
	Iris F-stop	Iris Reduction Factor	ND Filter Optical Density	ND Filter Reduction Factor	Total Light Reduction	Camera Max Signal Level	Maximum cd/m^2 Reading	Calibration Slope
Gen 2 Configuration	*f*/4	1/16	1.8	1/64	0.00098	4016	2008	0.5
Gen 3 Configuration	*f*/9.15	137/3098	1.8	1/64	0.00019	4076	10664	2.6

Where Table 109 light reduction column descriptions are:

- **Iris F-stop:** The approximate f-stop setting of the camera's iris or aperture
- **ND Filter Optical Density:** The ND factor of the camera's neutral density filter
- **Iris Reduction Factor:** The factor by which iris setting reduces the light that reaches the camera sensor
- **ND Filter Reduction Factor:** The factor by which the ND filter reduces the light that reaches the camera sensor

- **Total Light Reduction:** The total factor by which light is reduced before reaching the camera sensor

We use a 12-bit camera sensor, which means that the maximum signal level of the camera (the number that would represent the brightest possible pixel) is 4096 or 2^{12}, minus the black level value. By reducing how much light reaches the sensor, this maximum signal can be matched to a higher luminance reading, which increases the maximum luminance PCL's camera can measure before clipping its readings.

The following values were calculated for each camera configuration, shown on Table 109:

- **Camera Max Signal Level:** The maximum signal level of the camera after taking out the black level
- **Maximum cd/m^2 Reading:** The maximum possible cd/m^2 measurement targeted for each camera configuration
- **Calibration Slope:** The approximate calibration slope that can be obtained given the maximum cd/m^2 range targeted; this value is obtained by dividing the Maximum cd/m^2 Reading by the Camera Max Signal Level

PCL set PCL's Gen 3 cameras to a master black level of 20 camera signal levels to avoid non-linear response at low luminance readings. As detailed in PCL's camera technical white paper, this non-linearity arises because the camera is designed to prevent negative pixel values when the black level is set to zero. In low light, individual pixel noise naturally fluctuates by a few signal levels in both positive and negative directions. When negative values are clipped to zero, the average pixel level becomes artificially elevated, inflating low screen-average luminance measurements. By setting the black level sufficiently above the noise floor, it is ensured that these small negative excursions remain representable, thereby maintaining a linear and accurate response at low luminance.

This higher maximum luminance of the camera comes at a cost of lower digital resolution. Each signal level in the Gen 2 camera represents 0.5 cd/m^2, whereas in the Gen 3 camera each signal level represents 2.6 cd/m^2. However, since PCL's screen-average measurement represents the mean value of tens of thousands of pixels, the effective digital resolution of PCL's screen-average luminance readings is still exceptionally small, even in the Gen 3 camera.

Table 110 shows the camera system's active pixels at different test distances and aspect ratios.

Table 110: Active camera pixels at different test distances

Display Type	Test Distance	Aspect Ratio	Active Pixels
TV/DSD	1.77x width	16:9	50,000
Computer monitor	1.28 x Width	16:9	230,000
DSD	1.77x width	32:9	25,000
Computer monitor	1.28 x Width	32:9	115,000

For most common use cases, the camera has between 25,000 and 230,000 active pixels measuring luminance across the display area. The luminance measurement is of average luminance across the entire pixel array. This averaging dramatically improves effective resolution.

Each pixel also exhibits random measurement noise with a standard deviation of approximately 5 cd/m^2. When averaging across 50,000 independent pixel measurements, the standard error of the mean (SEM)—which reflects the uncertainty in the average due to random noise—is calculated as:

$$SEM = \frac{5\ cd/m^2}{\sqrt{50{,}000}} \approx 0.022\ cd/m^2$$

This means that, although each individual pixel has a coarse digital resolution at 2.6 cd/m^2 per level and moderate noise, the effective resolution of the average luminance measurement is approximately ±0.022 cd/m^2. This level of precision allows for high-confidence measurement of screen-average luminance.

Implementation

This section details the testing conducted to finalize the Gen 3 camera system configuration.

As previously described, expanding the camera system's measurable luminance range required reducing the amount of light reaching the sensor so that the camera's maximum signal level would correspond to a luminance reading of 10,000 cd/m².

We can achieve this light reduction using two hardware-based methods: darkening the camera's neutral density (ND) filter and closing the camera lens's iris or aperture.

To determine the optimal combination of these methods, PCL calibrated using three different ND filters. Table 111 summarizes the ND and light reduction factors of the filters tested.

Table 111: Summary of ND filters tested

ND Factor	Light Reduction Stops
1.8	6 stops
2.1	7 stops
2.4	8 stops

For each ND filter, the iris was adjusted to achieve a maximum luminance target of 10,000 cd/m². PCL then compared the calibration results to identify which configuration offered the lowest measurement error and the most linear response. Table 112 summarizes the results.

Table 112: Summary of calibration results for different potential camera configurations

Iris F-stop	ND Factor	Calibration Pattern	Camera Signal	Reference Device	Calibrated Camera	Calibration Error %
8	1.8	1	71.64	179.40	179.37	0.0%
		2	15.42	38.28	38.66	1.0%
		3	8.76	22.37	21.99	-1.7%
		4	0.90	2.38	2.32	-2.2%
		5	0.11	0.27	0.36	33.5%
5.6	2.1	1	74.59	181.30	181.30	0.0%
		2	15.99	38.81	39.00	0.5%
		3	8.85	22.02	21.66	-1.6%
		4	0.85	2.31	2.23	-3.6%
		5	0.15	0.27	0.52	89.5%
4	2.4	1	70.44	180.40	180.47	0.0%
		2	15.18	39.31	39.05	-0.6%
		3	8.51	22.14	21.98	-0.7%
		4	0.88	2.33	2.45	5.1%
		5	0.12	0.28	0.50	81.2%

Where the columns are:

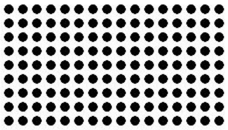
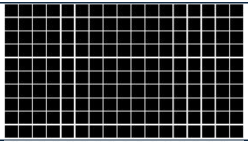
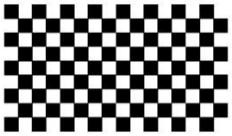
- **Iris F-stop:** The approximate f-stop setting of the camera's iris or aperture
- **ND Factor:** The ND filter strength, expressed as the optical density value by which incoming light is reduced
- **Calibration Pattern:** The specific test pattern measured, corresponding to one of the patterns from the CCF clip introduced in Table 96
- **Camera Signal:** The raw signal level recorded by the camera prior to calibration
- **Reference Device:** The luminance value measured by the reference device, the PR-655 SpectraScan
- **Calibrated Camera:** The luminance value output by the camera after applying calibration coefficients
- **Calibration Error %:** The percentage error between the calibrated camera reading and the reference device measurement

As shown in Table 112, the three configurations performed similarly across most luminance levels, with the greatest differences occurring below 0.3 cd/m^2. We chose the ND 1.8 filter with an iris f-stop of 8, as it delivered the lowest error in this low-luminance range.

Curved and Ultrawide Displays

To accommodate curved and ultrawide displays, the screen area detection and geometry correction code was modified (what is referred to as “screen configuration”) in PCL’s NEEA TV EASY software to ensure support across diverse display configurations. The NEEA TV EASY software now gives the option to select among three screen configuration patterns, each designed to optimize a specific test case (Table 113).

Table 113: Screen configuration patterns

Pattern	Pattern Name	Usage
	Dots	General TV and DSD testing
	Lines	General computer monitor testing[54]
	Checkerboard	Low pixel density display testing (see 0 Low Pixel Density for details)

The updated screen configuration code adds re-projection error analysis, allowing us to evaluate calibration accuracy across the entire display surface. This helps us correct for distortion by compensating for lens-induced warping, so that straight lines and uniform spacing in the captured image more closely match their true physical layout. This is especially valuable for curved screens, where the pinhole camera model (commonly used for distortion correction in software) may not fully account for the additional distortion introduced by the display’s curvature. The updated grid detection logic also improves handling of non-linear spacing between calibration points, which is more common on curved surfaces, by ensuring neighbor relationships and grid spacing are evaluated dynamically.

The software’s approach to perspective correction was refined.[55] It adjusts for camera orientation and position (such as tilt, rotation, or off-axis viewing) so that the entire grid appears properly aligned and proportioned from a frontal viewpoint.

Lastly, the option to generate custom screen configuration patterns was added to NEEA TV EASY (Figure 118) to accommodate non-16:9 aspect ratios.

---

[54] The Lines pattern was implemented after concluding PCL’s laboratory testing, so PCL’s computer monitor testing was completed using the Dots pattern instead, which worked adequately. The Lines pattern is more resilient when testing curved screens, meaning that the tester can complete screen configuration with a lower failure rate.

[55] Perspective correction refers to the global, linear transformation required to map the observed grid onto an idealized flat reference plane.

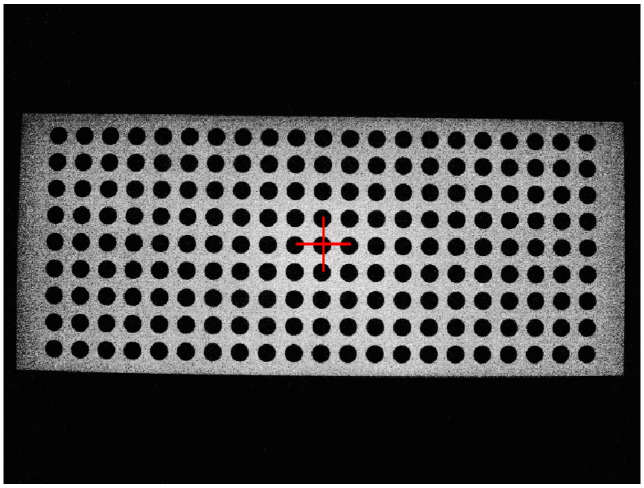


Figure 118: A 21:9, 2500R curved screen, pre-screen configuration

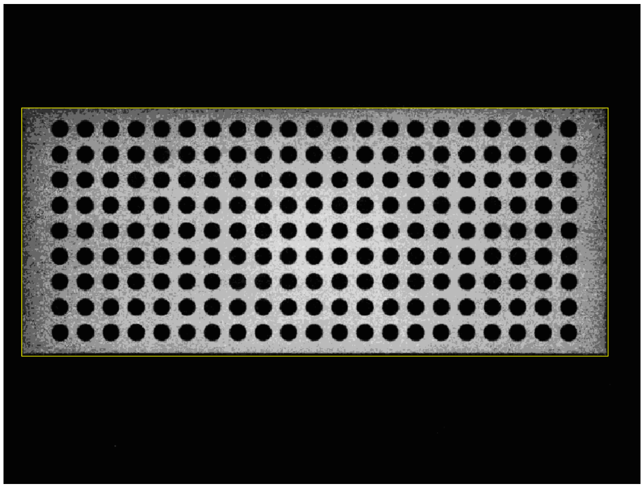


Figure 119: The same screen, post-screen configuration

This was an important adjustment to the PCL camera system, as the monitor market is seeing an increased adoption of curved and ultrawide displays. Ultrawide and curved monitors (Figure 120) introduce non-traditional aspect ratios and geometry that can affect the camera photometer's screen-area detection and geometry correction. Similarly, digital signage displays (DSDs) offer greater design flexibility, with unconventional aspect ratios (Figure 121) and layouts tailored to specific applications such as video walls, public transport signage, and checkout kiosks.

Figure 120: The Samsung Odyssey Neo G9 gaming monitor

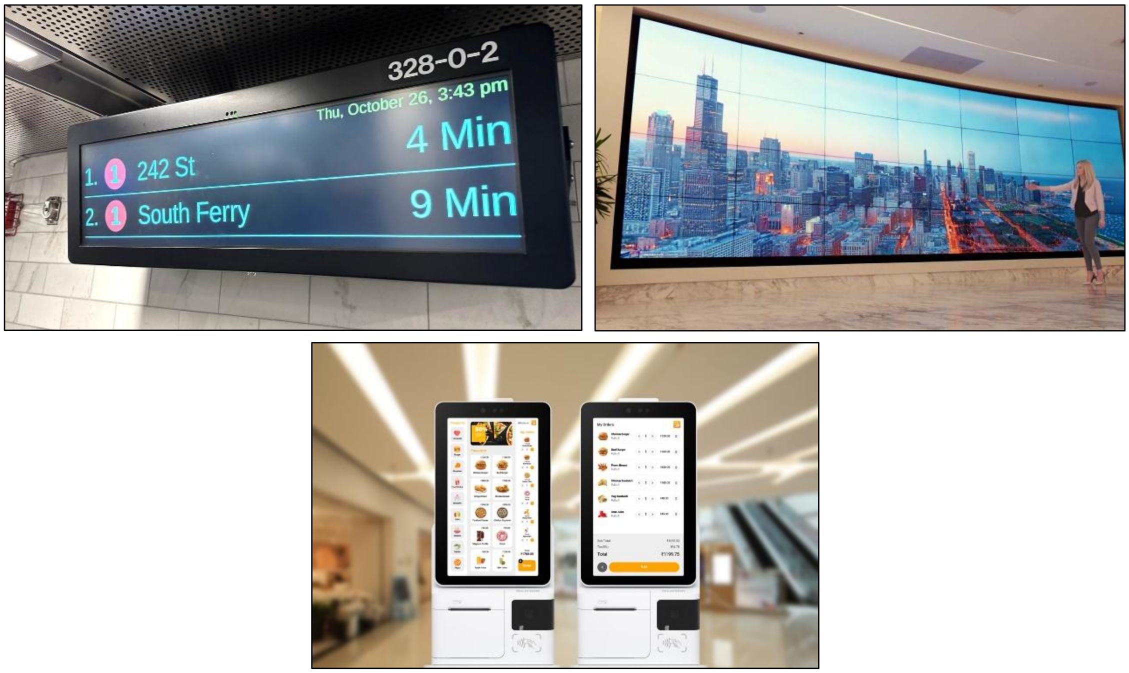


Figure 121: Digital signage can stray from the traditional 16:9 aspect ratio

Low Pixel Density

As shown in the previous section, the screen area detection method relies on a grid of black dots on a white background. However, since low-pixel-density displays cannot render this pattern clearly due to resolution limitations, the software was not previously able to accurately recognize the screen area border of these displays.

An example of a low pixel density display is the SZ CHANHONGRUN D16 display (Figure 122). This is a 160x64 resolution display with a pixel density of approximately 17.91 pixels/in^2, leading to visible pixels at close viewing distances (Figure 123). This type of pixel pitch is commonly used in applications where the display will be viewed from far away, such as in stadium fields.

Figure 122: The SZ CHANHONGRUN D16 display

Figure 123: A frame from the IEC broadcast test clip, shown on the D16 display

To accommodate displays with low pixel density, a checkerboard calibration pattern was implemented, which enables more reliable screen configuration across a wider range of display pixel pitches (Figure 124).

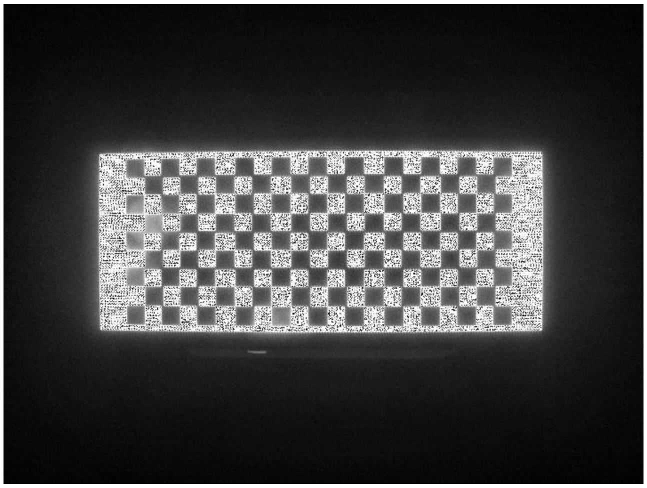


Figure 124: 160x64 display, pre-screen configuration

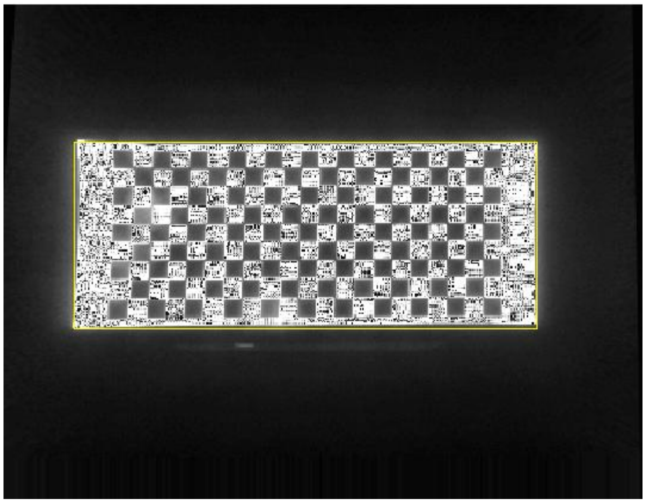
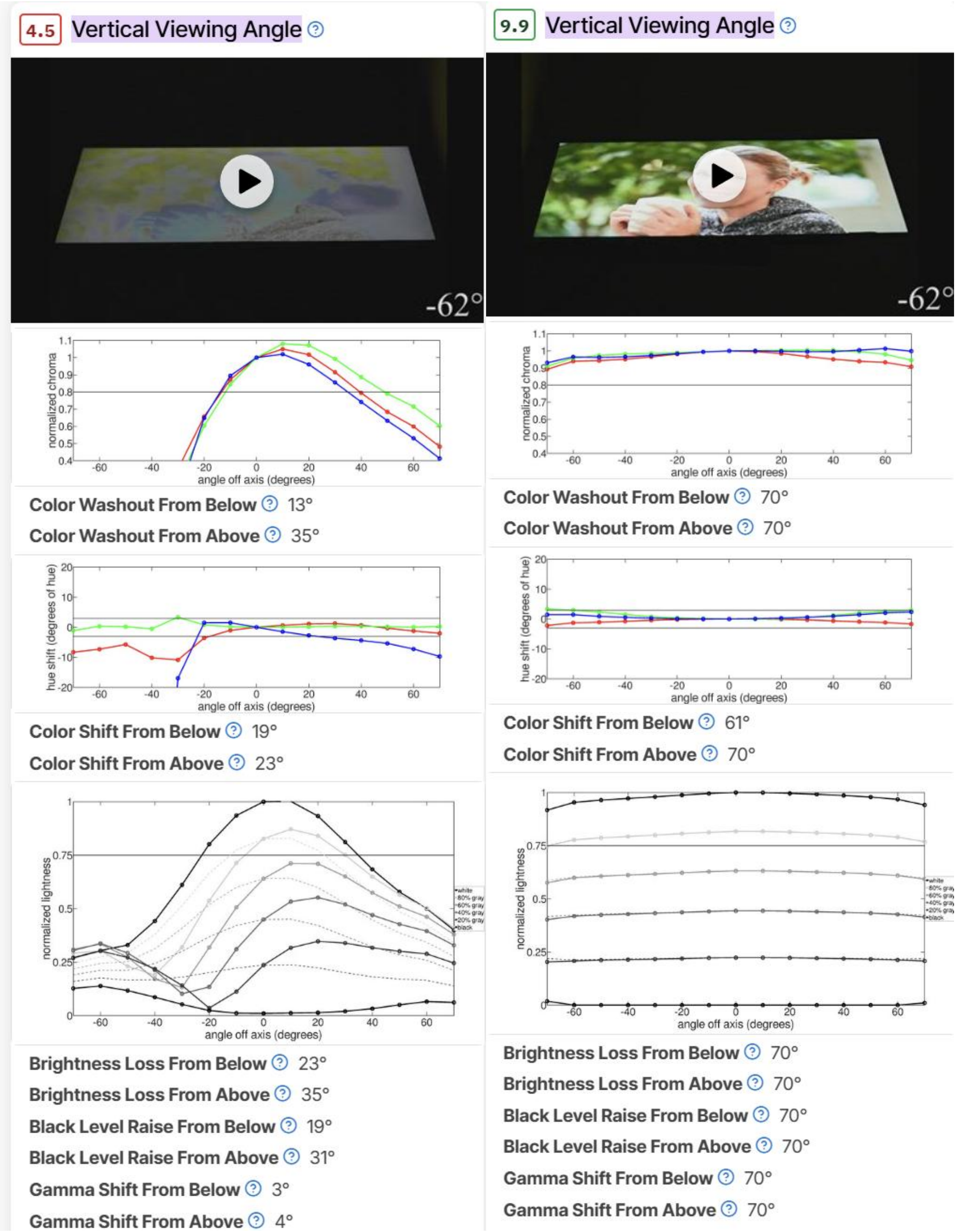


Figure 125: 160x64 display, post-screen configuration

Improved Calibration Method for Different Display Panel Types

Initial testing showed high calibration error in computer monitors using Twisted Nematic (TN) panel technology. Unlike other LCD technologies like In-Plane Switching (IPS) and Vertical Alignment (VA) panels (which is expanded on in section DISPLAY TECHNOLOGIES), TN monitors displayed non-linear luminance behavior that results in significant measurement error, as illustrated in Figure 126 which shows viewing angle data from RTINGS, a website that shares picture quality (and other) testing results of televisions and computer monitors.



4.5 Vertical Viewing Angle

Color Washout From Below 13°

Color Washout From Above 35°

Color Shift From Below 19°

Color Shift From Above 23°

Brightness Loss From Below 23°

Brightness Loss From Above 35°

Black Level Raise From Below 19°

Black Level Raise From Above 31°

Gamma Shift From Below 3°

Gamma Shift From Above 4°

9.9 Vertical Viewing Angle

Color Washout From Below 70°

Color Washout From Above 70°

Color Shift From Below 61°

Color Shift From Above 70°

Brightness Loss From Below 70°

Brightness Loss From Above 70°

Black Level Raise From Below 70°

Black Level Raise From Above 70°

Gamma Shift From Below 70°

Gamma Shift From Above 70°

Figure 126: Vertical viewing angle test results from RTINGS

The ASUS ROG Swift Pro PG248QP with a TN panel (left) shows a non-linear panel response across viewing angles when compared to the ASUS ROG Swift PG27AQDM with an OLED panel (right). While the color washout, color shift, and brightness loss remain consistent across viewing angles with the OLED panel, the TN panel shows sudden drops at around-20 degrees vertically.

This issue potentially arises from luminance non-uniformity between white and grey patterns on TN panels, coupled with the stray light sensitivity of camera photometers. To address this issue, the following modifications were made, which also improved calibration accuracy for other panel types tested:

- An updated distribution of gray levels in the CCF video clip that avoids 100% white
- A minimum luminance level requirement for CCF measurements
- Polynomial vs. linear CCF corrections
- CCF test clips with limited-range video output

Testing shows this approach significantly reduces measurement error in TN monitors and improves accuracy overall.

The slide deck found at this link in PCL's Google Drive summarizes PCL’s initial issues with calibration error when testing TN LCD panels, as well as the updates made to PCL’s calibration method that led to higher-accuracy readings across panel types.

Note on Using the Camera as a Spot Photometer

PCL’s camera should not be used as a spot photometer with high-contrast patterns. Due to stray light, which can scatter within the optical system, adjacent lighter or darker areas may influence screen-center readings and reduce measurement accuracy.

PCL evaluated how stray light might impact screen-center measurements taken with PCL’s camera photometer. To do this, a test pattern consisting of a solid background with a center square that covers approximately 4.5% of the display area was used (Figure 127).

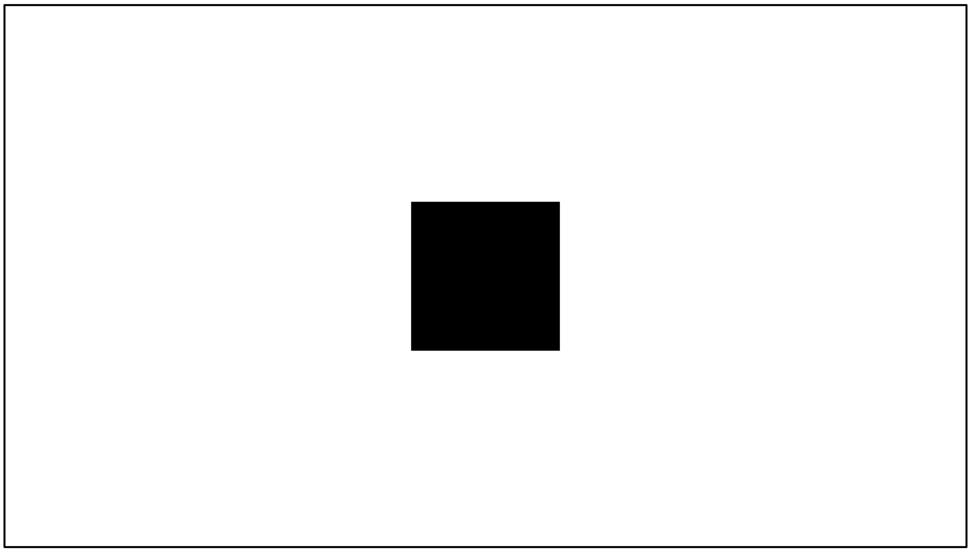


Figure 127: Test pattern used to evaluate the camera as a spot photometer

We alternated the colors of the background and center square between black and white to simulate high and no contrast scenarios and then took screen-center measurements using the camera photometer and the PR-655 spectroradiometer as a reference device. As Table 114 shows, high-contrast patterns reduce screen-center measurement accuracy.

Table 114: Results of high-contrast screen-center luminance readings

Square Color	Background Color	Reference Reading (cd/m^2)	Camera Photometer Reading (cd/m^2)
Black	White	0.38	20.97
Black	Black	0.01	0.42
White	Black	249.90	228.56
White	White	251.20	251.78

These findings warn against using the camera photometer as a spot photometer unless measuring solid color test patterns.

Minimum Camera Screen Width Constraint

The suggested test method uses the focus distance method defined in section 8.2.5.1 of ANSI/CTA-2037-D to avoid moiré effect during testing. In this method, the camera is focused at a closer distance from the screen and then moved back to a farther test distance so that it is slightly out of focus. The equation used to determine the focus distance, along with the lens's minimum working distance, limit the minimum screen width that the camera system can support.

The Basler C125-0618-5M f6 mm lens has a minimum working distance of 100 mm. Therefore, the focus distance equation must yield a result of at least 100 mm:

$$Focus\ distance = \frac{dfX_{test}}{f(d+2p)\ +\ 2pX_{test}}$$

Where:

- f is focal length
- d is aperture diameter
- p is sensor pixel size
- X_{test} is the test distance at which the camera is positioned

For the Gen 3 camera system, this becomes:

$$Gen\ 3\ camera\ focus\ distance = \frac{0.66 *\ 6 *\ X_{test}}{f(0.66+2*0.0069)+\ 2*\ 0.0069*X_{test}}$$

Solving for a focus distance of 100 mm, the required test distance (X_{test}) must be at least 156.74 mm.

As described in section

TEST Set-up, PCL recommends a test distance of 1.28 x screen width for computer monitors and 1.77 x screen width for DSDs and TVs. Since the 1.77 x multiplier results in a longer test distance, this is used as the basis for determining the minimum screen width that satisfies both the focus and test distance requirements.

Solving for screen width:

$$\frac{156.74\,mm}{1.77} \approx 88.56\,mm$$

A screen width of 88.56 mm (3.487”) corresponds to a screen area of approximately 6.84 in^2 for a 16:9 aspect ratio. A square display with this width would have the largest possible screen area across aspect ratios, which would be 12.15 in^2.

Annex E: Justifying a Measurement Distance for Computer Monitors

Introduction

The standardized measurement distance proposed for computer monitors, scaled to 1.28 times the screen's physical width, is a metric intentionally chosen to represent the optimal and most common viewing habits for desktop monitors. This standard satisfies two key goals:

- **Ergonomic Foundation:** For all common 16:9 desktop monitors (up to 32 inches), the 1.28 x width distance falls within the universally recognized ergonomic comfort zone of 20 to 40 inches (50 to 100 cm).[56] This ensures the metric is grounded in typical and safe viewing practices.
- **Technical Consistency:** This scaling factor provides a practical standard for screen-average luminance measurements across various computer monitor sizes. It conveniently aligns with the field of view (FOV) of common C-mount photometer lenses (such as 6 mm focal length), enabling the test methodology to maximize camera sensor pixel utilization for superior measurement accuracy.

While 1.28 x width is representative of human use for standard computer monitors, its application to extremely wide formats (like 32:9 ultrawide displays) results in a test distance that exceeds the human physiological maximum (40 inches). This conflict represents a necessary technical trade-off that prioritizes standardization and repeatability over strict adherence to representative viewing distance in edge-case scenarios.

Foundational Principles

The primary concern for any display evaluation must be compliance with the fixed physiological limitations established for comfortable, sustained human viewing. This sets the acceptable measurement range.

Ocular Physiology and the Comfort Range

To minimize strain on the eyes' ability to focus (accommodation) and turn inward (convergence), the viewing distance must be maximized while ensuring content legibility.[57]

Occupational health and safety guidelines universally define the acceptable operating zone:

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[56] eTools : Computer Workstations- Workstation Components- Monitors | Occupational Safety and Health Administration- OSHA, accessed November 19, 2025, https://www.osha.gov/etools/computer-workstations/components/monitors

[57] Computer Monitor Height, Angle, and Distance- Ergonomics Guidelines, accessed November 19, 2025, https://www.si.mahidol.ac.th/office_d/simi/hci/monitor-ergonomics.htm

- **Acceptable Range:** The preferred viewing range is between 20 and 40 inches (50 and 100 cm) from the eye to the screen surface, based on the "arm's length" rule.[58]
- **Minimum Distance:** OSHA mandates a strict minimum distance of at least 20 inches. Ergonomic researchers often advocate for a strict minimum of 25 inches or more for prolonged work.[59]

The target distance of 1.28 x width is specifically selected to reside comfortably within this 20–40 inch range for standard desktop sizes.

Kinematic Constraint and the Acceptable Field of View

The screen's physical width dictates the necessary field of view (FOV), which limits the potential for fatiguing head and neck rotation (cervical rotation).[60]

- **Ideal FOV:** Ergonomic analysis suggests the most comfortable viewing distance is achieved when the screen fits within a 40° horizontal FOV, typically achieved at approximately 1.4 times the screen's width.[61]
- **Maximum Acceptable FOV:** Occupational safety guidelines establish the maximum FOV threshold, advising that the monitor should never require viewing angles farther than 35 degrees to the left or right (a total FOV of 70°) for sustained work.[62]

The chosen 1.28 x W factor results in a viewing angle that is slightly wider than the ideal 40° FOV but remaining safely within the maximum 70° acceptable limit, confirming its suitability as a representative distance.

Justification for the 1.28 x Width Measurement Standard

The scaling factor of 1.28 x width is primarily adopted because it represents a practical and comfortable distance within the human ergonomic range, allowing for a single, consistent standard across computer monitors.

Standardized Metric Reflecting Typical Use

The 1.28 x width scaling factor is selected because it produces a distance that lands consistently in the sweet spot of the acceptable 20–40 inch human viewing range for common 16:9 displays. For instance, a 27-inch monitor (width of approx. 23.5 in) at 1.28 x W results in a distance of 30.08 inches, which is precisely within the optimal 30–34 inch range often advocated by comfort studies.

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[58] How Far Should Your Screen Be? Recommended Distances Explored | Zenni Optical Blog, accessed November 19, 2025, https://www.zennioptical.com/blog/recommended-screen-distances/

[59] Workstation Components- Desks | Occupational Safety and Health Administration, accessed November 19, 2025, https://www.osha.gov/etools/computer-workstations/components/desks

[60] How are Monitor Screen Sizes Measured These Days?- Eileen's Lounge, accessed November 19, 2025, https://eileenslounge.com/viewtopic.php?style=29&p=133068

[61] A Complete Guide to Choosing the Right Monitor Size- Acemagic, accessed November 19, 2025, https://acemagic.com/blogs/tips-tricks/monitor-size-guide

[62] Ideal Distance from Computer Screen to Eyes- Autonomous, accessed November 19, 2025, https://www.autonomous.ai/ourblog/ideal-distance-from-computer-screen-to-eyes

This factor is, therefore, a representative measurement standard that is **primarily driven by the geometry of typical viewing distance**. Its subsequent alignment with the field of view of standard C-mount lens configurations (e.g., 6 mm focal length), which are common in camera photometers, is a beneficial coincidence that aids measurement consistency.

Compliance with Standard and Ultrawide Trade-Off

Table 115 confirms compliance for standard monitors while demonstrating the conflict when the standard is applied to ultrawide computer monitors.

Table 115: Test distance analysis for computer monitors using 1.28 x W

Monitor Diagonal (D)	Aspect Ratio	Approx. Screen Width (W)	Target Distance (1.28 x W)	Max Ergonomic Distance	Compliance Status
24”	16:9	20.9”	26.75”	40”	Compliant (within typical range)
27”	16:9	23.5”	30.08”	40”	Compliant (within optimal range)
32”	16:9	27.9”	35.71”	40”	Compliant (within optimal range)
49”	32:9	47.17”	60.38”	40”	Non-Compliant

The analysis confirms that for extremely wide computer monitors (e.g., 49-inch 32:9), the 1.28 x width measurement standard yields a test distance of about 60 inches, which is significantly farther than the 40-inch maximum human comfort distance.

While this method results in a greater than typical viewing distance for ultrawide monitors, maintaining the 1.28 x width standard is necessary to ensure standardization repeatability for the most common display type (16:9):

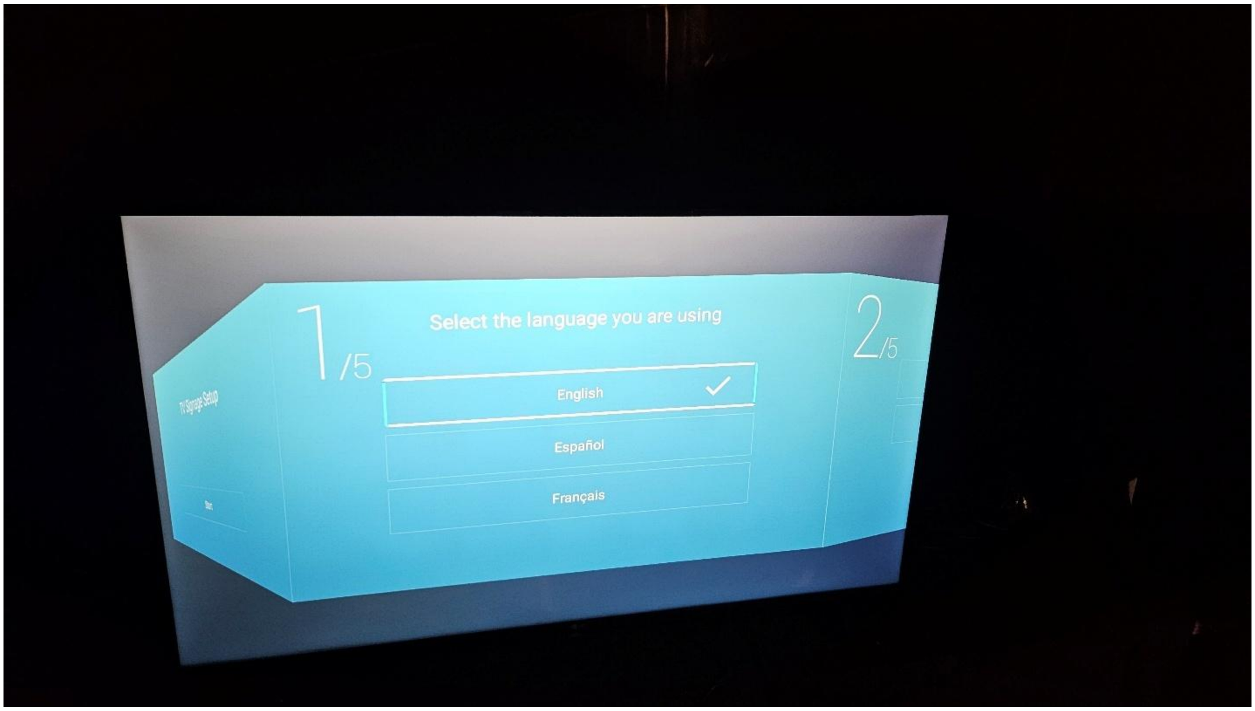
- **Rationale for 1.28 x width:** This specific factor, often achieved with a common 6 mm C-mount lens, ensures the width of a standard 16:9 monitor uses the maximum possible number of pixels on the camera sensor, providing the highest possible spatial resolution and luminance measurement accuracy.
- **The Cost of Changing to a Wider Angle Lens:** To achieve a human-representative test distance (i.e., less than or equal to 40 inches) for an ultrawide monitor, a wider-angle lens (e.g., 4 mm) would be required. However, using this wider-angle lens with a standard 16:9 monitor would cause the monitor to occupy only a fraction of the camera sensor's width, resulting in fewer sensor pixels dedicated to the measurement and, consequently, lower measurement resolution.

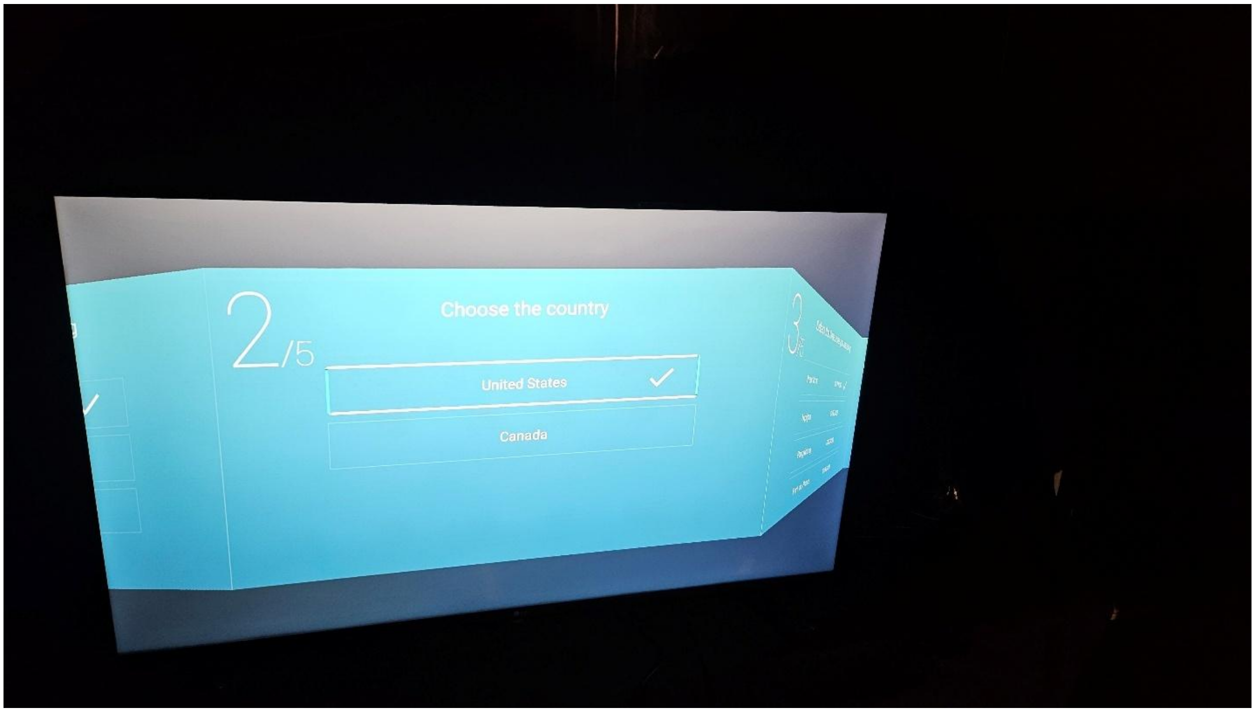
In this context, the technical benefit of maximizing sensor pixels for measurement consistency across the most common monitor sizes is deemed to outweigh the benefit of achieving a strictly human-representative test distance for extremely wide formats. It must be noted, however, that others may argue against this decision, favoring the use of a wider-angle lens to ensure all tests are performed at or below the 40-inch physiological maximum.

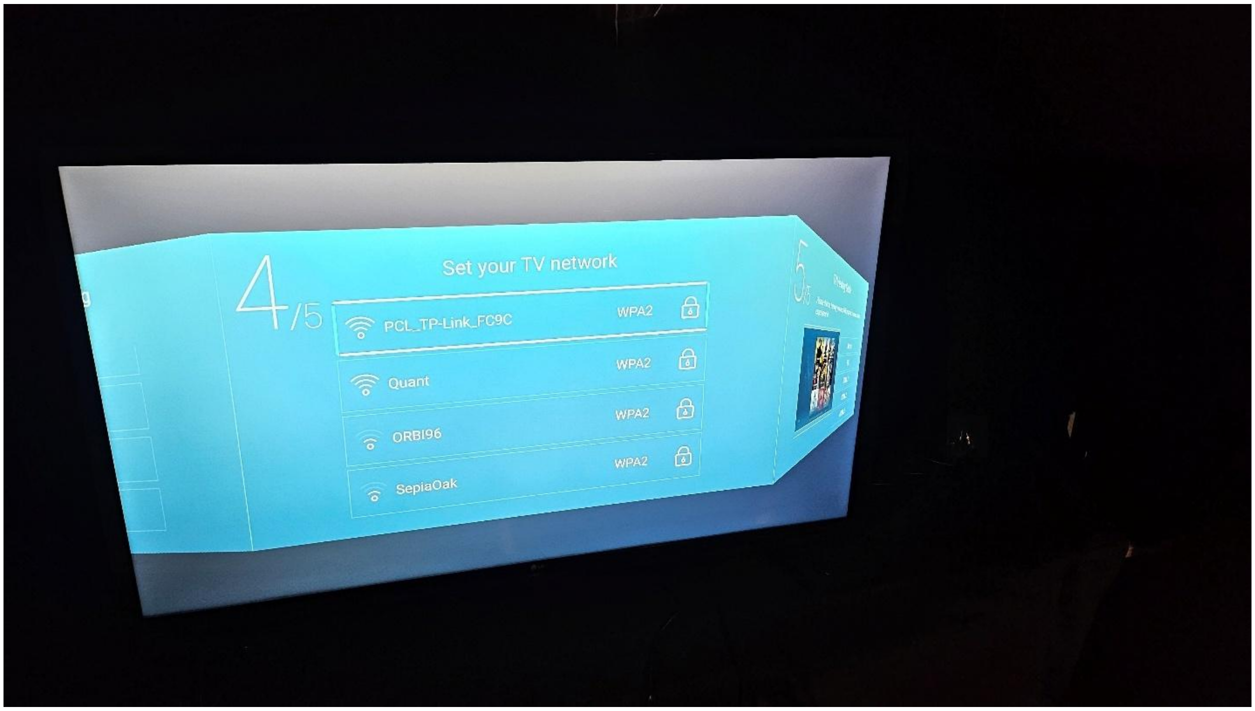
Annex F: Pictures of DSD Set-up Menus

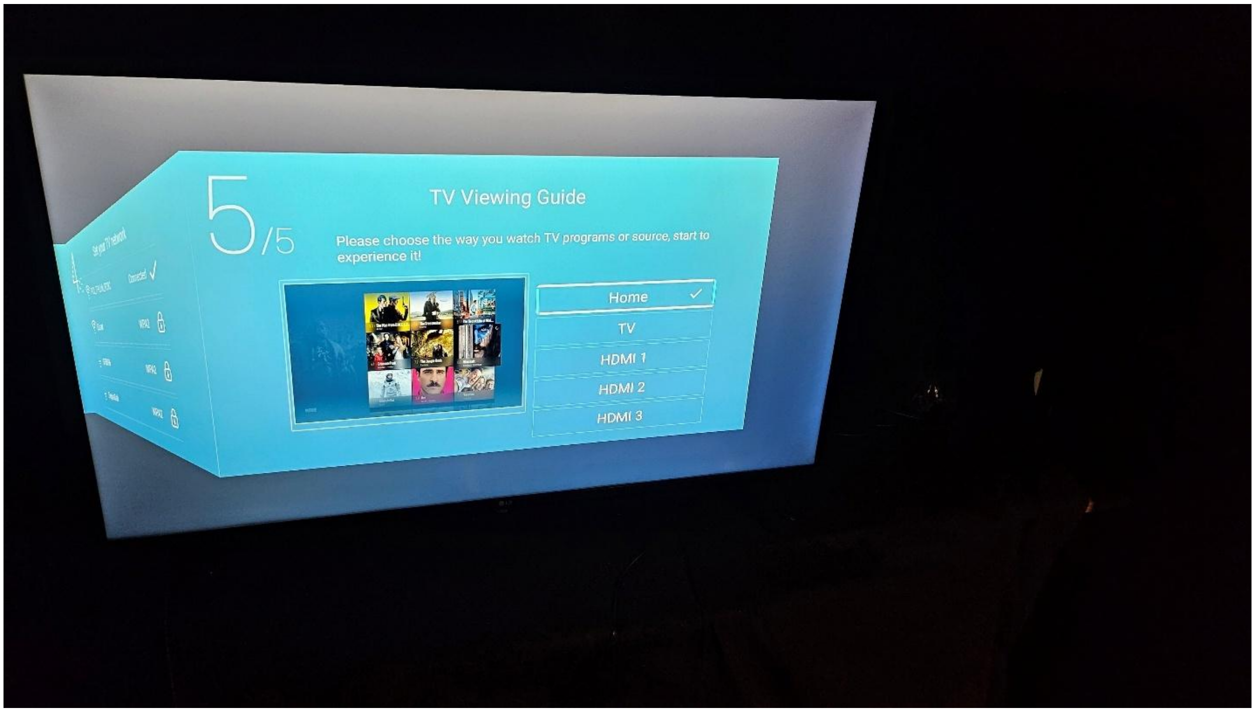
This annex shows pictures of the set-up or forced menus of the DSDs tested. As most monitors do not have set-up menus, pictures of these were not included.

LG 43UM340E



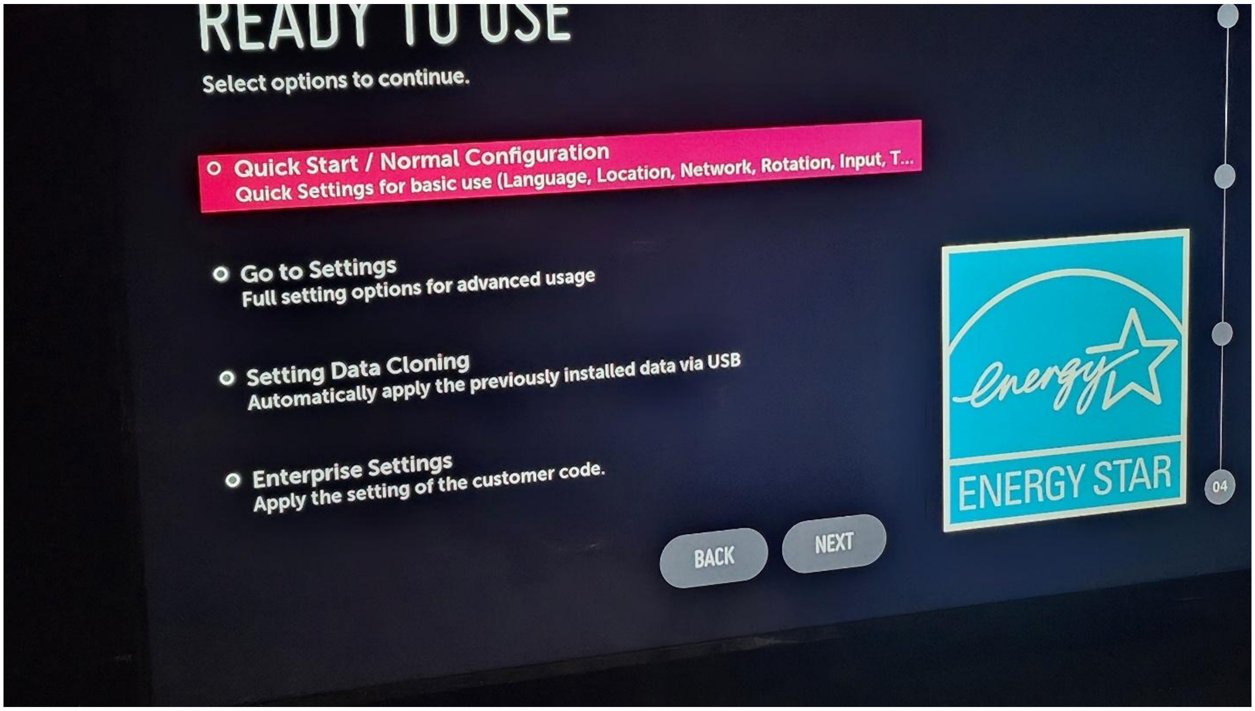

2/5
Choose the country
United States ✓
Canada


4/5
Set your TV network
PCL_TP-Link_FC9C WPA2
Quant WPA2
ORBI96 WPA2
SepiaOak WPA2



Please choose the way you watch TV programs or source, start to experience it!

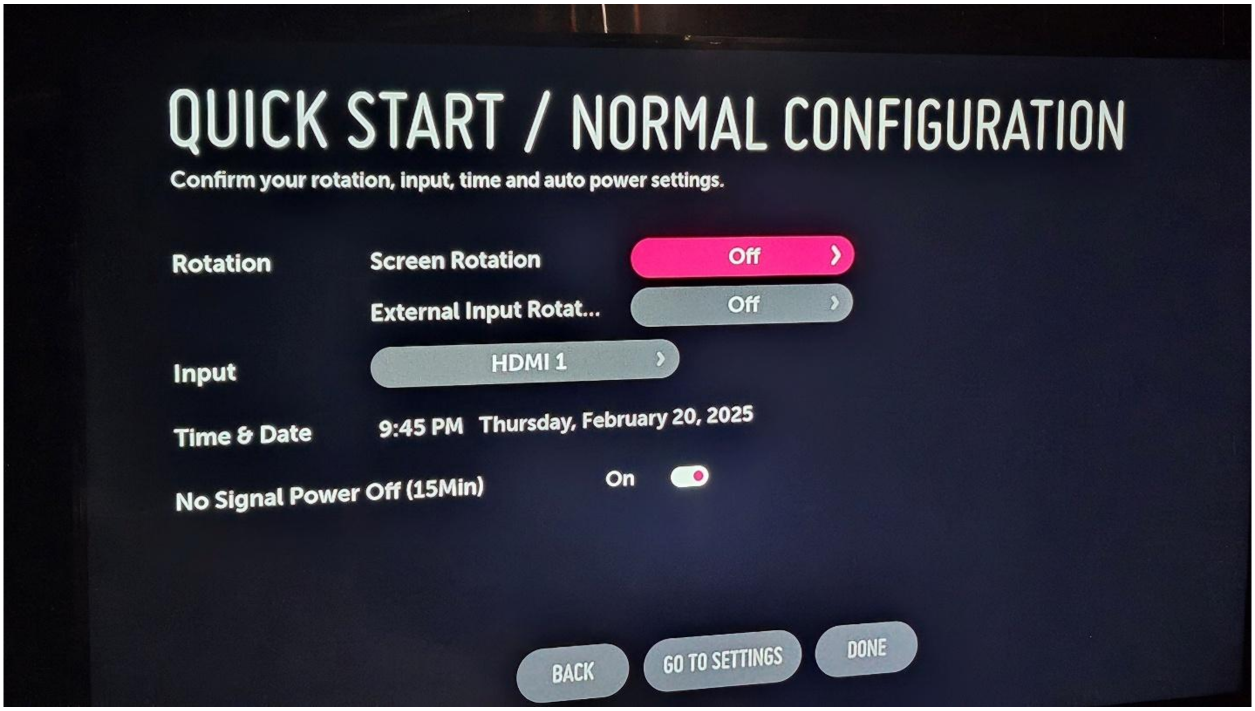
LG 50UL3J-M



READY TO USE

Select options to continue.

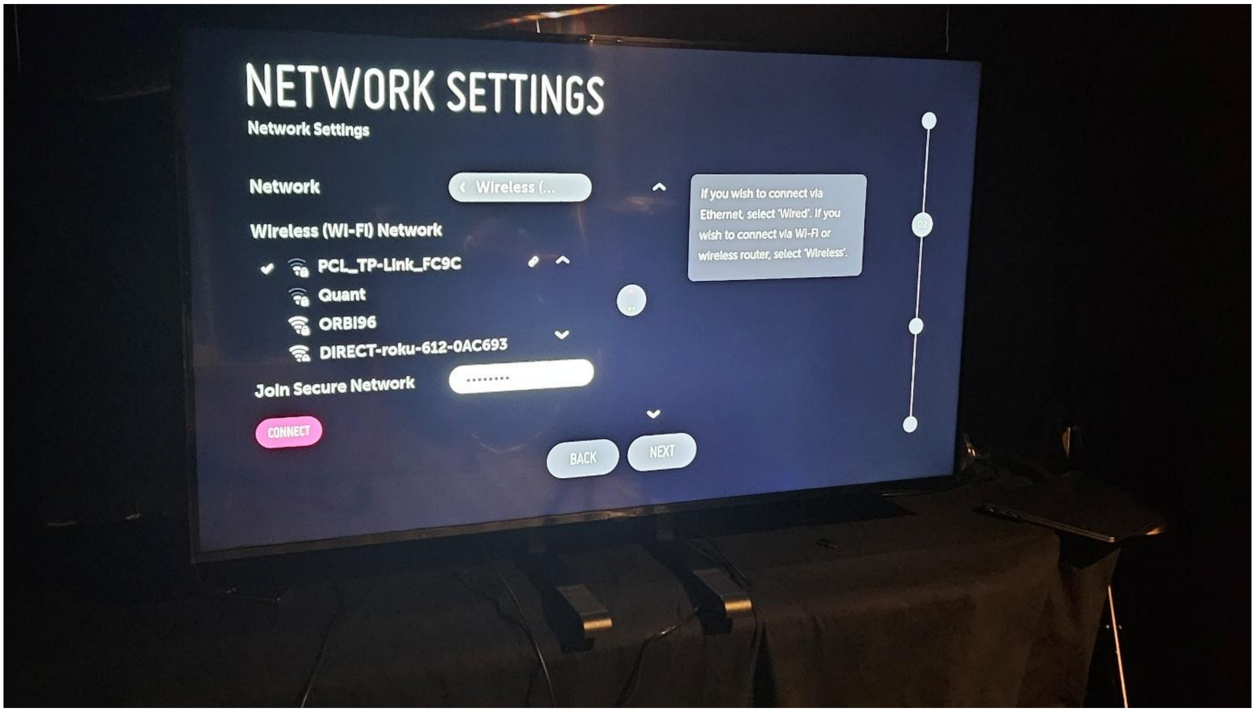
- ○ **Quick Start / Normal Configuration**
  Quick Settings for basic use (Language, Location, Network, Rotation, Input, T...
- ○ **Go to Settings**
  Full setting options for advanced usage
- ○ **Setting Data Cloning**
  Automatically apply the previously installed data via USB
- ○ **Enterprise Settings**
  Apply the setting of the customer code.



QUICK START / NORMAL CONFIGURATION

Confirm your rotation, input, time and auto power settings.

Rotation	Screen Rotation	Off
	External Input Rotat...	Off
Input	HDMI 1	
Time & Date	9:45 PM Thursday, February 20, 2025	
No Signal Power Off (15Min)	On	



NETWORK SETTINGS

Network Settings

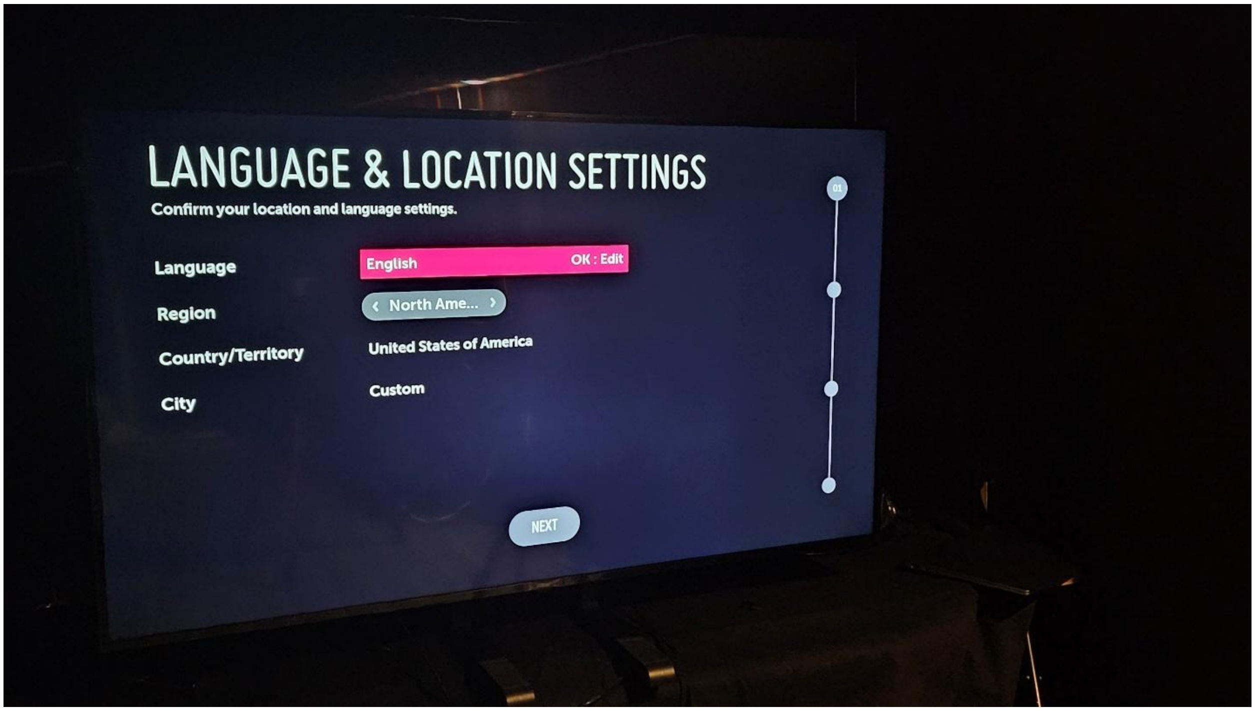
Network: Wireless (...

Wireless (Wi-Fi) Network

- ✓ PCL_TP-Link_FC9C
- Quant
- ORBI96
- DIRECT-roku-612-0AC693

Join Secure Network: ········

If you wish to connect via Ethernet, select 'Wired'. If you wish to connect via Wi-Fi or wireless router, select 'Wireless'.



LANGUAGE & LOCATION SETTINGS

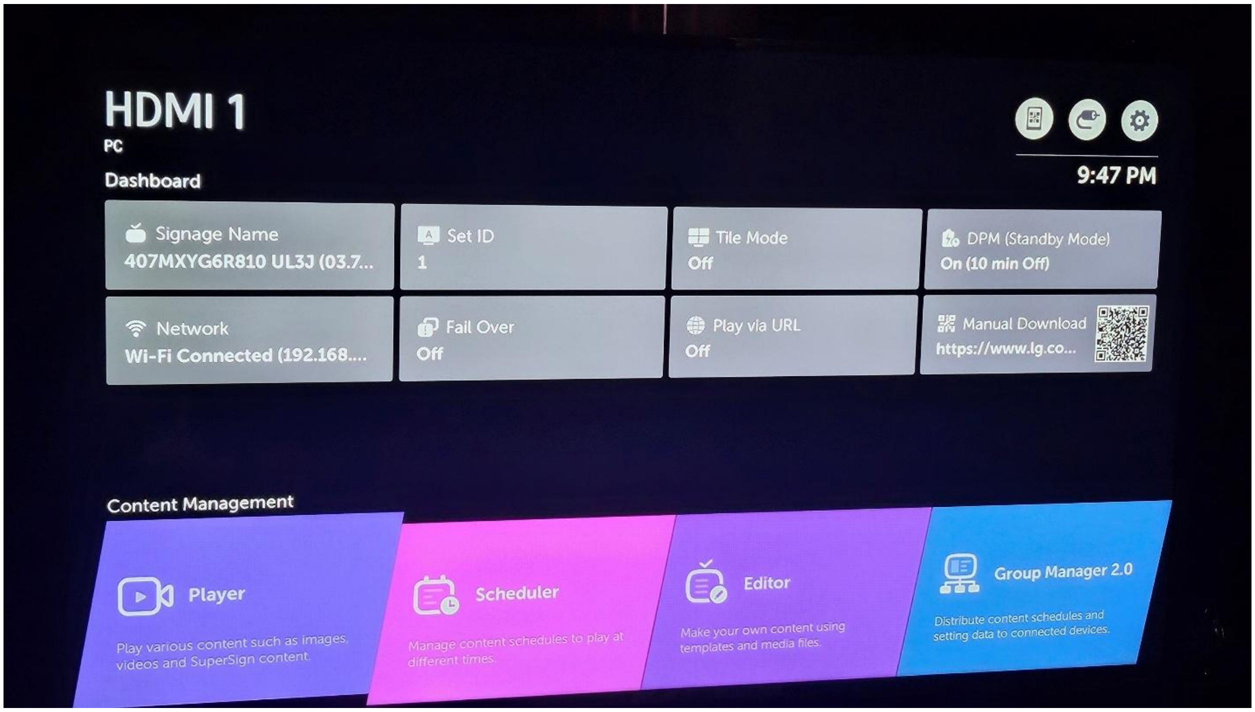
Confirm your location and language settings.

Language: English (OK : Edit)

Region: North Ame...

Country/Territory: United States of America

City: Custom



Signage Name: 407MXYG6R810 UL3J (03.7...

Set ID: 1

Tile Mode: Off

DPM (Standby Mode): On (10 min Off)

Network: Wi-Fi Connected (192.168....

Fail Over: Off

Play via URL: Off

Manual Download: https://www.lg.co...

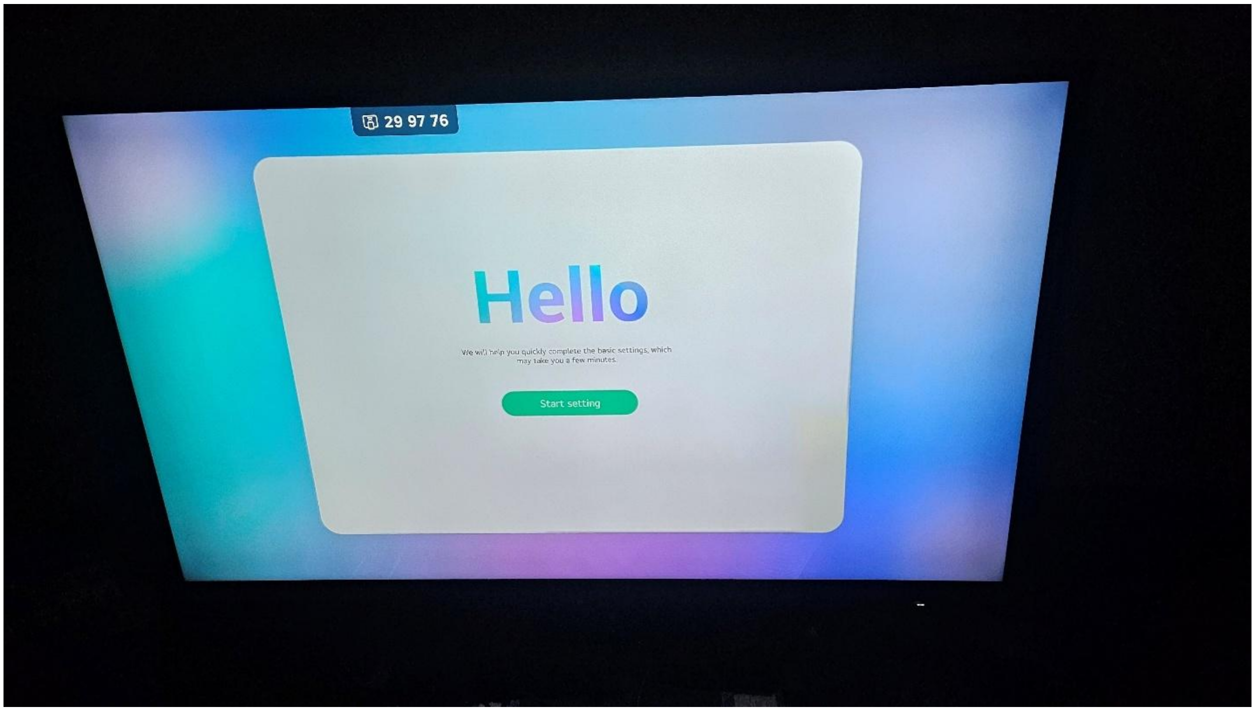
Player: Play various content such as images, videos and SuperSign content.

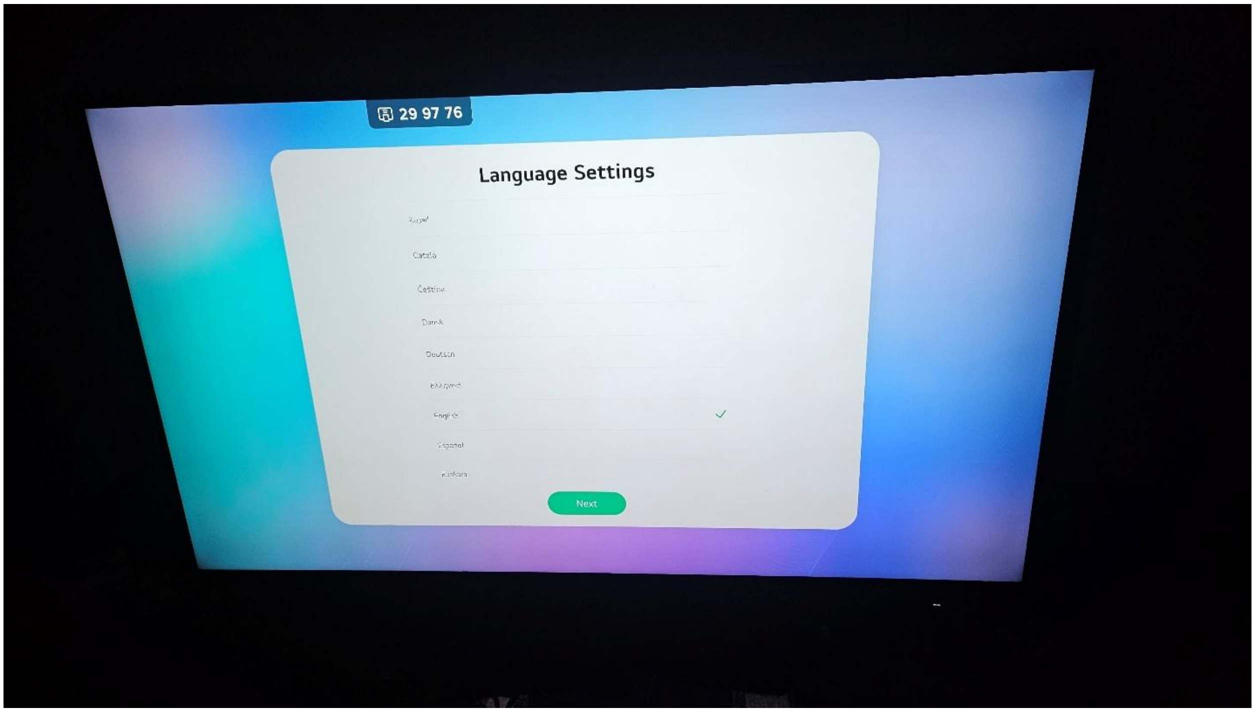
Scheduler: Manage content schedules to play at different times.

Editor: Make your own content using templates and media files.

Group Manager 2.0: Distribute content schedules and setting data to connected devices.

LG 75TR3DK-B

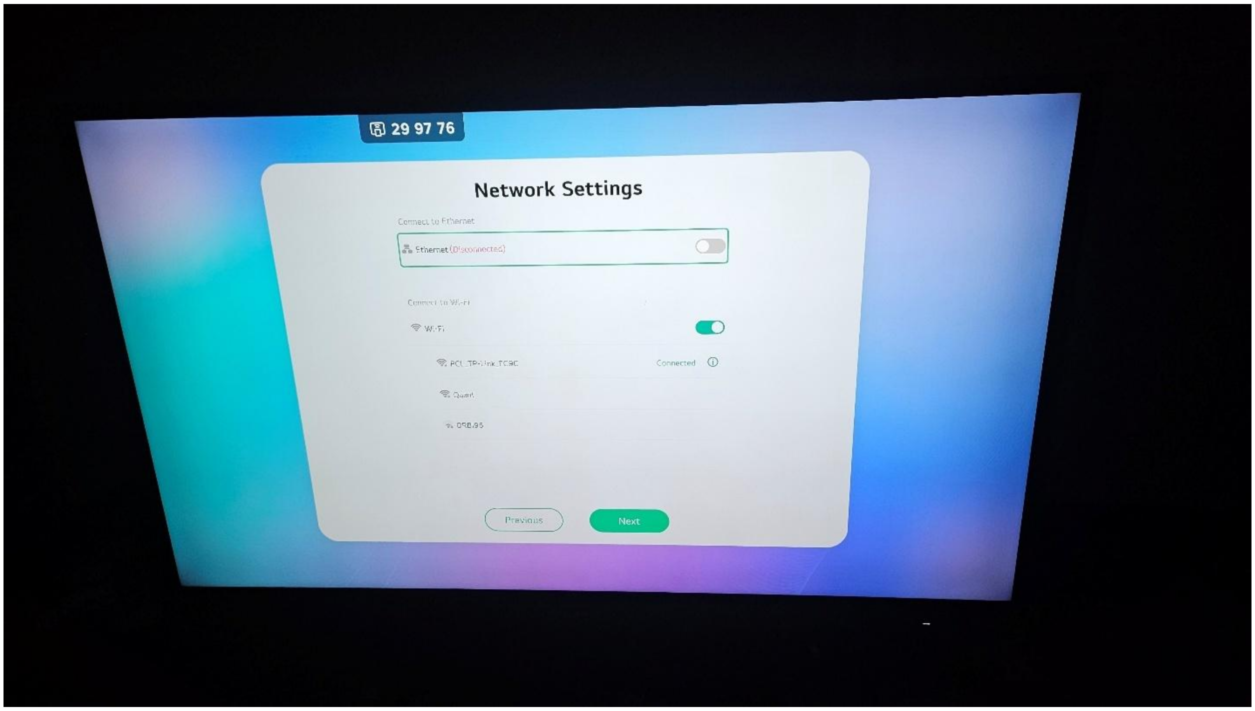

29 97 76
Hello
We will help you quickly complete the basic settings, which may take you a few minutes.
Start setting



29 97 76

Language Settings

- [illegible]
- Català
- Čeština
- Dansk
- Deutsch
- Ελληνικά
- English ✓
- Español
- Euskara



29 97 76

Network Settings

Connect to Ethernet

Ethernet (Disconnected) ○

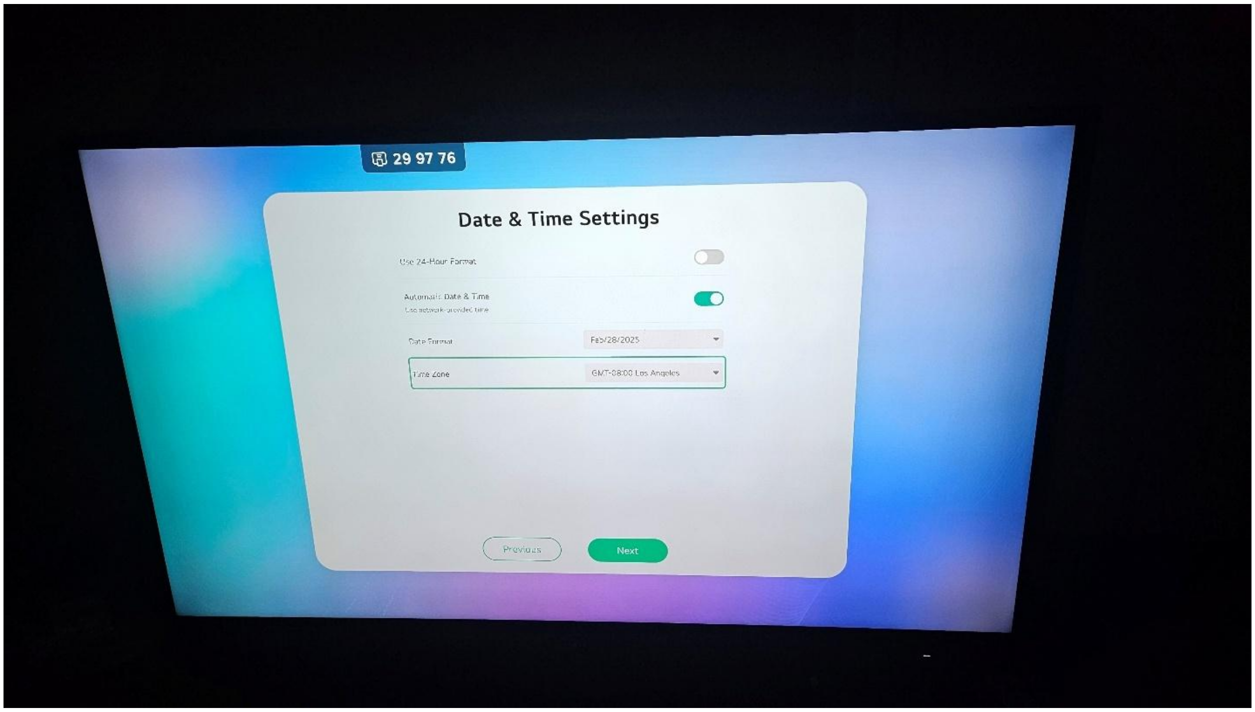
Connect to Wi-Fi

Wi-Fi ●

PCL_TP-Link_TC9C Connected ⓘ

Quant

ORBI95



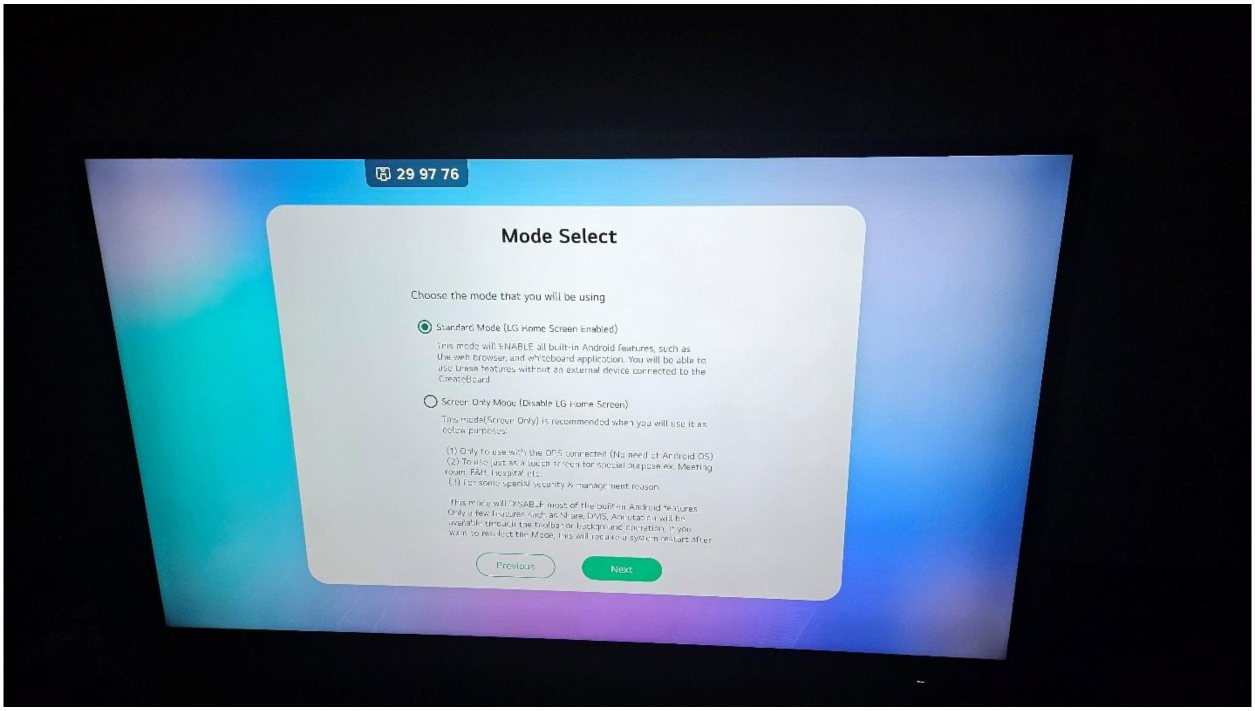
Date & Time Settings

Use 24-Hour Format ○

Automatic Date & Time ●
Use network-provided time

Date Format: Feb/28/2025

Time Zone: GMT-08:00 Los Angeles



Mode Select

Choose the mode that you will be using

● Standard Mode (LG Home Screen Enabled)

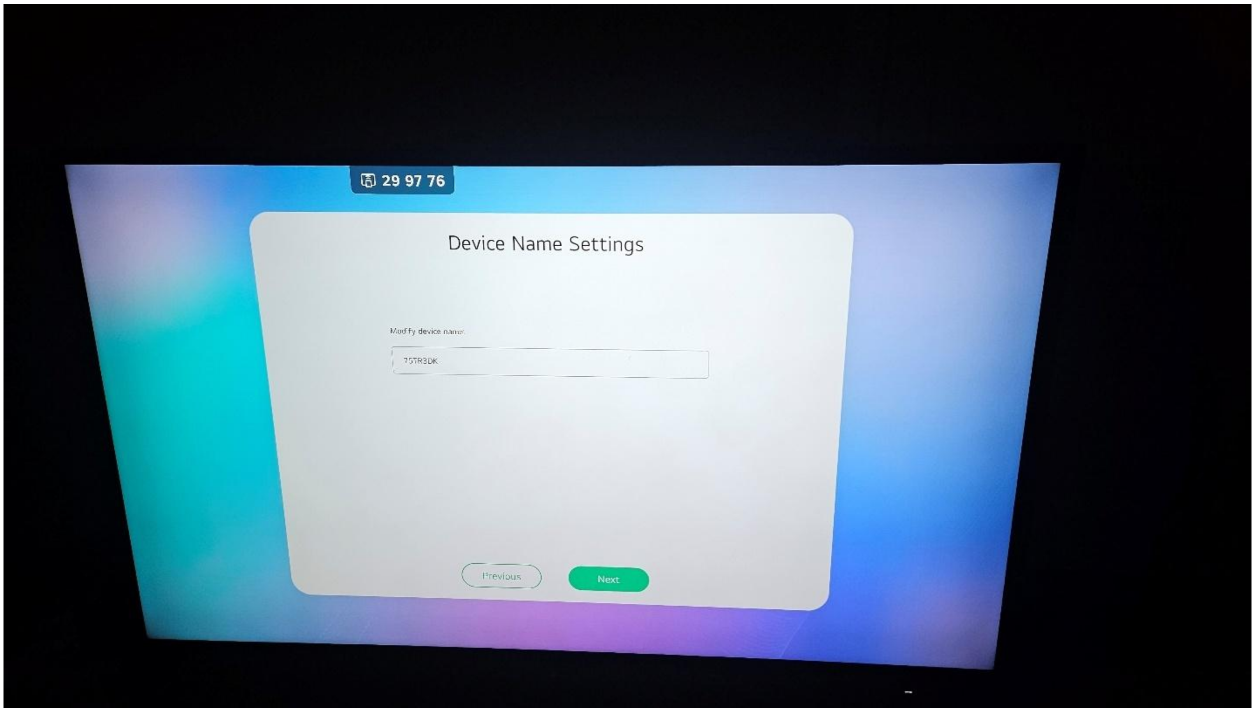
This mode will ENABLE all built-in Android features, such as the web browser, and whiteboard application. You will be able to use these features without an external device connected to the CreateBoard.

○ Screen Only Mode (Disable LG Home Screen)

This mode(Screen Only) is recommended when you will use it as below purposes:

(1) Only to use with the OPS connected (No need of Android OS)
(2) To use just as a touch screen for special purpose ex. Meeting room, F&B, Hospital etc.
(3) For some special security & management reason

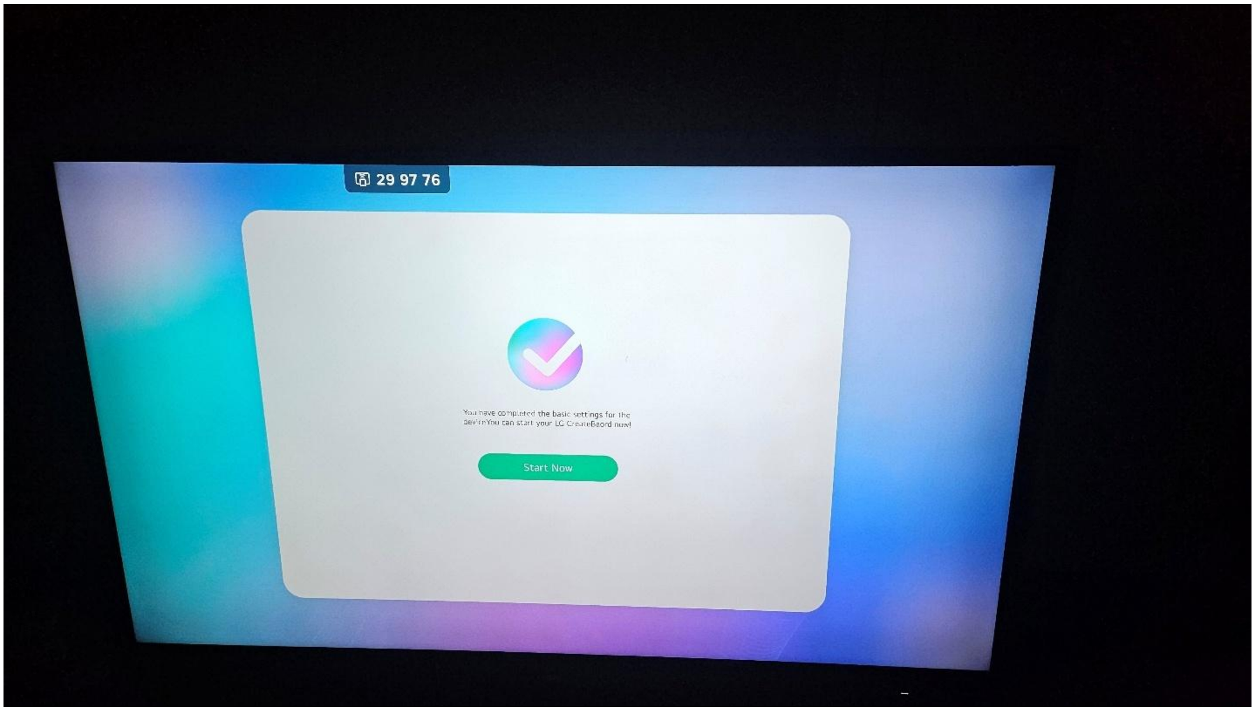
This mode will DISABLE most of the built-in Android features. Only a few features such as Share, DMS, Annotation will be available through the toolbar or background operation. If you want to reselect the Mode, this will require a system restart after



Device Name Settings

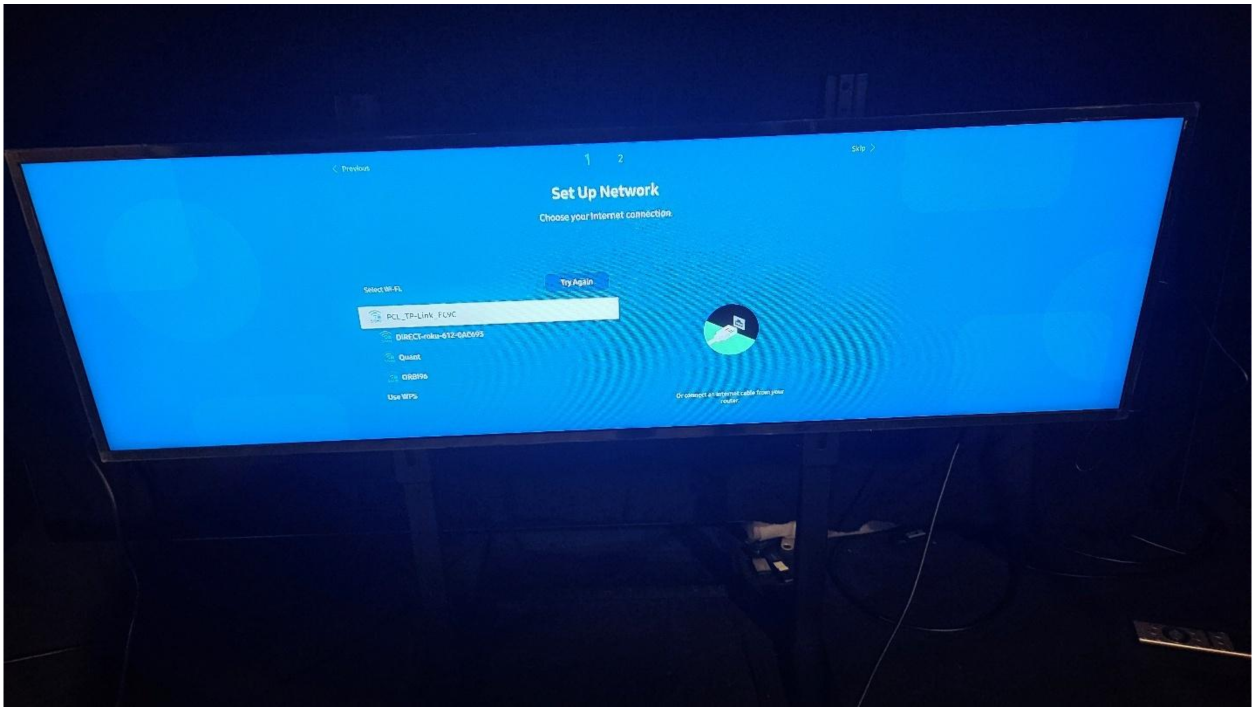
Modify device name:

75TR3DK



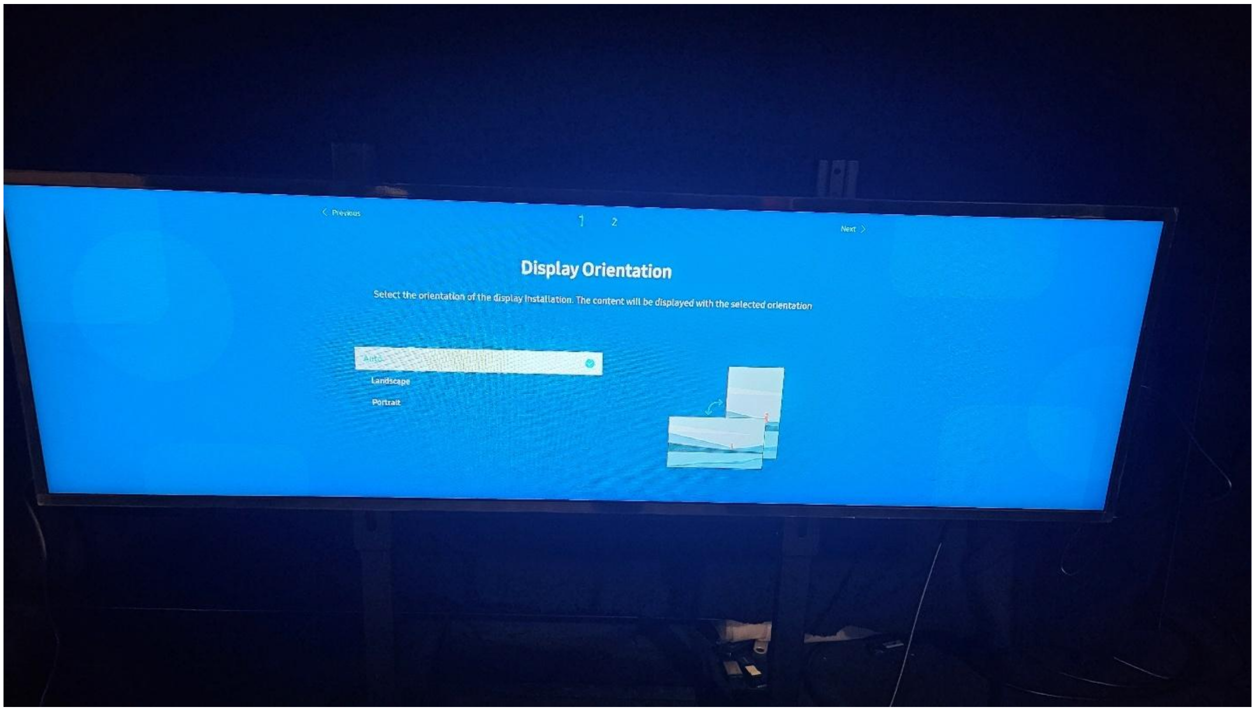
You have completed the basic settings for the device.You can start your LG CreateBaord now!

Samsung SH37C



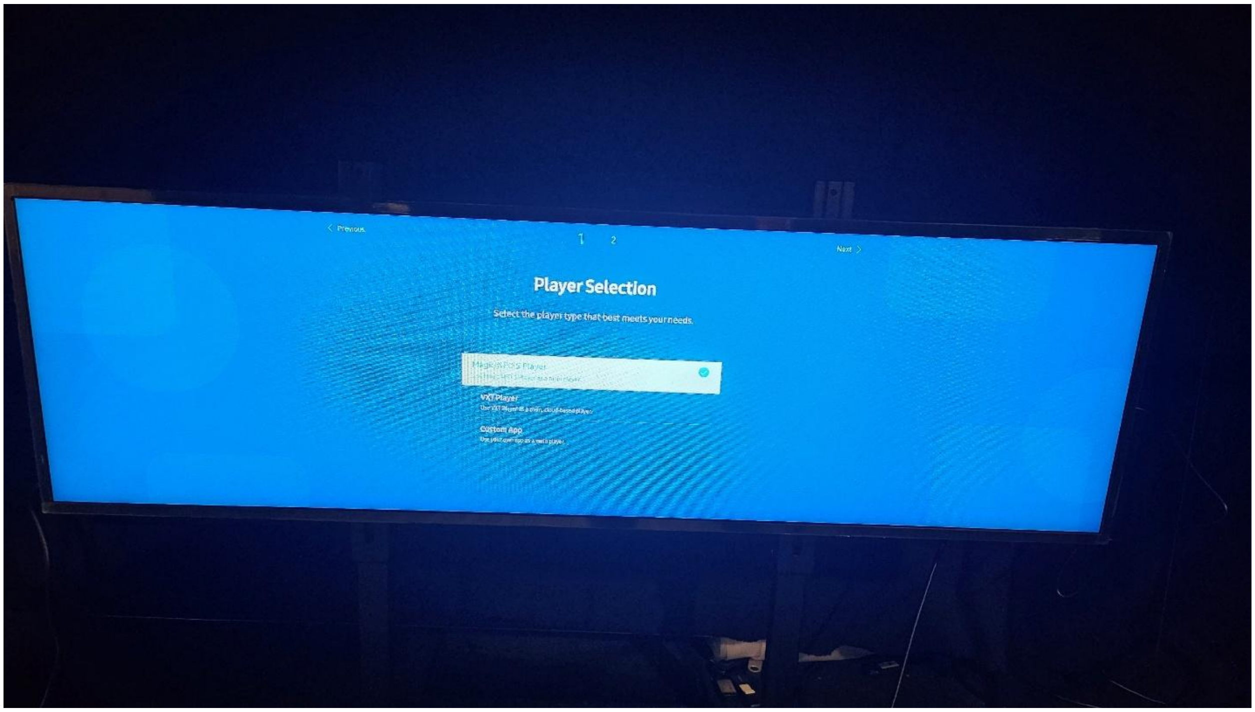
Set Up Network

Choose your Internet connection.



Display Orientation

Select the orientation of the display installation. The content will be displayed with the selected orientation



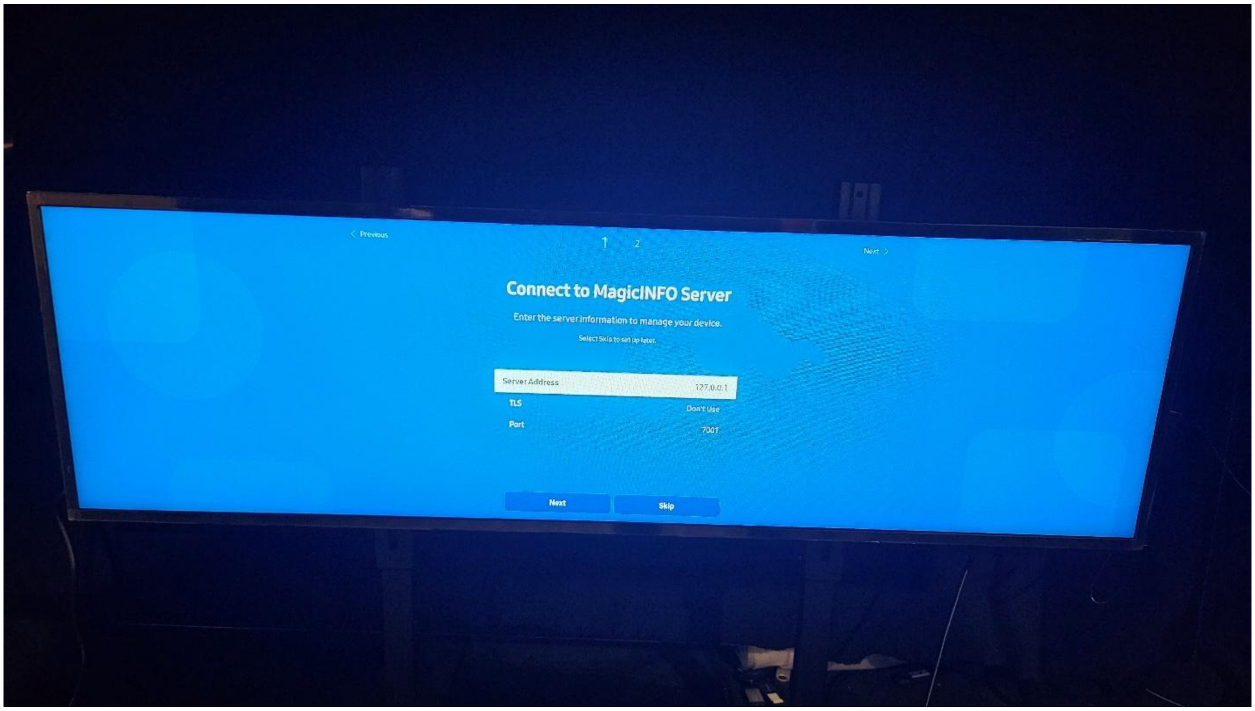
Player Selection

Select the player type that best meets your needs.

MagicINFO S Player ☑
Use MagicINFO S Player as a main player.

VXT Player
Use VXT Player as a main, cloud-based player.

Custom App
Use your own app as a main player.

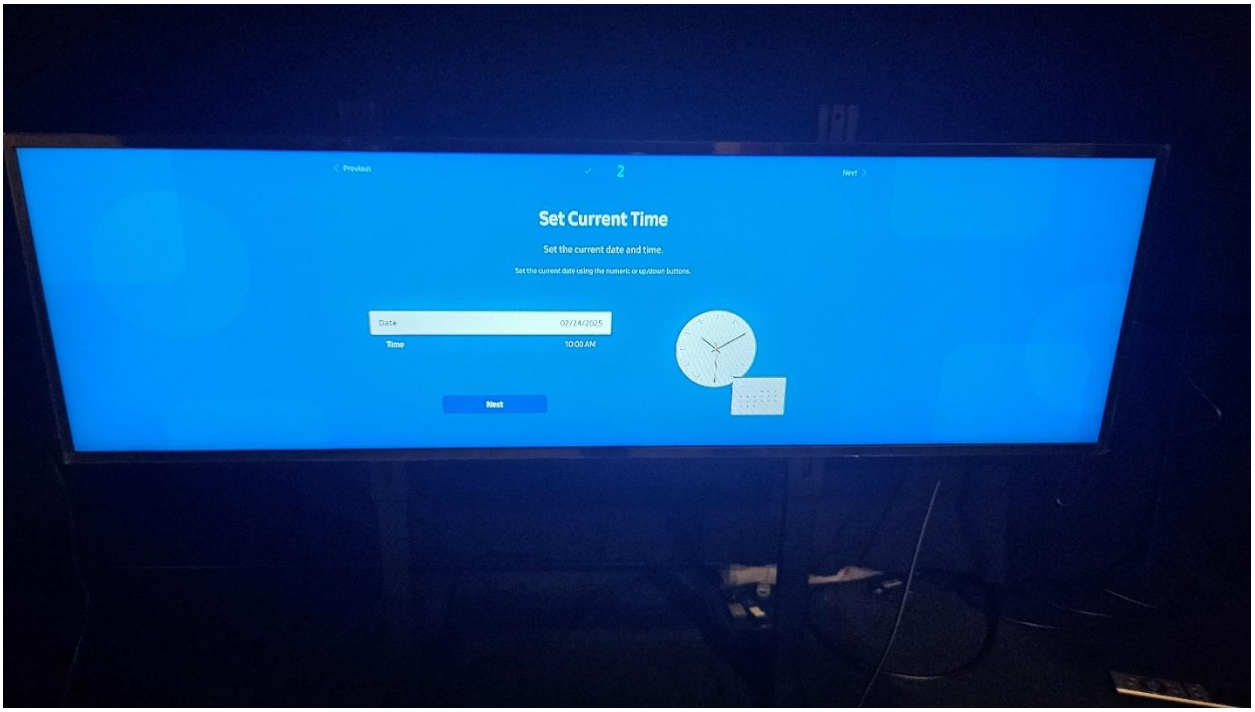


Connect to MagicINFO Server

Enter the server information to manage your device.

Select Skip to set up later.

Server Address: 127.0.0.1
TLS: Don't Use
Port: 7001



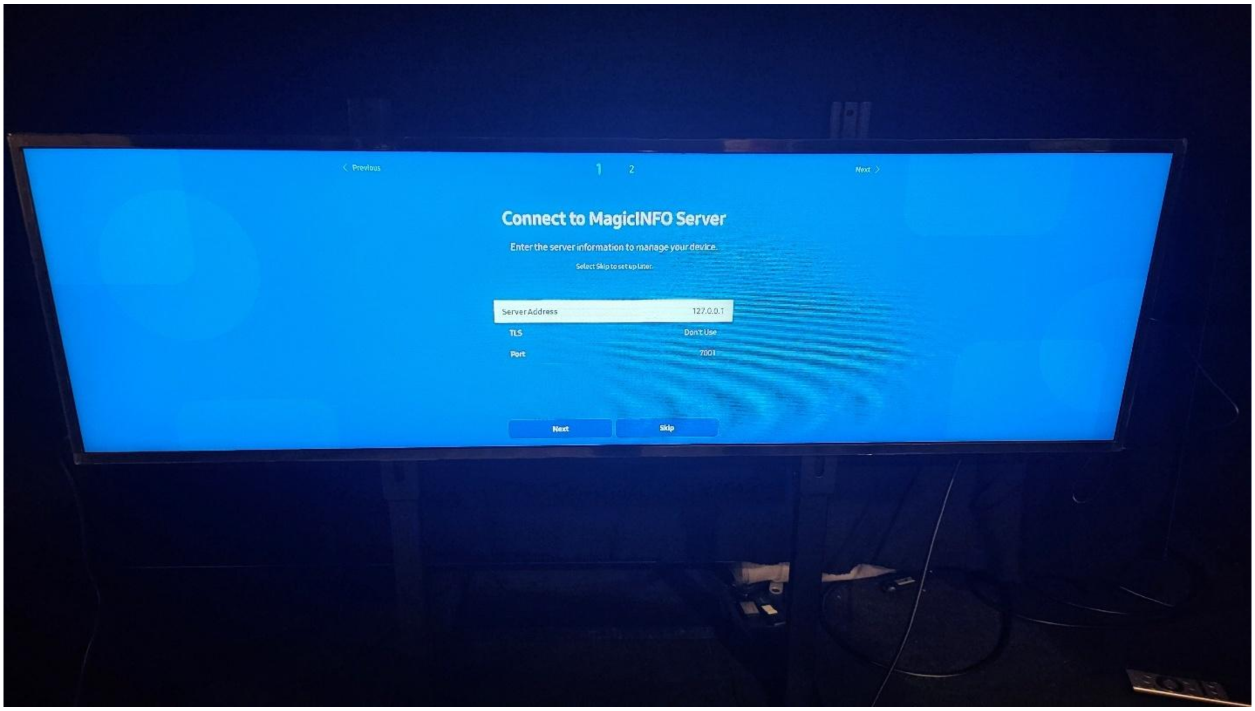
Set Current Time

Set the current date and time.

Set the current date using the numeric or up/down buttons.

Date 02/24/2025

Time 10:00 AM



Connect to MagicINFO Server

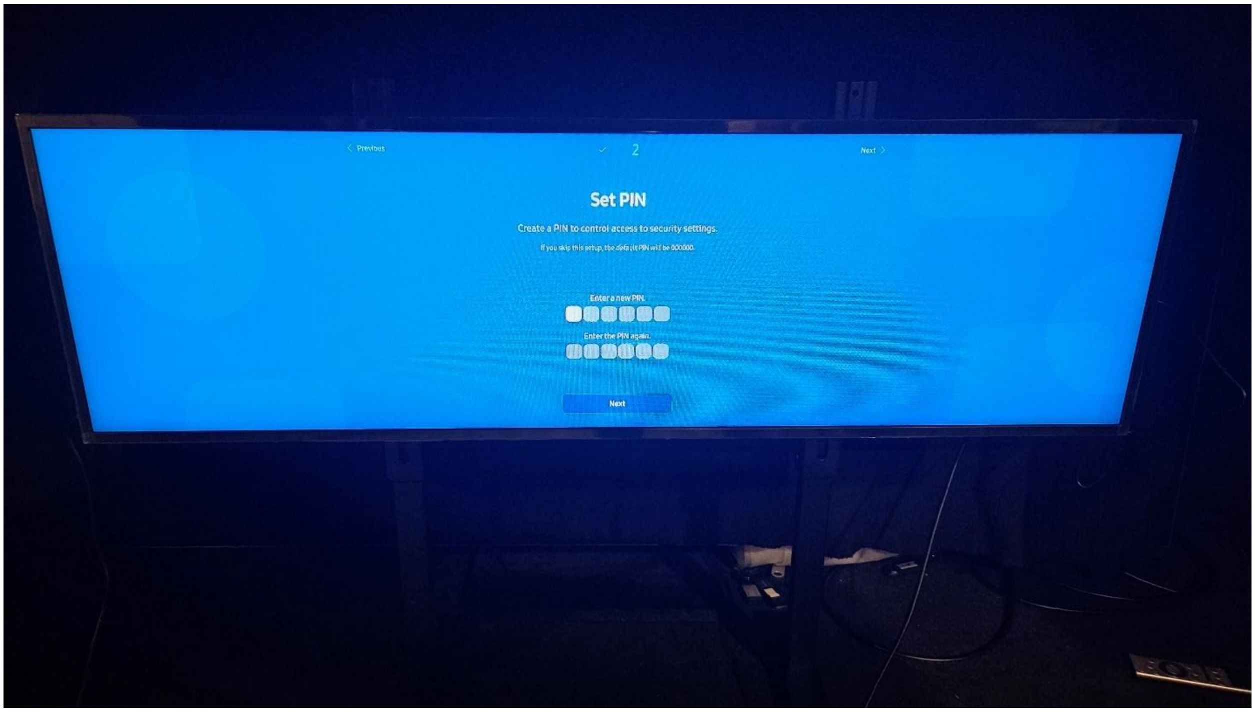
Enter the server information to manage your device.

Select Skip to set up later.

Server Address 127.0.0.1

TLS Don't Use

Port 7001



Set PIN

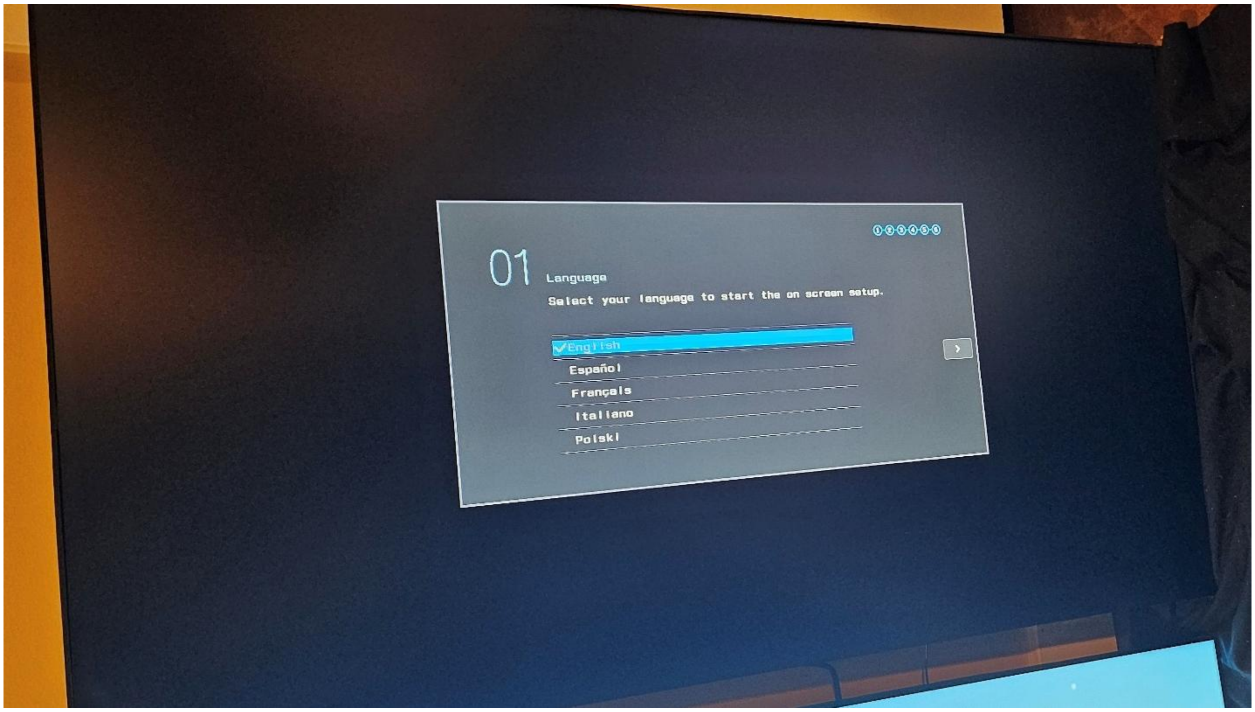
Create a PIN to control access to security settings.

If you skip this setup, the default PIN will be 000000.

Enter a new PIN.

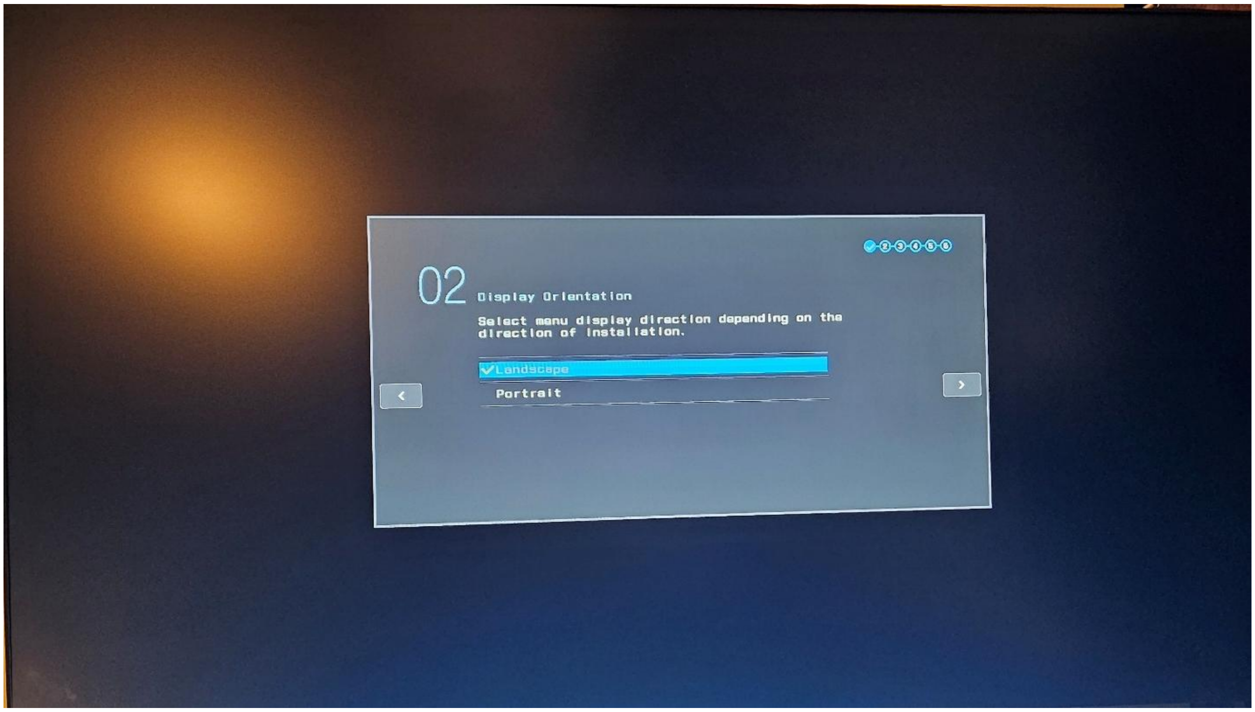
Enter the PIN again.

Samsung VH55R-R



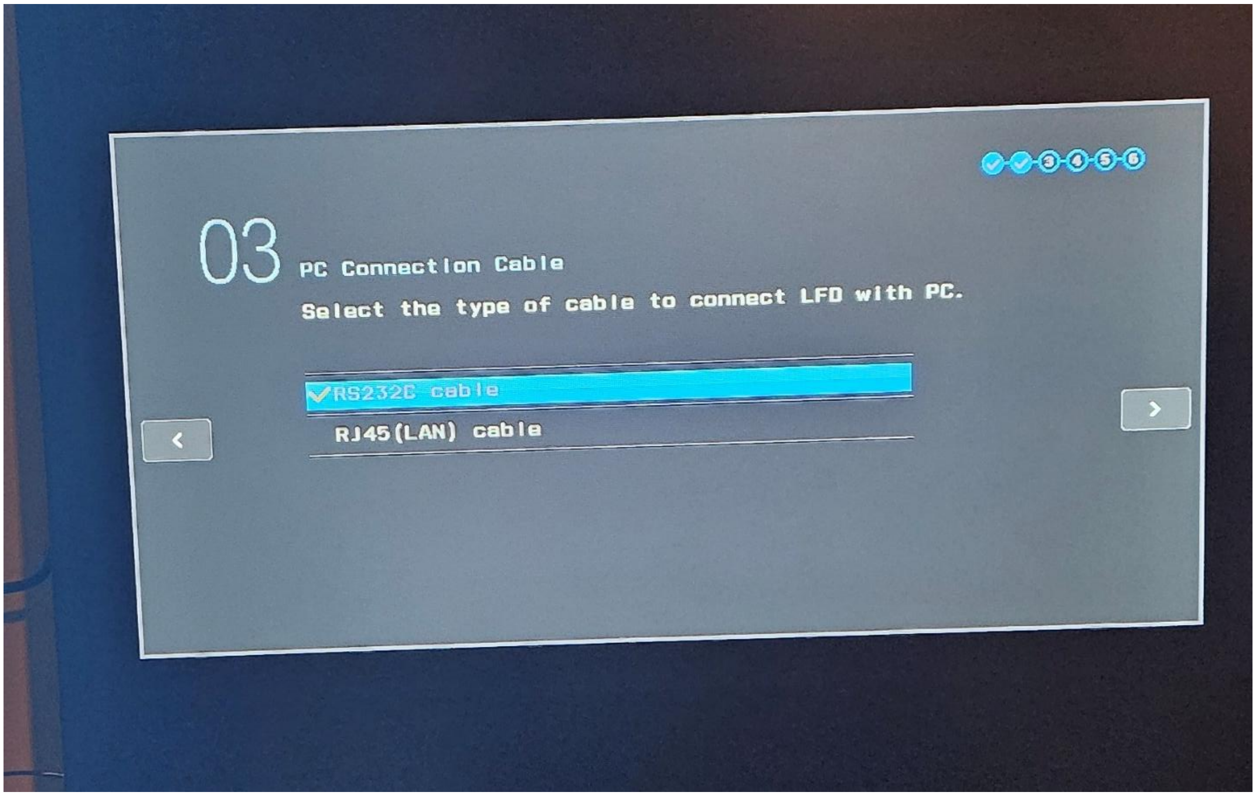
01 Language

Select your language to start the on screen setup.



02 Display Orientation

Select menu display direction depending on the direction of installation.

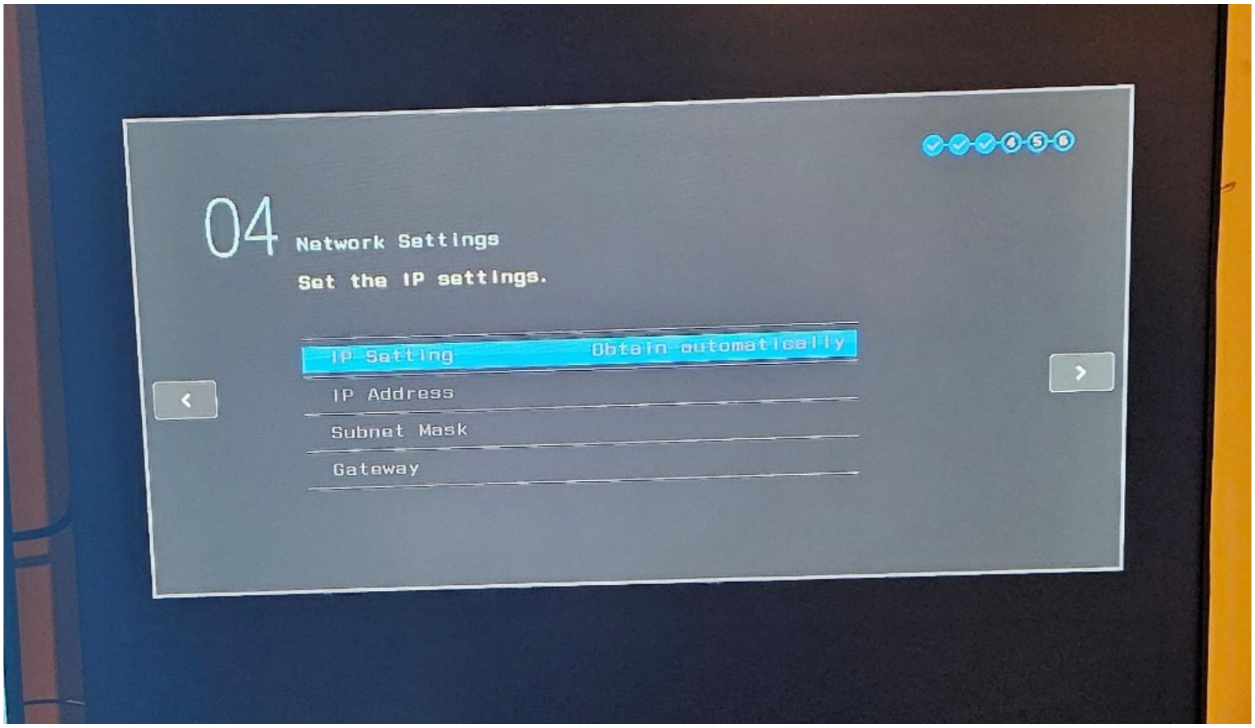


03 PC Connection Cable

Select the type of cable to connect LFD with PC.

✓RS232C cable

RJ45(LAN) cable



04 Network Settings

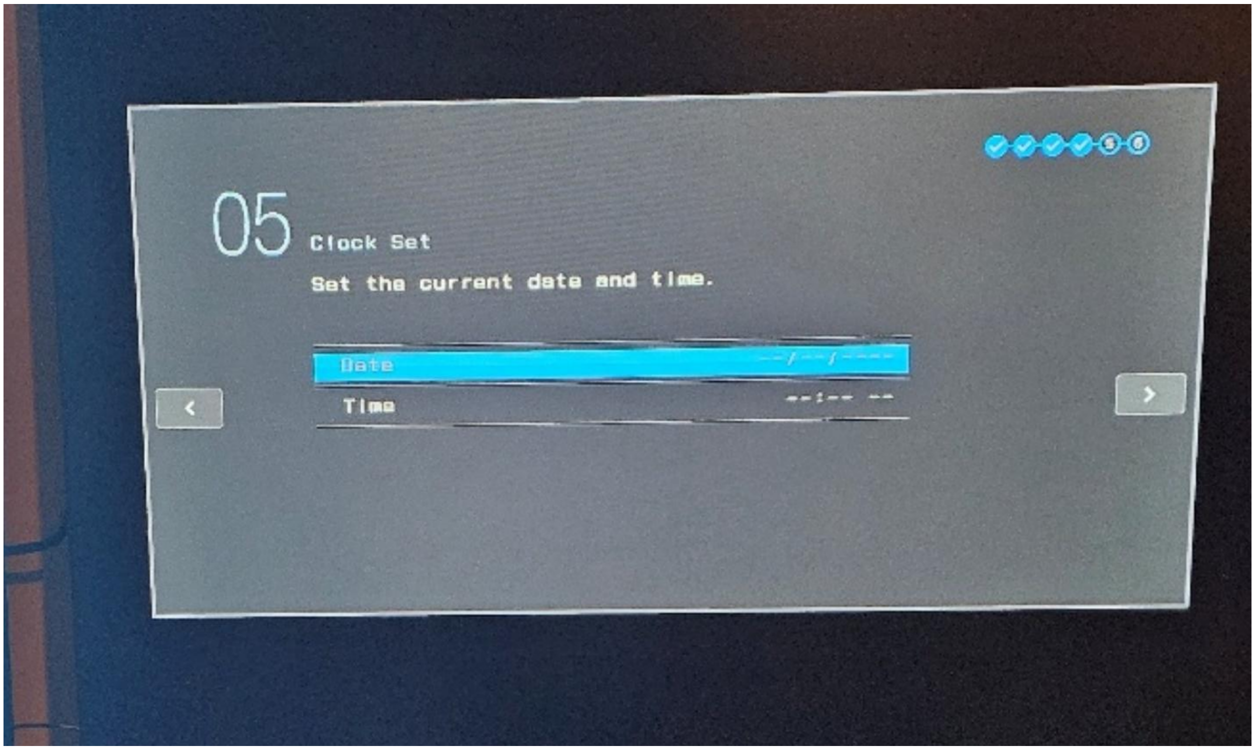
Set the IP settings.

IP Setting Obtain automatically

IP Address

Subnet Mask

Gateway

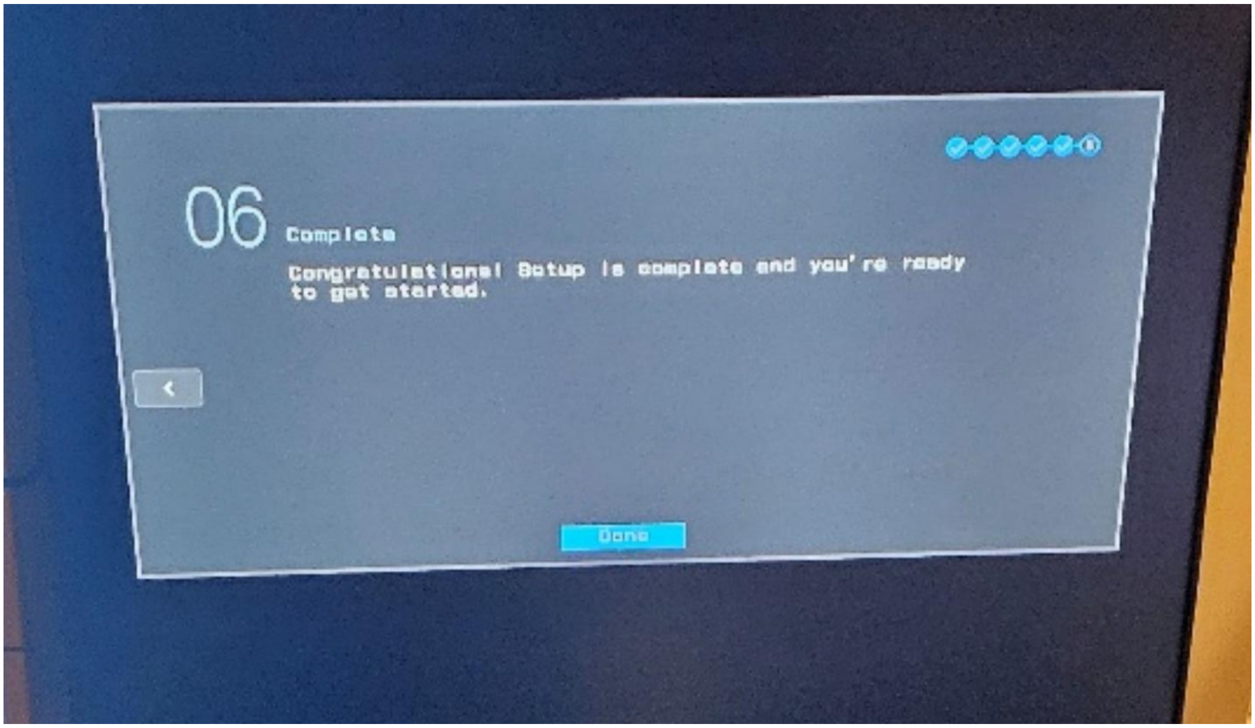


05 Clock Set

Set the current date and time.

Date --/--/----

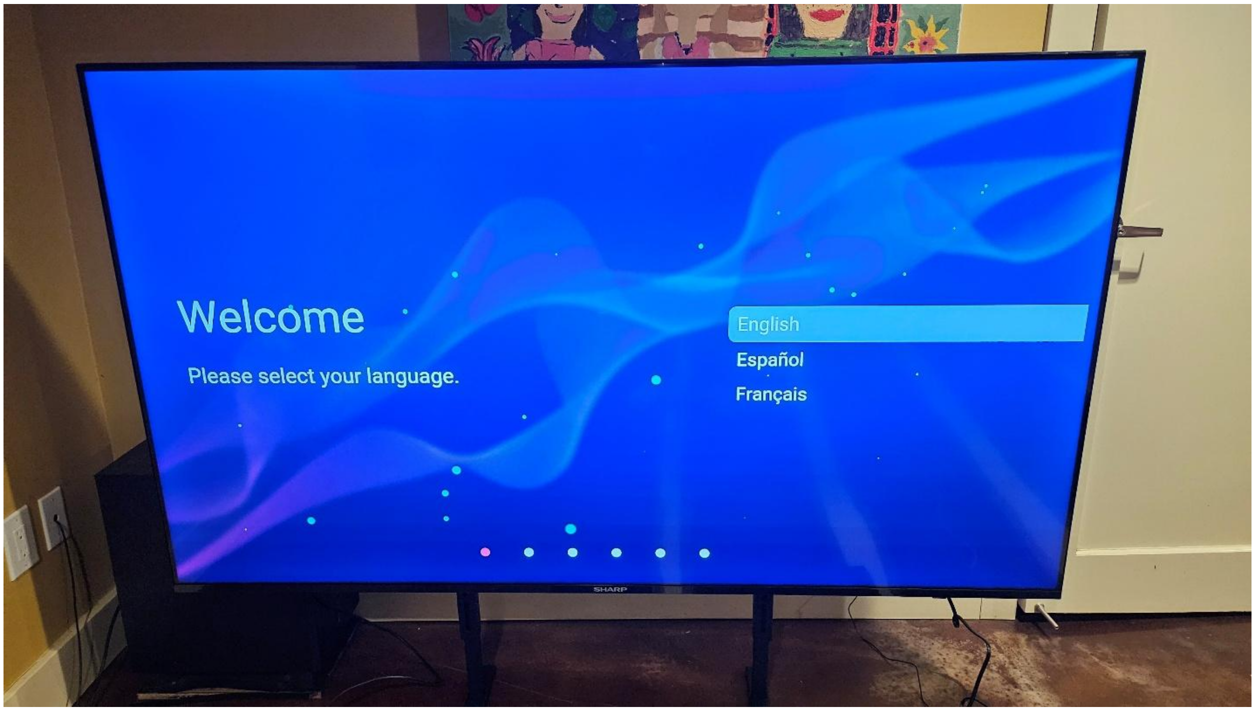
Time --:-- --



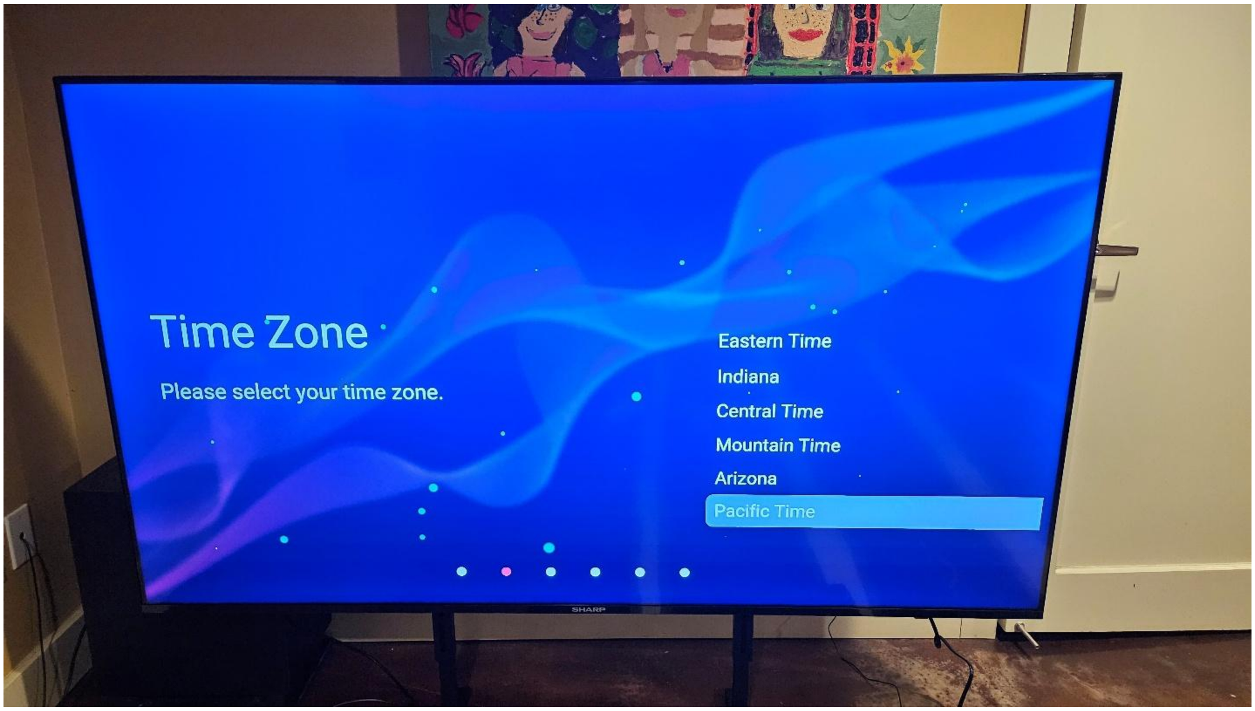
06 Complete

Congratulations! Setup is complete and you're ready to get started.

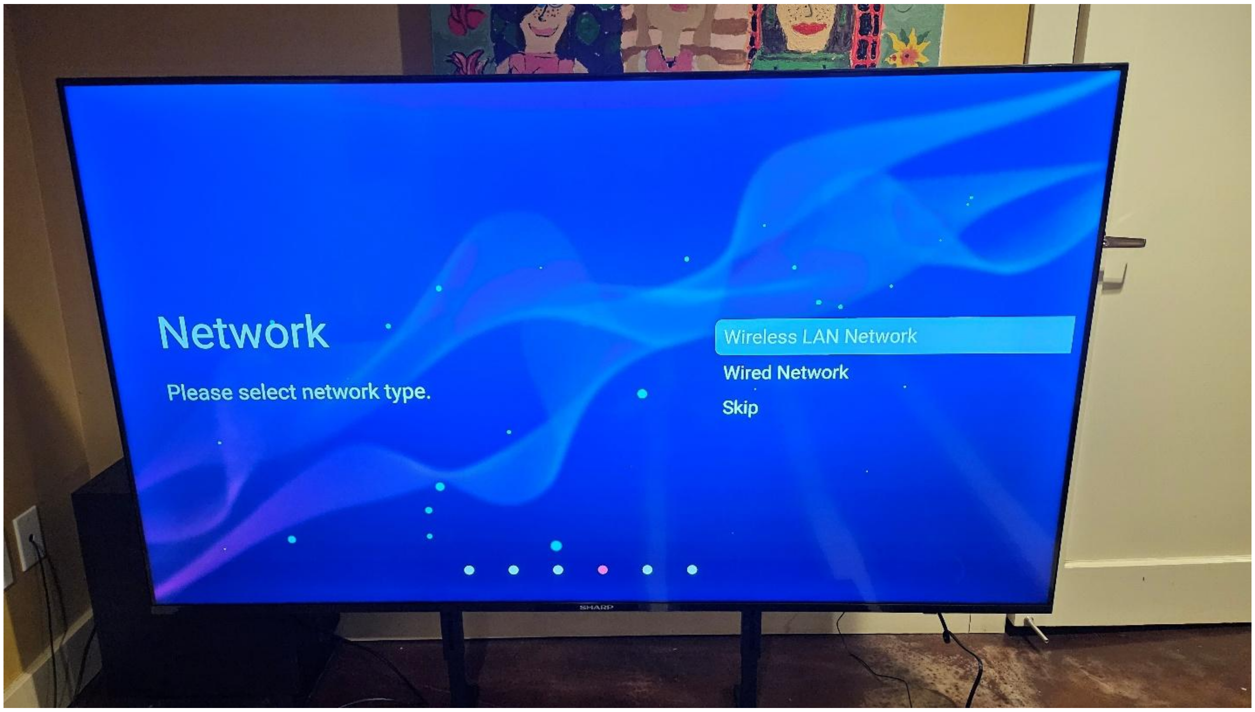
Sharp AQUOS 4P-B65EJ2U


Welcome

Please select your language.


Time Zone

Please select your time zone.



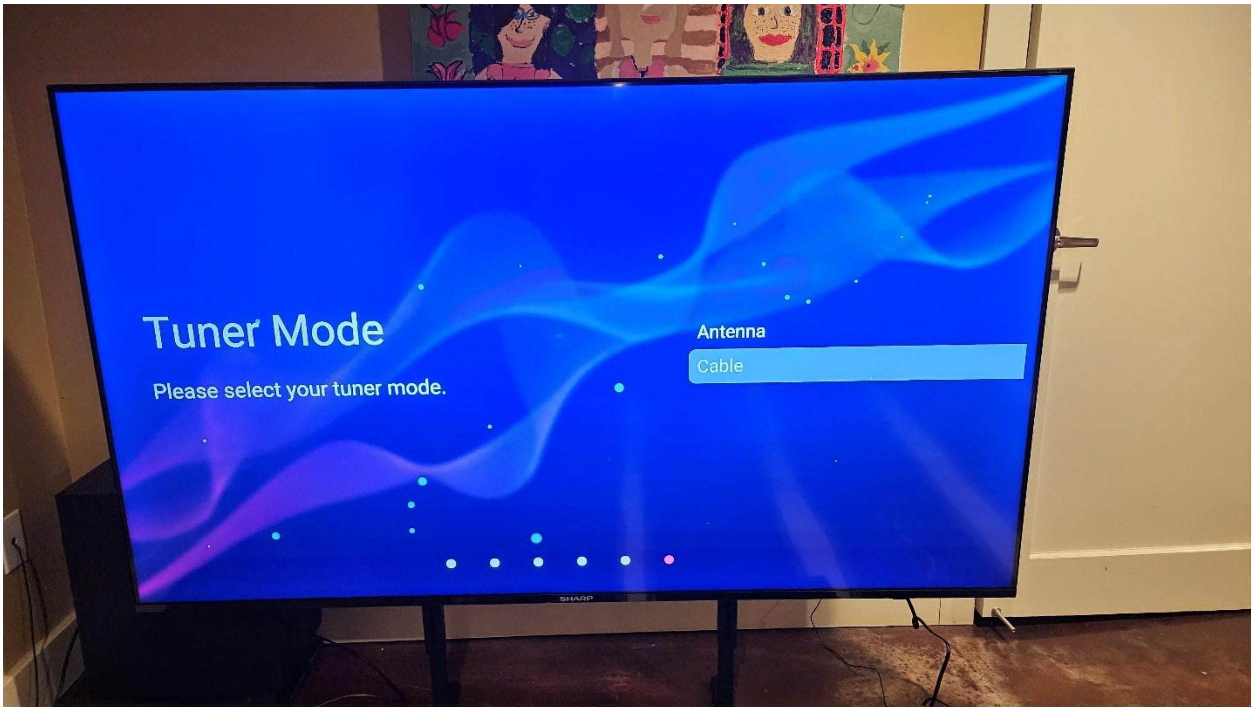
Network

Please select network type.

Wireless LAN Network

Wired Network

Skip

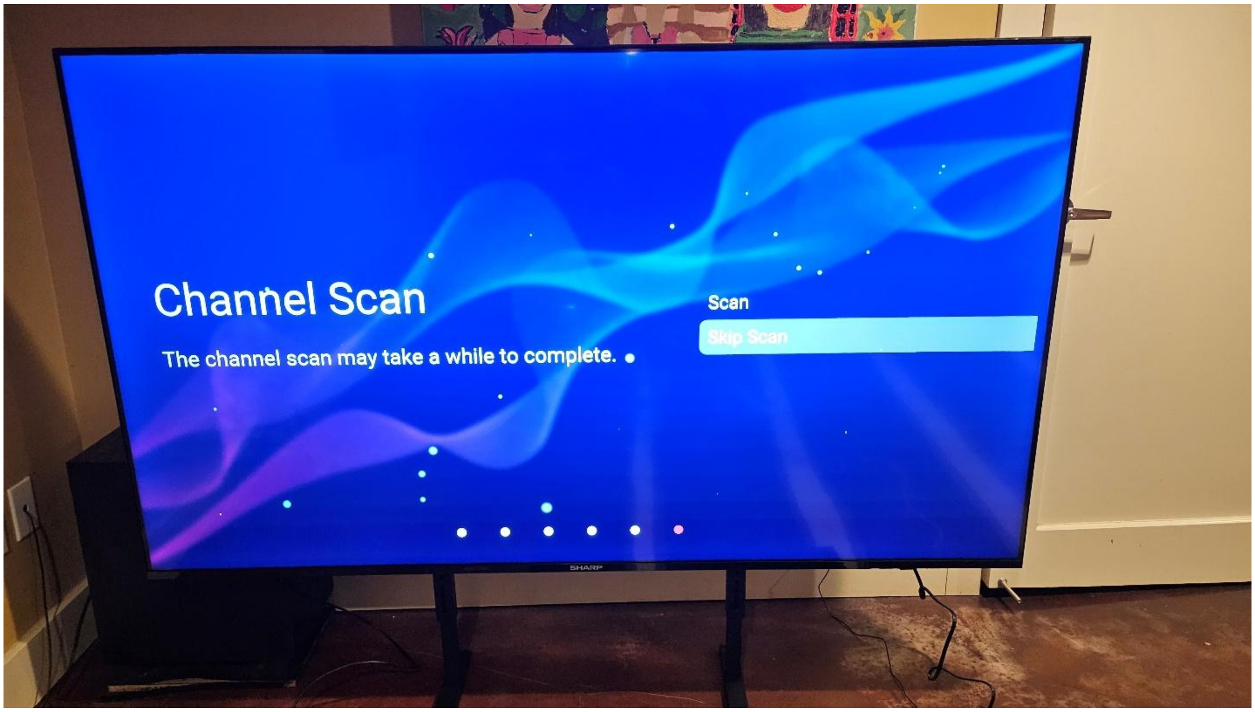


Tuner Mode

Please select your tuner mode.

Antenna

Cable



Channel Scan

The channel scan may take a while to complete.

Congratulations!!

Setup is completed. Enjoy!

Annex G: Incremental Cost Analysis for Global and Local Dimming in LCD Displays

This analysis provides a bottoms-up assessment of the incremental cost associated with adding dimming capabilities to an LCD display. PCL define the zero-cost starting point as a Fixed Backlight (a panel with no dimming capability). The cost structure is highly non-linear, with the primary cost driver being the mandatory shift in hardware complexity required for effective local dimming.

The research confirms that while the cost to add Global Dimming is negligible, the required hardware overhaul for True Local Dimming (Full Array Local Dimming, or FALD) necessitates a BOM increment established in the $50 to $250+ USD range.

Key Incremental Cost Benchmarks over Fixed Backlight

Table 116: Incremental cost per dimming architecture

Dimming Architecture	Zone Count Range	Validated BOM Incremental Cost (USD)[63]	Primary Technical Cost Driver
Global Dimming	1 zone	< $1	Control circuit/firmware integration. Mostly TCON firmware.[64]
Basic Full Array Local Dimming (FALD)	3–180 zones	$25–$150	Mandatory Direct-Lit Array hardware, backplane, and volume of driver integrated circuits (ICs)
Mini-LED Entry	200–800 zones	$100–$250	Massive chip volume (100k+), advanced driving schemes
Premium Mini-LED	800–5,000+ zones	$200–$400+	Non-linear scaling complexity, specialized thermal management

Bottoms-Up BOM Incremental Cost Assessment

The cost for dimming is calculated based on the necessary components, materials, and complexity required to integrate the feature into the fixed backlight baseline.

Global Dimming (1 Zone)

Incremental Cost Justification: Global dimming requires minimal hardware adjustment as the entire backlight array is adjusted uniformly.

- **Cost Driver:** This feature is achieved through simple control logic integrated into existing power management circuits or via a firmware update.[65]

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[63] Depends heavily on the display size and number of zones. Requires a backlight driver capable of handling multiple zones, as well as TCON firmware to control the dimming.

[64] A TCON board (short for Timing Controller) is the circuit board inside an LCD or OLED display that converts the video signal coming from the main board into the precise, high-speed timing signals needed to drive the panel's pixels.

[65] LED dimming interface IC | Infineon Technologies, accessed November 20, 2025, https://www.infineon.com/products/power/led-driver-ics/dimming-interface-ics

- **Validated BOM Cost:** The total incremental cost for adding this control is minimal, well under $1 USD.

Basic Full Array Local Dimming (FALD) (3–180 Zones)

The transition from a fixed backlight (often edge-Lit) to FALD requires a complete structural change to a Direct-Lit array placed behind the screen. This architectural change is the source of the major cost jump, detailed on Table 117.

Table 117: Example Incremental BOM Breakdown: 50" 4K FALD (approx. 144 zones)

Component Category	Function / Cost Driver	Estimated Incremental BOM Cost (USD)	Source/Notes
LED Array / Backplane	Thousands of LEDs, specialized PCB texture, and light guides. This is the largest component cost segment.	$10–$85	Represents the physical array structure[66]
Driver ICs and Control	Multiple multi-channel constant-current LED driver ICs (e.g., 7 ICs for 144 zones 9) for zone addressing.	$5–$15	Specialized ICs required for local control[67]
Thermal Management	Heat dissipation materials and assembly complexity necessary for a dense LED array.[68]	$10–$30	Increases complexity over fixed baseline
Total FALD BOM Increment	Sum of materials, drivers, and specialized assembly	$**25–$**130+	Aligns with the FALD industry range[69]

High-Density Local Dimming: Mini-LED (200–5,000+ Zones)

Mini-LED (MLED) systems scale costs rapidly due to the requirement for massive volumes of miniaturized chips and the complexity of the driving scheme.

- **Cost Driver:** Component Volume: A single 65-inch MLED display may require over 100,000 chips to create 1,000+ dimming zones, significantly multiplying material and assembly costs.[70]

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[66] Is it possible for local dimming algorithm of FALD monitors to be performed on PC?- Reddit, accessed November 20, 2025, https://www.reddit.com/r/Monitors/comments/1atwwu3/is_it_possible_for_local_dimming_algorithm_of/

[67] Hisense U7N / U78N / U75N series of 4K Mini LED TVs are launched in North America, accessed November 20, 2025, https://www.displayspecifications.com/en/news/92debeb

[68] LED Display Market Analysis- US, China, Japan, South Korea, Germany- Size and Forecast 2024-2028 | Technavio, accessed November 20, 2025, https://www.technavio.com/report/led-display-market-industry-analysis

[69] Dispelling the Myths of MiniLED TVs Impact on OLED TV Sales- Display Daily, accessed November 20, 2025, https://displaydaily.com/dispelling-the-myths-of-miniled-tvs-impact-on-oled-tv-sales/

[70] Cost Management as Key for Mini LED Backlight Technology to Beat OLED- LEDinside, accessed November 20, 2025, https://www.ledinside.com/news/2020/7/miniled_backlight_cost

- **Driver and Assembly Complexity:** The need for high-density placement and specialized driving solutions (like Active Matrix schemes to reduce IC count[71]) increases the backplane material cost and assembly effort.
- **Validated BOM Cost:** The incremental BOM for MLED over a fixed backlight is consistently benchmarked between $100 and $250 USD, confirming the required cost magnitude for high-performance HDR systems.

Efficiency and Power Consumption Trade-offs

The financial justification for the incremental cost of local dimming is split between the performance gain (HDR contrast) and the operational efficiency achieved through power scaling.

Power Scaling Benefit (Reduced Operating Cost)

Local dimming achieves significant power savings through its ability to modulate the backlight output in real-time:

- **Dynamic Power Reduction:** Local dimming saves energy by selectively turning off or dimming sections of the LED backlight that correspond to dark areas in the image.[72] This means power consumption is dramatically reduced when displaying content with high contrast or large black areas.
- **Efficiency Gains:** Televisions incorporating local dimming frequently achieve ENERGY STAR certification and are up to 70% more energy efficient than conventional fixed-backlight models.[73] This efficiency translates into quantifiable life cycle cost savings, helping to offset the initial retail premium.

Fixed Processing and IC Power Overhead

Implementing multi-zone dimming introduces a fixed power overhead that must be overcome to realize energy savings:

- **IC Power Draw:** Each dimming zone requires control circuitry (driver ICs). These ICs require a certain amount of fixed power to function, regardless of the backlight level. This collective power consumption constitutes a small, fixed energy drain.
- **Processing Overhead:** Local dimming requires advanced, proprietary algorithms to analyze video frames and calculate the precise brightness for each zone in real-time. This complex computational load strains the system-on-chip (SoC) and demands more powerful processors, adding to the fixed power consumption of the control system.

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[71] Cost Management as Key for Mini LED Backlight Technology to Beat OLED- LEDinside, accessed November 20, 2025, https://www.ledinside.com/news/2020/7/miniled_backlight_cost

[72] Mini-LED Backlight: Advances and Future Perspectives- MDPI, accessed November 20, 2025, https://www.mdpi.com/2073-4352/14/11/922

[73] The MiniLED Road to Success- Display Daily, accessed November 20, 2025, https://displaydaily.com/the-miniled-road-to-success/

In essence, local dimming increases the baseline power consumption (the fixed overhead) but achieves significant net power savings by drastically reducing the overall backlight output most of the time (the power scaling benefit).

Retail Price Premium and Market Strategy

The high incremental retail prices observed in the market reflect strategic positioning and feature bundling, in addition to the BOM cost.

- **Value Segment Multiplier:** In competitive segments, the retail markup is kept low (1.5x–2.5x the BOM) to drive adoption, as seen in models like the TCL QM5K[74] or Hisense U7N.
- **Premium Segment Multiplier:** For flagship models, MLED is bundled with high-margin technologies (e.g., 8K resolution,[75] specialized AI processing) to justify a high retail multiplier (5x–10x the BOM), resulting in prices exceeding $3,499.

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[74] Why I don't believe in FALD | [H]ard|Forum, accessed November 20, 2025, https://hardforum.com/threads/why-i-dont-believe-in-fald.2019103/

[75] Automotive 144-Zone Local Dimming Backlight Reference Design- Texas Instruments, accessed November 20, 2025, https://www.ti.com/lit/ug/tiduea1/tiduea1.pdf

Annex H: ABC Lamp SPD Analysis

Goal

The objective of this annex is to identify a practical and technically sound artificial light source—referred to here as the ABC lamp—for use in testing automatic brightness control (ABC) systems in outdoor and semi-outdoor digital signage displays (DSDs). The goal is to select an artificial light source that:

1. Can produce lux levels sufficient to activate ABC limits in DSDs (typically >2,000 lux),
2. Minimizes spectral error to sunlight and, more importantly, sensor error relative to a perfect lux meter,
3. Provide lens or barn doors that enable the tester to reduce the amount of light that hits the tested area of the screen, and
4. Keeps test burden low.

Input Data

The analysis was based on the following input data. We limited the evaluation of light sources to those that can provide bright, directional light. This excluded D65[76] light sources since D65-based reference lighting is generally not available in the high-lux, directional, and stage-lighting formats required for outdoor ABC testing.

We chose a simple approximation of daylight spectral power since so much variation exists in daylight SPD based on angle, orientation and seasonality (Figure 128).

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[76] CIE D65 represents an idealized version of midday daylight in Western Europe and North America during specific seasons and conditions.

CIE 15:2018 – "Colorimetry" (4th Edition)

Published by the **International Commission on Illumination (CIE)**

- D65 is a **standard daylight illuminant** representing average midday light in Western Europe/Northern latitudes with a **correlated color temperature (CCT)** of approximately **6504 K**.
- It was originally derived from **measured atmospheric daylight spectra** and then mathematically smoothed and standardized.

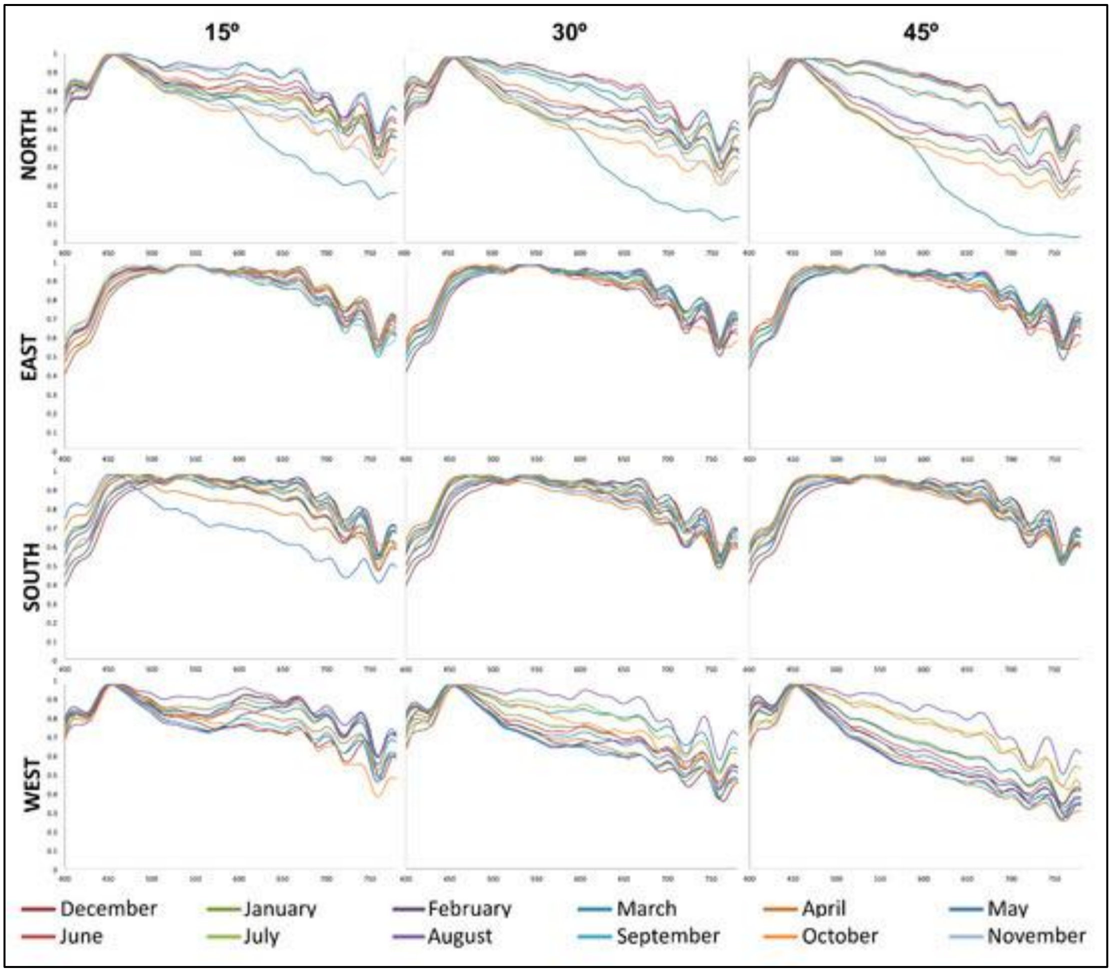

Figure 128: Sunlight SPD as a function of angle, orientation and seasonality[77]

The SPDs of light sources evaluated are depicted in Figure 129. PCL evaluated the SPDs and response curves from 300-1,100 nm since the photodetector response curves were specified across that range.

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[77] https://www.mdpi.com/2076-3417/11/13/5996

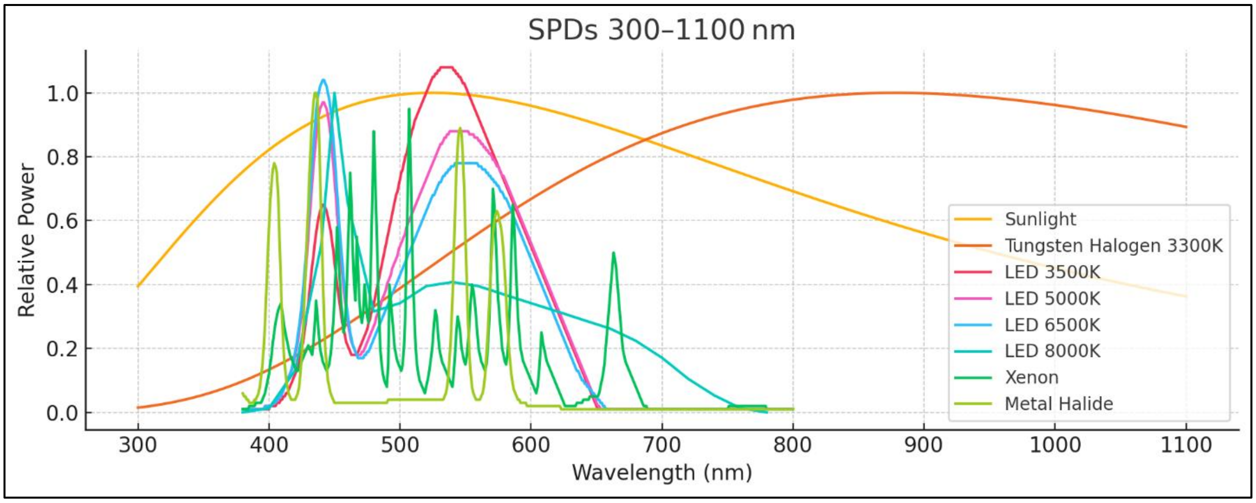

Figure 129: SPD of light sources evaluated

Note: PCL selected serval light sources that are commonly used in stage lamps, a widely available lighting segment that offers the high brightness and directionality needs of ABC testing. Sunlight (daylight) is the base case against which spectral error is assessed.

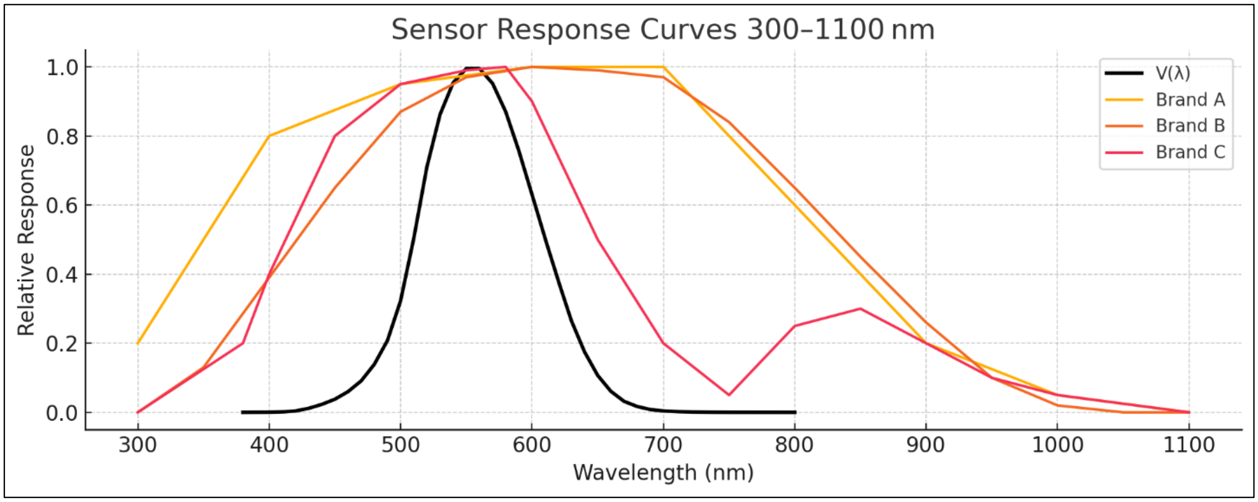

Figure 130: Spectral response curves of common ABC photo detectors

Note: We used publicly available ABC photodetector data. It is clear that the response curves of these sensors differs significantly from the response curve of the human eye (CIE 1931 v-lambda). It seems likely that the Brand B sensor response range extends below 300 nm; however, PCL did not extrapolate. This is a minor limitation of this analysis.

The figures below show the different lamp types considered.

Figure 131: Tungsten lamp

Figure 132: Xenon lamps

Figure 133: Metal halide lamp

Figure 134: LED lamp

Error Types and Purpose

This study uses two complementary error metrics—both now calculated **relative to natural sunlight** (300–1100 nm)—to guide selection of an ABC test lamp:

Spectral Error %

Measures how different a test SPD is from **sunlight** in terms of **shape** only.

- **Normalization **: Each SPD is area-normalized over 300–1,100 nm (so total area = 1), isolating differences in spectral distribution rather than intensity.

- **Calculation**: Compute the root-mean-square error (RMSE) between the normalized test SPD and normalized sunlight SPD, then divide by the mean of the sunlight SPD and multiply by 100:

$$\text{Spectral Error }\% = \frac{\sqrt{\frac{1}{N}\sum_{\lambda}\left[\text{SPD}_{\text{test}}(\lambda) - \text{SPD}_{\text{sun}}(\lambda)\right]^2}}{\frac{1}{N}\sum_{\lambda}\text{SPD}_{\text{sun}}(\lambda)} \times 100$$

- **Purpose**: Quantifies how faithfully a lamp's spectrum **matches the shape of real sunlight**, independent of overall brightness.

Sensor Reading Error %

Measures how differently a **real-world photodetector** (calibrated to sunlight) reads **100 lux** of each light source, compared to a **perfect lux meter** (CIE V(λ) response).

- **Scaling**: Each test SPD is scaled so that an ideal V(λ)-based meter would register exactly **100 lux** of sunlight.
- **Sensor Output**: That same scaled SPD is passed through the photodetector's response curve to get **$\text{SensorOutput}_{\text{test}}$**.
- **Calculation**:

$$\text{Sensor Error }\% = \frac{\text{SensorOutput}_{\text{test}} - \text{SensorOutput}_{\text{sun}}}{\text{SensorOutput}_{\text{sun}}} \times 100$$

where **$\text{SensorOutput}_{\text{sun}}$** is the detector's reading of 100 lux of real sunlight.

- **Purpose**: Captures the practical error a cheap ambient sensor will introduce when using a non-sunlight lamp—directly tied to how the ABC algorithm will behave under each test source.

By combining **Spectral Error** (shape fidelity) with **Sensor Reading Error** (practical lux accuracy), it is ensured the chosen test lamp both resembles real sunlight and drives the sample ABC system in a repeatable, predictable way under real-world sensor characteristics.

Calculation Results

Table 118 and Table 119 below reflect the results of these calculations.

Spectral Error vs. Sunlight (300–1100 nm)

Table 118: ABC light source spectral error

Light Source	Spectral Error (%)
Sunlight	0.0
Tungsten Halogen 3300 K	27.6
5000 K LED	31.2
6500 K LED	31.6
3500 K LED	33.8
8000 K LED	34.2
Xenon	32.0
Metal Halide	63.6

Note: All LEDs and Xenon sit within a tight 31%–34 % "shape mismatch" band, while Metal Halide is an outlier (63.6 %). Tungsten is most similar to daylight, but sensor error is high.

Sensor Reading Error vs. Sunlight (300–1100 nm)

Each source scaled to 100 lux by V(λ) before sensor curve application

Table 119: ABC light source spectral error

Light Source	Error Brand A	Error Brand B	Error Brand C
Sunlight	0.0%	0.0%	0.0%
Tungsten Halogen 3300 K	+53.0%	+69.2%	–23.1%
3500 K LED	–47.3%	–53.1%	–10.1%
5000 K LED	–44.8%	–50.4%	–12.7%
6500 K LED	–43.8%	–49.4%	–12.2%
8000 K LED	–42.5%	–48.1%	–11.8%
Xenon	–22.5%	–27.8%	–5.6%
Metal Halide	–43.4%	–48.6%	–11.3%

Notes:

Tungsten: inconsistent (significant over-reading on A/B, under-reading on C).

Xenon: best sensor agreement (under-reads ~–25 %), but these lamps are burdensome to use in a lab environment.

Metal Halide and LEDs (3500–8000 K): all under-read by 10%–55 %.

Recommendation

Below is a simple grading table that scores three candidate lamp types against the four key criteria. Each cell is rated A (best), B (good), C (marginal/poor), or D (unacceptable).

Table 120: ABC lamp evaluation results table

Criterion	5,000–8,000 K LED	Xenon Arc	Tungsten Halogen
1. Output ≥ 2 000 lux at the ABC sensor	A	A	C
2. Minimizes spectral and sensor error vs. sunlight	A–B	A–B	C–D
3. Optics (barn-doors/lenses) to limit stray light	A	B	B
4. Low test burden (cost, setup, maintenance)	A	C	C

Notes:

1. **Output:** Typical 200–300 W LED spots reach 3,000–10,000 lx at the sensor plane; high-power Xenon fixtures can exceed 30,000 lx; halogen follow spots rarely exceed 2,000 lx below ~1 kW input.
2. **Spectral and sensor error vs. sunlight:** 5,000–8,000 K LEDs show ~31–34% spectral error and -42% to-50% sensor error on broad-band sensors; Xenon shows ~32% spectral error and ~–25% sensor error; halogen has the lowest spectral error (~28%) but sensor error swings widely (+69% to –23%).
3. **Beam control:** LED fixtures almost always ship with adjustable lenses and barn doors. Xenon follow spots may offer shutters or irises but are heavy and slow to adjust. Halogen fixtures generally lack fine beam-control accessories without expensive add-ons.
4. **Test burden:** LEDs run under ~$800 per fixture with plug-and-play drivers, no warm-up, and minimal maintenance. Xenon fixtures exceed $10,000, require specialized power supplies, warm-up/cool-down cycles, lamp replacement, and UV-safety controls. Halogen fixtures sit under ~$5,000 but produce very high heat, need bulky ballasts, have short lamp life, and draw high power.

Summary

- 5,000–8,000 K LEDs earn mostly A’s, a B for sensor-error at the upper color temperature end, and excel on practicality.
- Xenon scores well on raw error and output but falls short on cost, complexity, and lab-to-lab reproducibility.
- Tungsten Halogen has a strong spectral match but fails on sensor consistency, output efficiency, and operational burden.

Recommendation: Standardize on 5,000–8,000 K LED fixtures for ABC testing. They meet all technical requirements while keeping cost, test burden, and maintenance low.

Annex I: ABC Policy Recommendations for Outdoor Displays

This annex is intended to answer the broader set of research questions focused on ABC testing for semi-outdoor and outdoor displays.

This section frames high-level ABC test method requirements for semi-outdoor and outdoor displays as follows:

1. The light sources provides sufficient light to hit the upper ABC lux limit of outdoor or semi-outdoor DSDs and is oriented at a representative angle of incidence
2. The light source lens or barn doors enable the tester to control the beam to reduce the amount of light that falls on the measured screen area
3. The light source minimizes spectral related error relative to daylight
4. The light source is affordable and practical to operate

We address these requirements below in order.

Lux levels and angle of incidence

Outdoor and semi-outdoor displays operate across a wide range of ambient light levels per Table 121.

Table 121: Typical daylight lux levels

Natural Light Condition	Typical Lux (lx)
Direct Sunlight (clear day, midday)	32,000 to 120,000+
Full Daylight (not direct sun, clear day)	10,000 to 25,000
Ambient Daylight (shade, clear sky, midday)	~20,000
Overcast Day (midday)	1,000 to 2,000
Sunrise or Sunset (clear day)	300 to 400

A truly representative ABC test would scale ABC lux levels all the way up to levels associated with direct sunlight (> 100,000 lx). However, this is difficult and unnecessary given that displays hit their ABC adjustment limit well below that level. In other words, it appears that displays emit maximum luminance well before lux levels associated with direct sunlight. We are unable to measure the ABC lux limit of a large sample of outdoor or semi-outdoor displays. However, one popular model from the market leader was tested and secondary research was performed. The model tested hit the ABC limit at about 2,000 lx. And secondary research[78] suggests that:

Ideal Screen Brightness (cd/m^2) *= Ambient Light (cd/m2) ÷ 2*

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[78] https://www.crowntv-us.com/blog/why-high-brightness-displays-outdoor-digital-signage/

Conversely:

Ambient Light (lux) = Peak Brightness (cd/m^2) *x 2*

So, a display with peak brightness of 10,000 cd/m^2 programmed with that logic would reach its maximum luminance level at 20,000 lx (2 x 10,000 cd/m^2). Here displays only as bright as 10,000 cd/m^2 peak brightness are considered since that is the proposed scope limit for peak brightness. Since there is little data to inform this discussion beyond this rule of thumb, it is proposed to require that the ABC light source be capable of generating 1.5 times that lux level (i.e., 30,000 lx) at a distance of 3 meters, which is sufficient assuming a 45° angle of incidence and the screen area scope limit recommended in this report. 30,000 lx is achievable across the ambient light technologies considered in this report at a price point below $600.

In the field, outdoor ambient light sensors are exposed to a wide diversity of light angles of incidence. No one angle is representative. So, as with the TV test method (e.g., IEC 62087-3 Ed3), PCL proposes 45° as an informed guess that could be most representative of real-world conditions.

Beam control

In the laboratory tests both a narrow focused-beam lamp and one with adjustable shutters were able to minimize the amount of light that fell on the display screen area. The HID focused beam stage light was able to direct a near parallel beam towards the ABC sensor. Further information is in section 1.1.1.15.3: AUTOMATIC BRIGHTNESS CONTROL.

Figure 135: Moving beam stage light example

Note: This type of stage light, powered by an LED light source, is capable of achieving 0.2 degree beam angle and can achieve mid-day direct sunlight lux levels during ABC testing at a reasonable price point (~$600).

In the case of the LED spotlight, the adjustable shutters allowed the tester to partially block light that would otherwise fall on the display screen.

Figure 136: LED stage light with adjustable shutters

Note: While this stage light is affordable, easy to use, and can achieve lux levels at the top of the ABC range of the outdoor display tested, it is not bright enough to meet the requirements identified above.

While it would be representative of real-world conditions to test the display with uniform ambient light exposure across the entire display surface, including the ABC sensor, attempting to do so with artificial light sources would introduce spectral and spatial camera reading error. The ABC test method for TVs—involving an overhead LED reflector lamp—involves ambient light falling on the screen area, but the error is small given the low lux levels used for these tests.

Given the high lux levels needed for outdoor display ABC testing, PCL recommends minimizing ABC lamp light that falls on the tested screen area and subtracting whatever ambient reflects off the screen from the test results. Reflected light can be measured with the display screen off at each lux level and later subtracted from the screen-average luminance readings for ABC related tests. PCL has confirmed that this method of subtraction is effective.

Spectral power distribution

Finally, the goal is to find a light source with an SPD that is as close to daylight as possible. CIE D65[79] represents an idealized version of midday daylight in Western Europe and North America during specific

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[79] **CIE 15:2018 – "Colorimetry" (4th Edition)**
Published by the **International Commission on Illumination (CIE)**

- D65 is a **standard daylight illuminant** representing average midday light in Western Europe/Northern latitudes with a **correlated color temperature (CCT)** of approximately **6504 K**.
- It was originally derived from **measured atmospheric daylight spectra** and then mathematically smoothed and standardized.

seasons and conditions. While D65 is widely used as a reference point for colorimetry and lighting calibration, it is not a representation of all daylight conditions—which can vary significantly by time of day, season, and geographic location (Figure 137). The research in this section aims to minimize error relative to D65, but the limitations of this approach are noted in that D65 is an imperfect representation of real-world daylight.

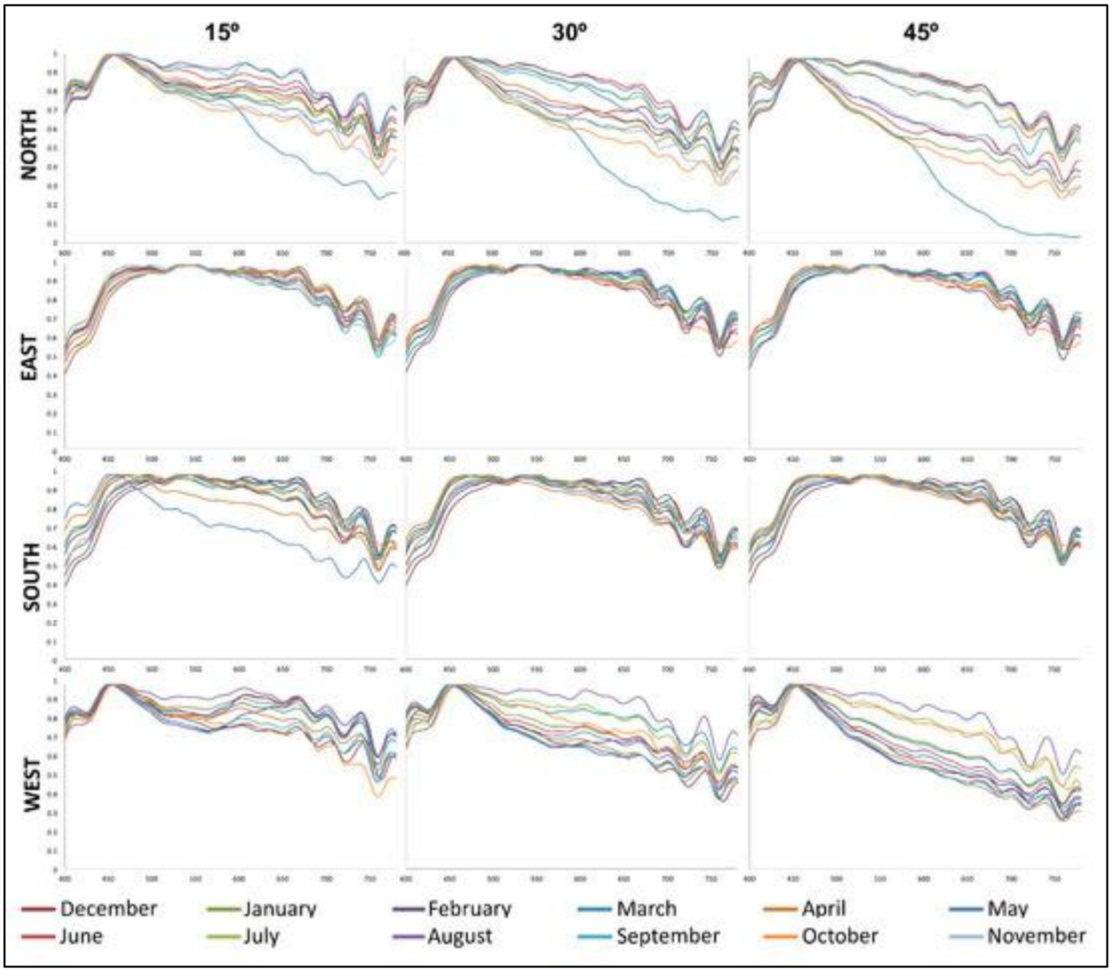

Figure 137: Sunlight SPD as a function of angle, orientation and seasonality[80]

Unfortunately, while some D65 light booths and other LED-tube D65 light sources exist, none of them are bright or focused enough (e.g., stage lights) for use when testing ABC for outdoor DSDs. Therefore, several common light sources used in bright, directional light sources like stage lights were considered. PCL summarize PCL's analysis approach below starting with input data.

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[80] https://www.mdpi.com/2076-3417/11/13/5996

Input data

PCL considered several lamp types that are sometimes used in stage lights. Figure 138 shows the SPDs of the light sources evaluated, plotted against D65, PCL's reference light source.

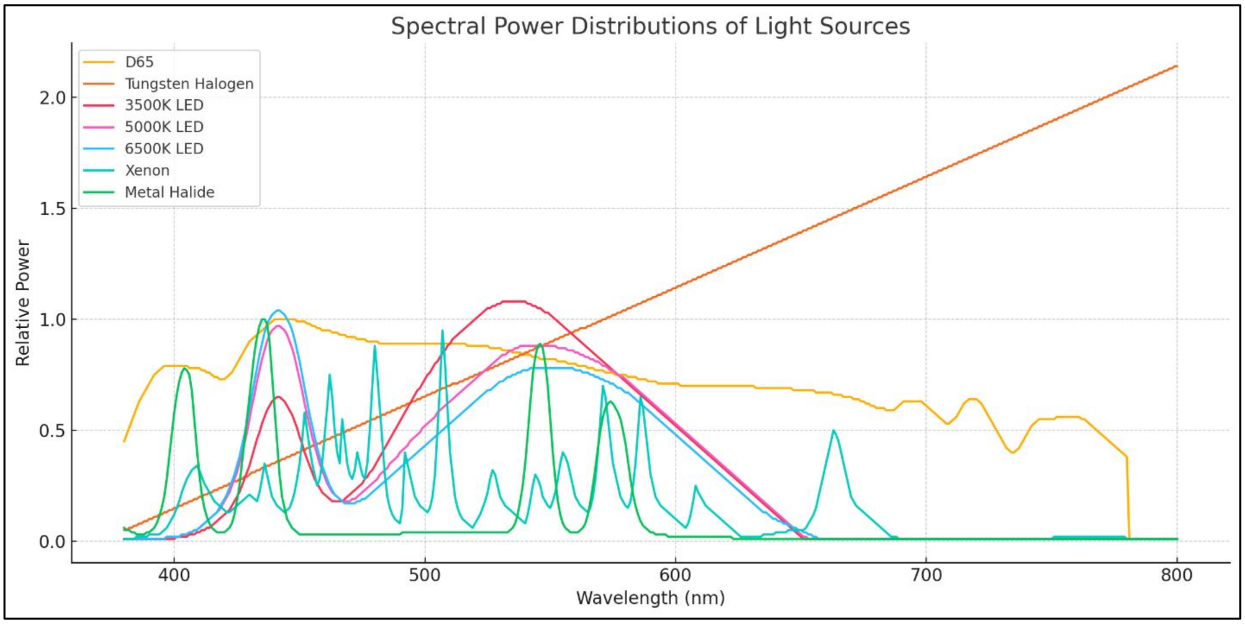

Figure 138: Spectral Power Distribution (SPD) of Bright Light Sources[81]

Note: **PCL** selected serval light sources that are commonly used in stage lamps, a widely available lighting segment that offers the high brightness and directionality needs of ABC testing. D65 is the based case against which spectral error is assessed.

While the LED light sources represented in Figure 138 are typical, there can be significant SPD variation across white LED lamps of the same color temperature per Figure 139. This limitation, along with the D65 limitation discussed above, increases the uncertainty of the results and conclusions and ABC testing in general.

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[81] Sources:

Xenon	https://www.nature.com/articles/s41598-023-31883-3
Metal Halide	https://zeiss-campus.magnet.fsu.edu/articles/lightsources/metalhalide.html
D65	https://www.waveformlighting.com/color-matching/what-is-d65-and-what-is-it-used-for
LED	https://luminusdevices.zendesk.com/hc/en-us/articles/4403685063437-What-do-CCT-CIE-and-SPD-mean-in-LED-lighting
Tungsten	https://www.nature.com/articles/s41598-023-31883-3

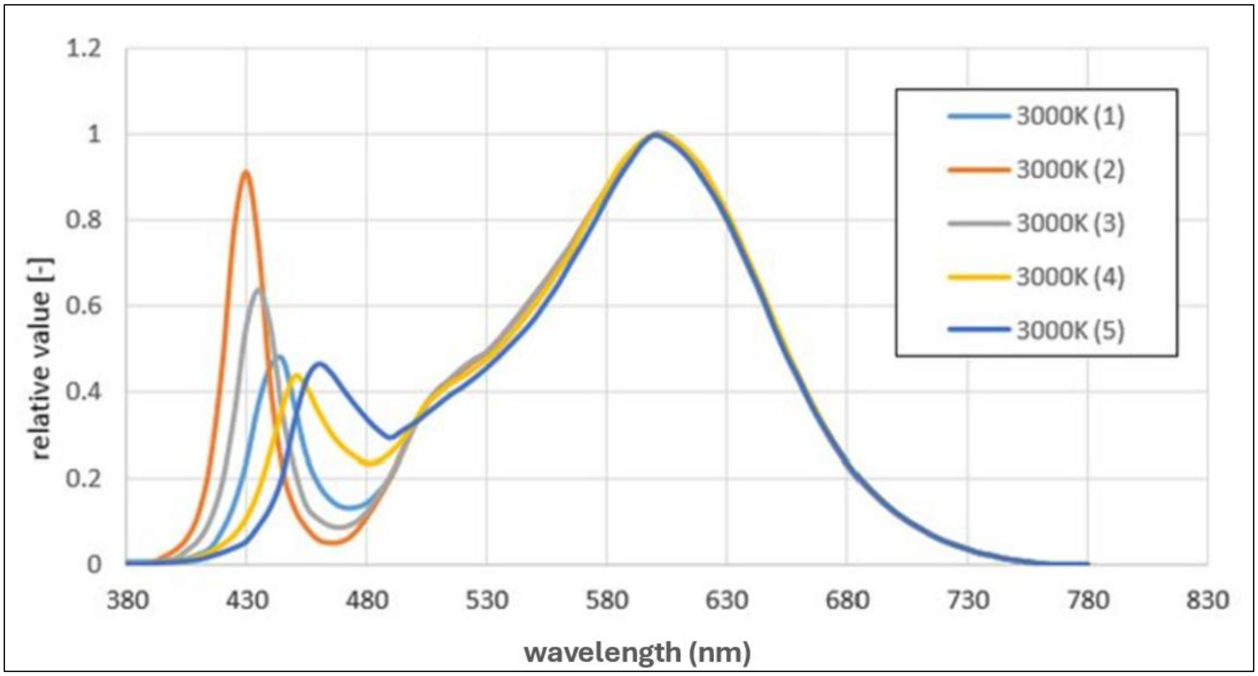

Figure 139: SPD variation at same white LED color temperature

Figure 140 reflects the spectral response curves of the few photo sensors for which PCL has data.

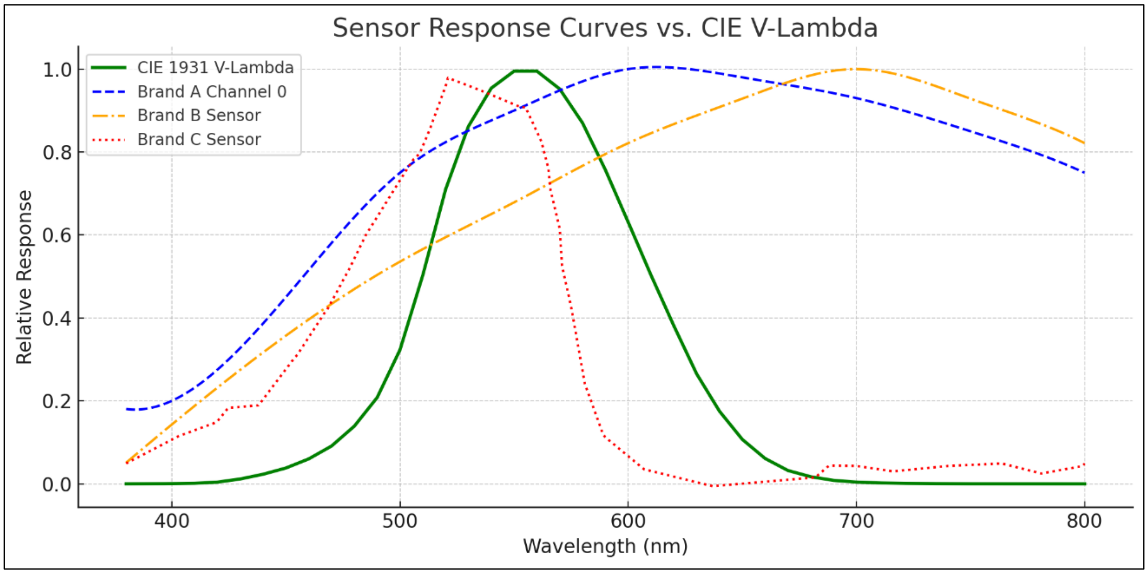

Figure 140: Relative Response Curve of Sample ABC Sensor vs. Human Eye (V-Lambda)[82]

Note: We used ABC photodetector data evaluated during IEC workgroup test method deliberations in 2022. It is clear that the visible spectrum (380–800nm) response curves of these sensors differs significantly from the response curve of the human eye (v-lambda).

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[82] Source: Brand A and B data discussed in IEC ABC subgroup in 2022. Brand C — https://www.renesas.com/en/document/apn/an1421-ambient-light-sensor.

Error Types and Purpose

Two error metrics were calculated:

1. **Spectral Error %**: Measures how different a test SPD is from D65 in terms of shape. All SPDs are normalized by area, and root mean square error (RMSE) is used:

$$\text{Spectral Error }\% = \frac{\text{RMSE}_{\text{test vs D65}}}{\text{mean SPD}_{\text{D65}}} \times 100$$

This metric tells us how faithfully the SPD emulates D65, independent of intensity.

2. **Sensor Reading Error %**: Measures how differently a sensor perceives 100 lux from each light source, assuming the sensor is calibrated to D65. Each SPD is scaled to produce 100 lux using V lambda and then passed through each sensor curve. Error is:

$$\text{Sensor Error }\% = \frac{\text{SensorOutput}_{\text{test}} - \text{SensorOutput}_{\text{D65}}}{\text{SensorOutput}_{\text{D65}}} \times 100$$

Calculation Results

Table 122: Spectral error relative to daylight and example sensor reading error

Light Source	Spectral Error (%) Relative to D65 [absolute value]
Tungsten Halogen	27.6%
3500K LED	33.8%
5000K LED	31.2%
6500K LED	31.6%
Xenon	32.0%
Metal Halide	63.6%

Table 123: Per-brand sensor error

	Sensor Error (%)		
Light Source	Brand A	Brand B	Brand C
Tungsten Halogen	53.0%	69.2%	-23.1%
3500K LED	-47.3%	-53.1%	-10.1%
5000K LED	-44.8%	-50.4%	-12.7%
6500K LED	-43.8%	-49.4%	-12.2%
Xenon	-22.5%	-27.8%	3.1%
Metal Halide	-43.4%	-48.6%	-11.3%

Interpretation and Recommendation

- Tungsten Halogen has the lowest spectral error but produces large errors in real-world sensors.
- Xenon yields the lowest sensor error, but its spectral error is moderate, and it emits more heat and has poor spectral smoothness.
- Metal Halide generally performs poorly on both fronts.
- 5,000K and 6,500K LEDs strike a **balance**: relatively modest spectral error and reasonably consistent (though underestimated) sensor readings.

Lamp type

PCL recommends the following lamp requirements when testing ABC performance of outdoor or semi-outdoor displays:[83]

- White LED
- 3,500–8,000K color temperature range
- Focused beam
- Capable of generating 30,000 lx at 3 meters

While the LED light sources considered in Table 122 did not have the lowest spectral error relative to D65 in all cases, the provided the most balanced solution. LED lamps offer more luminance stability than halogen lamps. This enables the use of these lamps without needing an expensive controlled AC power source that requires annual calibration. LED focused beam stage lights, similar to the one tested, are capable of achieving lux levels associated with direct sunlight, so they offer the ability to adapt to future policy adjustment that might require ABC testing across the full range of lux levels experienced in the field.

PCL suggest a wide color temperature range since white LED color temperate is not a major driver of spectral error and the wide range ensures broad availability of cost-effective lamps that meet the lamp specification.

ABC credit

When considering how to incorporate ABC performance into measurement methods and energy efficiency compliance determination for outdoor or semi-outdoor displays, it is important to keep in mind the conclusion that a lot of measurement uncertainty is present relative to real-world conditions when testing the ABC performance of these displays.

The primary sources of ABC test measurement uncertainty relative to real-world conditions are:

- Diversity of real-world spectral and spatial light characteristics

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[83] Example: https://yuerlights.com/products/400w-led-moving-head-light-atomization-zoom-strobe-pattern-effect-for-dj-disco-stage-wedding-party-lighting-show-bar-party-club?srsltid=AfmBOorMy4xNXGasCJZJ_LB6mXefT_AKLwDc-NzhmH65l5lKxHBNwApV&variant=45362642026774

- Single SPD and angle of incidence chosen for testing compared to real-world diversity
- Imperfect spectral and cosine response curves associated with low-cost ABC photodetectors
- Test equipment positioning tolerances

None of this uncertainty applies to the shape of the dimming line determined using the proposed test method. Rather it represents uncertainty about where on the dimming line the display operates in real-world conditions. While ANSI/CTA-2037-D requires that PPSs with ABC enabled by default are tested with ABC enabled and that the average of the four ABC measurements represents the Active Mode power of that PPS, here PCL recommends that policymakers developing MEPS take an alternative approach more similar to the approach used in European policy today, in which Active Mode power is determined with ABC disabled, and an ABC credit is provided for displays that meet certain ABC setting and performance requirements.

In this case, because displays are graded on light-based energy efficiency, which is largely unaffected by ABC performance, PCL proposes a reduction in reported power but not reported efficiency. In other words, for displays that meet ABC credit eligibility requirements, compliance would be determined against the ABC-off power and luminance measurements without any ABC credit. However, some means would exist for reporting and communicating the fact that eligible displays generally operate at 10%–20% lower power than measured and reported with ABC off. Energy labels might have to be redesigned to communicate the benefits of and incentivize the pursuit of this ABC credit.

PCL recommends starting stakeholder discussions of power and luminance scaling eligibility criteria with the following frameworks (in addition to fulfilling all other ABC criteria previously stated):

Table 124: ABC eligibility criteria per outdoor display peak brightness

		ABC Credit Eligibility Criteria	
ABC	Outdoor Display ABC Lux Levels	Power	Luminance
Off	-	-	-
On	2 * Peak Brightness (cd/m^2)	≥ 100% of ABC off	≥100% of ABC off
On	1.2 * Peak Brightness (cd/m^2)	≤ 91% of level at max lux	65%–95% of level at max lux
On	0.7 * Peak Brightness (cd/m^2)	≤ 85% of level at max lux	50%–80% of level at max lux
On	0.24 * Peak Brightness (cd/m^2)	≤ 80% of level at max lux	35%–70% of level at max lux

The lux levels preserve the scaling percentages used in current Ecodesign ABC requirements:

Table 125: Ambient illuminance scaling

Lux	% of 141 lx
141	100%
85	60%
49	35%
17	12%

while scaling the ABC requirements to display peak brightness given the rule of them discussed before:

Ideal Screen Brightness (cd/m²) = Ambient Light (lux) ÷ 2, or

Ambient Light (lux) = Peak Brightness (cd/m²) x 2

While this proposal recommends test and list for DSDs, and therefore compliance would not need to be determined, PCL offers the above input on ABC eligibility requirements in anticipation of future MEPS or to support policy discussions about DSD labeling, which might factor ABC eligibility.

Summary

This section proposed methods, metrics, and incentives for outdoor and semi-outdoor display ABC capability and enablement. Recommendations include lux levels, lamp angle, beam control, lamp specifications, and policy incentives.

The ABC light source should be a white LED stage light with a 3,500–8,000 K color temperature, a focused beam, and the ability to deliver 30,000 lx at 3 meters. Light should be directed at the ABC sensor at a 45° angle of incidence (consistent with IEC 62087-3 Ed3 for TVs). Beam control—via narrow focused-beam optics or adjustable shutters—should be used to minimize light falling on the screen area, with any residual reflected light measured screen-off and subtracted from screen-average luminance readings.

Two error metrics were used to evaluate candidate lamp types against CIE D65: (1) Spectral Error %, the area-normalized RMSE of each lamp's SPD relative to D65, which captures how faithfully the lamp emulates daylight independent of intensity; and (2) Sensor Reading Error %, the percentage difference between a D65-calibrated photodetector's response to 100 lx of D65 versus 100 lx of the candidate lamp, which captures the practical reading error a real ABC sensor would experience. Across the lamps evaluated, 5,000 K and 6,500 K white LEDs offered the most balanced combination of moderate spectral error and consistent (though underestimated) sensor readings.

Given the substantial measurement uncertainty inherent in outdoor ABC testing relative to real-world conditions, PCL recommends determining Active Mode power with ABC disabled and offering a separate ABC credit — modeled on the current European approach — for displays that meet defined ABC setting and performance requirements. Because efficiency is graded on a light-based metric largely unaffected by ABC, the credit takes the form of a reduction in reported power (typically 10–20%) rather than a change in reported efficiency.

Annex J: Overview of Current Display Policies

Ecodesign

Active Mode Testing

Power Measurements

- The Unit Under Test (UUT) is tested in its default Standard Dynamic Range (SDR) Preset Picture Setting (PPS) with Automatic Brightness Control (ABC) disabled.
- Power consumption is measured during the IEC 10-minute SDR test video.
- High Dynamic Range (HDR) power consumption is also measured using the IEC HDR test clip, but only for labeling purposes, not for compliance.

Luminance Measurements

- The tester cycles through L10 to L80 patterns (where L10 indicates a 10% white center screen) and records screen center luminance at each step. A simplified approach uses the L40 pattern for displays between 6" and 12" diagonally, and L20 for displays that are 12" diagonally or larger.
- The last luminance reading before any Automatic Brightness Limiting (ABL) occurs is selected as the final measurement.
- If ABC is enabled by default, luminance and power tests are conducted at multiple ambient light levels to verify that both luminance and power decrease in response to lower light levels.

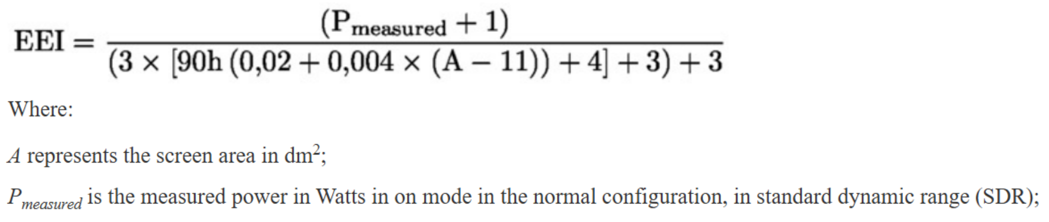
Non-Active Mode Testing

The UUT is tested in Non-Active Mode under two conditions:

- Passive standby (no network connection).
- Networked standby mode, where the monitor is tested with a network reactivation function enabled.

Active Mode Metrics and Power Limits

The maximum allowable Active Mode power consumption is determined by a formula that accounts for screen area, with an additional power allowance for high-resolution displays (i.e., resolutions above 1920 × 1080).



$$\mathbf{EEI} = \frac{(\mathbf{P_{measured}} + 1)}{(3 \times [90\mathbf{h}\,(0{,}02 + 0{,}004 \times (\mathbf{A} - 11)) + 4] + 3) + 3}$$

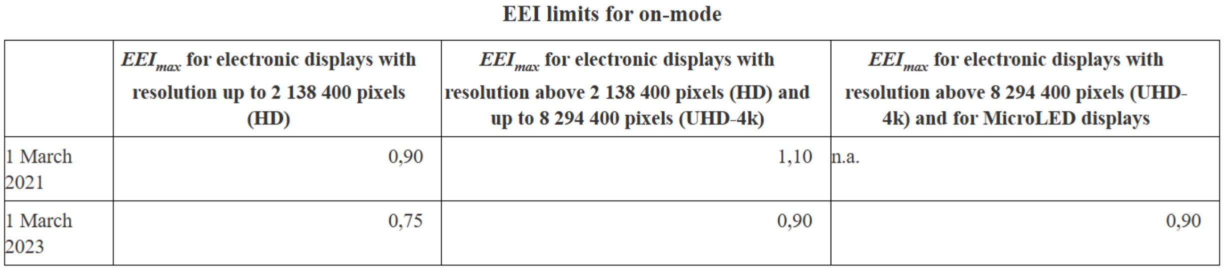
Where:

A represents the screen area in dm^2;

$P_{measured}$ is the measured power in Watts in on mode in the normal configuration, in standard dynamic range (SDR);

Figure 141: Ecodesign's Energy Efficiency Index

Table 126: Ecodesign's limits based on the EEI



EEI limits for on-mode

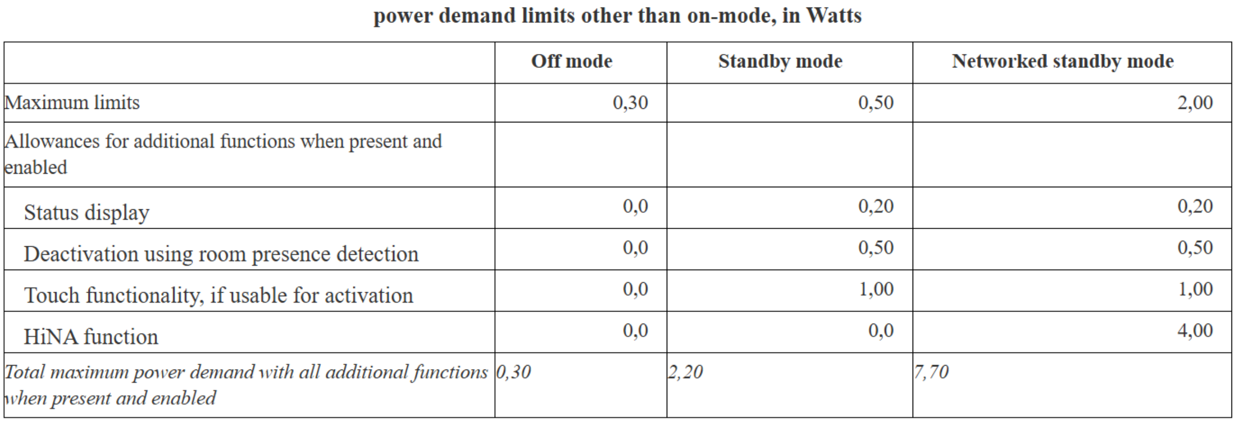
	EEI_{max} for electronic displays with resolution up to 2 138 400 pixels (HD)	EEI_{max} for electronic displays with resolution above 2 138 400 pixels (HD) and up to 8 294 400 pixels (UHD-4k)	EEI_{max} for electronic displays with resolution above 8 294 400 pixels (UHD-4k) and for MicroLED displays
1 March 2021	0,90	1,10	n.a.
1 March 2023	0,75	0,90	0,90

If ABC is enabled by default across PPSs and is proven to work, measured power is reduced by 10% when graded against the power limit.

Standby Metrics and Power Limits

Standby has different limits for each mode, with power adders given if certain functions are present and enabled.

Table 127: Ecodesign's Standby power limits



power demand limits other than on-mode, in Watts

	Off mode	Standby mode	Networked standby mode
Maximum limits	0,30	0,50	2,00
Allowances for additional functions when present and enabled			
Status display	0,0	0,20	0,20
Deactivation using room presence detection	0,0	0,50	0,50
Touch functionality, if usable for activation	0,0	1,00	1,00
HiNA function	0,0	0,0	4,00
Total maximum power demand with all additional functions when present and enabled	*0,30*	*2,20*	*7,70*

ENERGY STAR Displays 8.0

Active Mode Testing

Power Measurements

- The Unit Under Test (UUT) is tested in its "as shipped" condition, with a network connection if applicable.

- Uses the 10-minute IEC Standard Dynamic Range (SDR) test video for power measurements. If the UUT does not support the video, it defaults to the VESA FPDM2 L80 pattern.
- If Automatic Brightness Control (ABC) is not enabled, luminance is set to 200 cd/m^2.
- If ABC is enabled, the sensor is either disabled (if possible) or illuminated with 300 lx.

Luminance Measurements

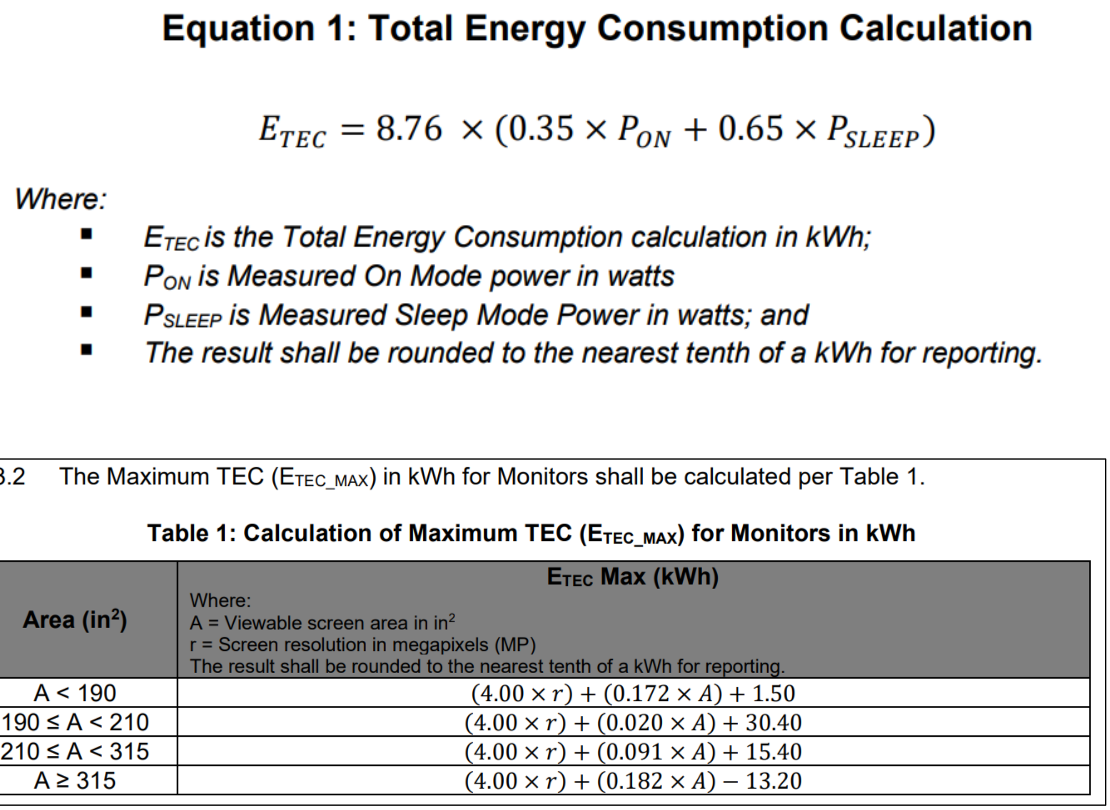
- Uses the IEC 62087:2011 three-bar video signal for luminance testing. If the UUT cannot display the three-bar video, it defaults to the VESA FPDM2 L80 pattern.
- The UUT is tested at maximum brightness and contrast, with all other settings left in the “as shipped” configuration.

Standby Testing

- Conducted in the “as shipped” condition, with a network connection if applicable.
- Sleep Mode is tested by putting the host machine into Sleep Mode; only these measurements are used for compliance evaluation.
- Off Mode is tested by turning off the monitor using its power switch.

Metrics and Power Limits

ENERGY STAR Displays 8.0 determines a maximum total energy consumption (TEC) requirement, which is calculated using both Active Mode and Sleep Mode power measurements.



Equation 1: Total Energy Consumption Calculation

$$E_{TEC} = 8.76 \times (0.35 \times P_{ON} + 0.65 \times P_{SLEEP})$$

Where:

- *E_{TEC} is the Total Energy Consumption calculation in kWh;*
- *P_{ON} is Measured On Mode power in watts*
- *P_{SLEEP} is Measured Sleep Mode Power in watts; and*
- *The result shall be rounded to the nearest tenth of a kWh for reporting.*

3.3.2 The Maximum TEC (E_{TEC_MAX}) in kWh for Monitors shall be calculated per Table 1.

Table 1: Calculation of Maximum TEC (E_{TEC_MAX}) for Monitors in kWh

Area (in^2)	**E_{TEC} Max (kWh)** Where: A = Viewable screen area in in^2 r = Screen resolution in megapixels (MP) The result shall be rounded to the nearest tenth of a kWh for reporting.
A < 190	$(4.00 \times r) + (0.172 \times A) + 1.50$
190 ≤ A < 210	$(4.00 \times r) + (0.020 \times A) + 30.40$
210 ≤ A < 315	$(4.00 \times r) + (0.091 \times A) + 15.40$
A ≥ 315	$(4.00 \times r) + (0.182 \times A) - 13.20$

Figure 142: ENERGY STAR Displays 8.0’s TEC and maximum TEC calculations

ENERGY STAR provides power adders for certain display features that may impact energy consumption:

- E_{EP}: adder for Enhanced Performance Displays, calculated according to color gamut coverage and E_{TEC_MAX}.
    - A display qualifies as an Enhanced Performance Display if it meets:
        - 32.9% or greater CIELUV color gamut
        - 2.3 MP or greater native resolution
        - Contrast ratio of at least 60:1 at a horizontal viewing angle of at least 85° from the perpendicular on a flat screen and at least 83° from the perpendicular on a curved screen, with or without a screen cover glass
- E_{ABC}: adder for Automatic Brightness Control, available for computer monitors that have it enabled by default and if the Active Mode power reduction is greater than or equal to 20% when comparing measurements at 12 lx and 300 lx.
- E_N: adder for Full Network Connectivity, fixed at 2.9 kWh.
- E_T: adder for touch technology, set at 17% of ETEC_MAX.
- E_C: adder for curved displays, set at 15% of ETEC_MAX.
- E_{HDR}: adder for DisplayHDR-certified displays, set at 5% for HDR 600 and 10% for HDR 1000.
- E_{USB}: adder for computer monitors with USB-C interfaces that can bring greater than or equal to 45 W to connected devices, fixed at 2.75 kWh.
- eff_{AC_DC}: standard adjustment for AC/DC power conversion losses, set at 1 for AC-powered displays and 0.85 for DC-powered displays.

California Energy Commission’s Title 20

Active Mode Testing

Power Measurements

- The Unit Under Test (UUT) is tested in its “as shipped” condition, with a network connection if applicable.
- Power is measured using a 10-minute IEC Standard Dynamic Range (SDR) test video. If the UUT does not support this clip, the VESA FPDM2 L80 pattern is used instead.
- If ABC is not enabled, the monitor’s luminance is set to 200 cd/m^2.
- If ABC is enabled, the ABC sensor is disabled if possible or illuminated with 300 lx.

Luminance Measurements

- Measured using the IEC 62087:2011 three-bar video signal or the VESA FPDM2 L80 pattern if the three-bar signal is unsupported.
- Luminance is recorded at both the as-shipped brightness setting and at maximum brightness and contrast.

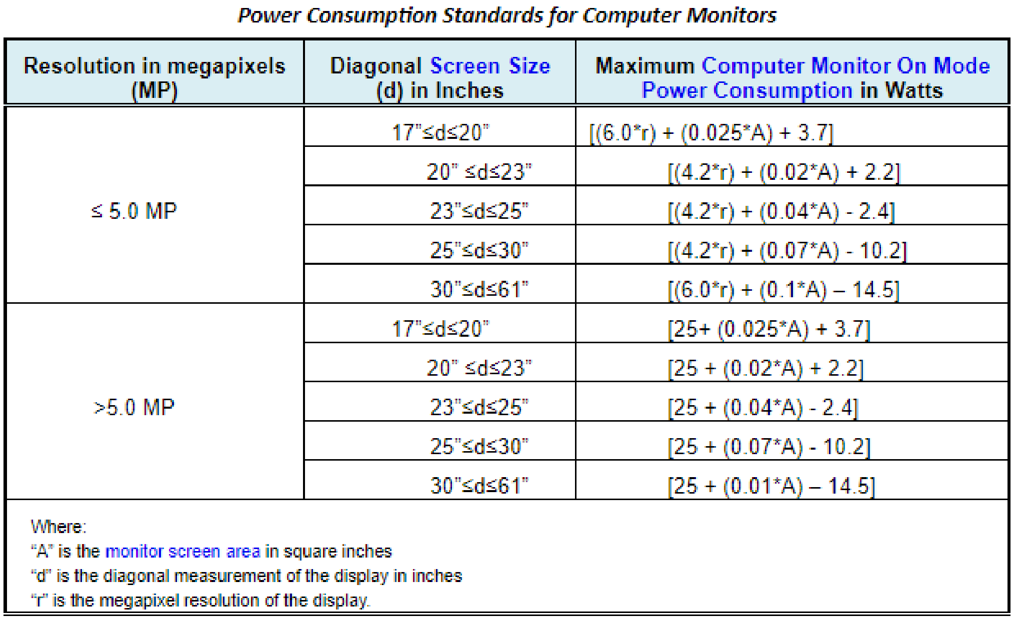
Standby Testing

- Conducted in the "as-shipped" condition, with a network connection if applicable.
- Sleep Mode power is tested by putting the host machine into Sleep Mode. These measurements are used to determine compliance.
- Off Mode power is tested by turning the monitor off using its power switch.

Active Mode Metrics and Power Limits

The maximum total energy consumption is calculated based on screen size and resolution.

Table 128: Maximum energy consumption for computer monitors in CEC Title 20



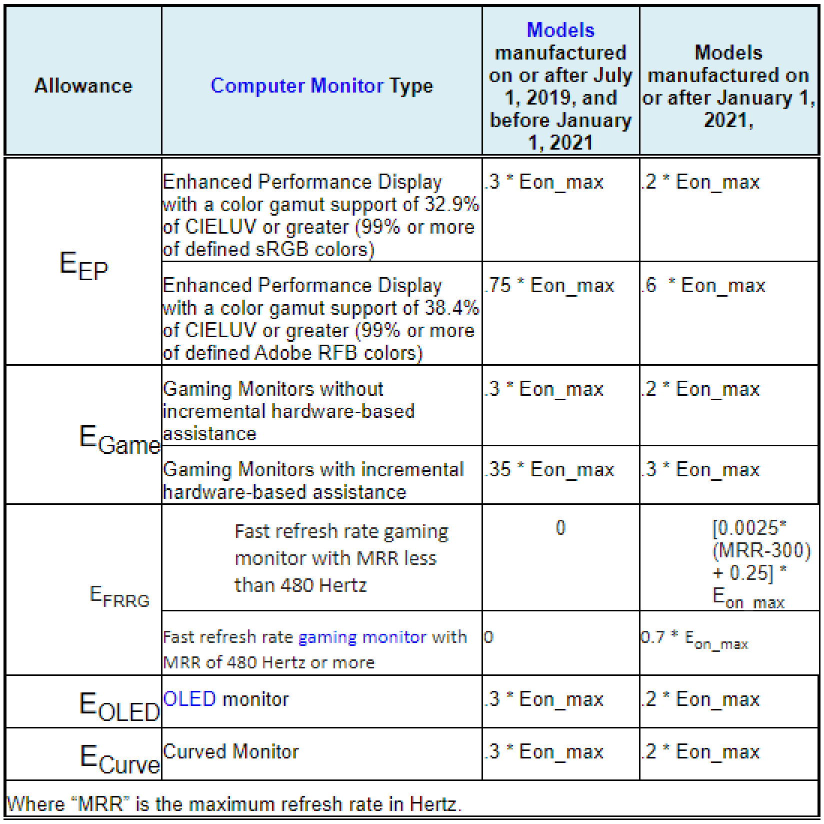
Power Consumption Standards for Computer Monitors

Resolution in megapixels (MP)	Diagonal Screen Size (d) in Inches	Maximum Computer Monitor On Mode Power Consumption in Watts
≤ 5.0 MP	17"≤d≤20"	[(6.0*r) + (0.025*A) + 3.7]
	20" ≤d≤23"	[(4.2*r) + (0.02*A) + 2.2]
	23"≤d≤25"	[(4.2*r) + (0.04*A) - 2.4]
	25"≤d≤30"	[(4.2*r) + (0.07*A) - 10.2]
	30"≤d≤61"	[(6.0*r) + (0.1*A) – 14.5]
>5.0 MP	17"≤d≤20"	[25+ (0.025*A) + 3.7]
	20" ≤d≤23"	[25 + (0.02*A) + 2.2]
	23"≤d≤25"	[25 + (0.04*A) - 2.4]
	25"≤d≤30"	[25 + (0.07*A) - 10.2]
	30"≤d≤61"	[25 + (0.01*A) – 14.5]

Where:
"A" is the monitor screen area in square inches
"d" is the diagonal measurement of the display in inches
"r" is the megapixel resolution of the display.

CEC grants additional power adders for certain display features:

Table 129: CEC Title 20 power adders



Allowance	**Computer Monitor Type**	**Models manufactured on or after July 1, 2019, and before January 1, 2021**	**Models manufactured on or after January 1, 2021,**
E_{EP}	Enhanced Performance Display with a color gamut support of 32.9% of CIELUV or greater (99% or more of defined sRGB colors)	.3 * Eon_max	.2 * Eon_max
	Enhanced Performance Display with a color gamut support of 38.4% of CIELUV or greater (99% or more of defined Adobe RFB colors)	.75 * Eon_max	.6 * Eon_max
E_{Game}	Gaming Monitors without incremental hardware-based assistance	.3 * Eon_max	.2 * Eon_max
	Gaming Monitors with incremental hardware-based assistance	.35 * Eon_max	.3 * Eon_max
E_{FRRG}	Fast refresh rate gaming monitor with MRR less than 480 Hertz	0	[0.0025*(MRR-300) + 0.25] * E_{on_max}
	Fast refresh rate gaming monitor with MRR of 480 Hertz or more	0	0.7 * E_{on_max}
E_{OLED}	OLED monitor	.3 * Eon_max	.2 * Eon_max
E_{Curve}	Curved Monitor	.3 * Eon_max	.2 * Eon_max

Where “MRR” is the maximum refresh rate in Hertz.

Standby Metrics and Power Limits

- Sleep Mode and Off Mode both have a fixed power limit of 1.2 W.

Annex K:Energy Savings Estimates

Overview

This assessment quantifies the energy consumption of electronic displays globally and in the European Union and estimates potential long-term savings from efficiency improvements and standby power reductions. The analysis covers televisions, computer monitors, LCD digital signage, and Direct-View LED (DVLED) video walls.

Key findings:

- Global display energy consumption: 582 TWh/year (approximately 2% of global electricity)
- EU display energy consumption: 76 TWh/year
- Long-term achievable savings with targeted policies: 63 TWh/year globally (11%), 16 TWh/year EU (21%)
- Economic value of savings: $7.5 billion/year globally, $4.5 billion/year EU
- CO_2 emissions reduction: 31 Mt CO_2e/year globally, 4 Mt CO_2e/year EU

The largest savings opportunities are: (1) eliminating smart wake standby penalties in televisions, (2) implementing true standby mode in DVLED cabinet-based systems, and (3) modest active-mode efficiency improvements in LCD-based displays.

Methodology

Annual energy consumption is calculated using the formula:

$$\textit{Energy (TWh)} = [\textit{Installed Base} \times \textit{Active Hours} \times \textit{Active Power} + \textit{Installed Base} \times \textit{Non-Active Hours} \times \textit{Non-Active Power}] \times 365 / 10^6$$

Key data sources include CLASP MEPSY (TV stock), IDC/TrendForce (monitors), Grand View Research (signage markets), Energy Star/EU Eco-design (power consumption), and industry expert consultation (DVLED standby behavior).

Rear projection video walls are excluded from savings estimates. This is a small and declining market segment, primarily serving legacy control room installations, as LCD and DVLED have largely displaced rear projection for new video wall deployments. The energy impact is negligible relative to other DSD categories.

The 8.6% Active Mode efficiency improvement estimate is based on an extensive analysis by Pacific Crest Labs of the California Energy Commission MAEDbS database for TVs, using MEPS similar to the 2025 example limits shown in this report, combined with Circana market research model pricing information. This scenario represents limits set to achieve today's average active efficiency levels across screen sizes and resolutions. These are long-term savings achievable after collecting additional data about all product classes and assessing how the supply chain responds to implementation of the initial policy recommendations described in this report.

The 8.6% Active Mode savings figure represents efficiency gains—less power required to produce the same luminance—rather than absolute power reductions. If average display brightness increases over time, total energy consumption could rise even as efficiency improves. The savings quantified in this report represent avoided consumption: the amount displays would have used at any given brightness setting without these efficiency improvements. This is analogous to vehicle fuel economy standards, where more efficient engines reduce fuel consumption per mile traveled, but total fuel use depends on how many miles are driven.

Complete baseline data, source justifications with hyperlinks, and calculation formulas are provided in the accompanying workbook.

Future Scenario Assumptions

The savings scenario models achievable efficiency improvements without sacrificing display performance:

Table 130: Sources of energy savings

Parameter	Future Value	Description
TV Non-Active Power	0.5 W	All TVs (eliminates smart wake penalty)
DVLED Non-Active Power	4 W/m²	True standby based on 1 W/cabinet (avg cabinet = 0.25 m²)
Indoor LCD Active Power	−8.6%	Efficiency gains in TVs, monitors, indoor signage
Outdoor LCD Active Power	No change	Mature technology; limited headroom
DVLED Active Power	No change	No Active Mode efficiency assumption

Table 131: Economic and environmental factors in savings scenario

Parameter	Global	EU	Source
Electricity Price ($/kWh)	$0.12	$0.28	IEA WEO 2024; Eurostat 2024
CO_2 Intensity (g/kWh)	494	250	IEA 2024; EEA 2023

Global Long-Term Savings by Category and Mode

Table 132: Global long-term savings

Product Category	Current (TWh/a)	Active (TWh/a)	Non-Active (TWh/a)	Total (TWh/a)	Savings %	($B/a)	(Mt CO_2e)
Televisions	410	32.6	16.8	49.4	12%	5.9	24.4
Computer Monitors	62	4.7	0.0	4.7	8%	0.6	2.3
Indoor LCD Signage	14	1.2	0.0	1.2	8%	0.1	0.6
Outdoor LCD Signage	5	0.4	0.0	0.4	8%	0.1	0.2
Indoor DVLED Signage	16	0.0	2.6	2.6	16%	0.3	1.3
Outdoor DVLED Signage	75	0.0	4.5	4.5	6%	0.5	2.2
GLOBAL TOTAL	582	38.9	23.9	62.8	11%	7.5	31.0
Share of Total		*62%*	*38%*				

EU Long-Term Savings by Category and Mode

Table 133: EU long-term savings

Product Category	Current (TWh/a)	Active (TWh/a)	Non-Active (TWh/a)	Total (TWh/a)	Savings %	($B/a)	(Mt CO_2e)
Televisions	51	3.4	10.1	13.5	26%	3.8	3.4
Computer Monitors	9	0.7	0.0	0.7	8%	0.2	0.2
Indoor LCD Signage	2	0.2	0.0	0.2	8%	0.0	0.0
Outdoor LCD Signage	1	0.1	0.0	0.1	8%	0.0	0.0
Indoor DVLED Signage	3	0.0	0.5	0.5	18%	0.1	0.1
Outdoor DVLED Signage	10	0.0	1.1	1.1	11%	0.3	0.3
EU TOTAL	76	4.4	11.7	16.1	21%	4.5	4.0
Share of Total		*27%*	*73%*				

Key Findings

Televisions

Televisions dominate display energy consumption, representing 70% of the global total (410 TWh/year) and 68% of the EU total (51 TWh/year). TV savings come from both Active Mode efficiency (8.6% improvement) and Non-Active Mode (eliminating smart wake penalty). The EU sees proportionally larger non-active savings because smart wake penetration is higher—25% of EU TVs versus 5% globally have smart wake features enabled at 14 W standby power.

DVLED Video Walls

DVLED signage (indoor and outdoor combined) consumes 91 TWh/year globally despite representing far less display area than TVs. Industry consultation confirms that most DVLED systems lack true standby capability—when displaying a black screen, driver ICs remain energized at 10%–20% of peak power. A 1 W per cabinet limit would save 7.1 TWh/year globally assuming cabinet size of 0.25 m^2. The majority of these savings would be captured by an initial 16 W/m^2 limit (4 W per cabinet), with incremental savings from subsequent tightening to 4 W/m^2. This limit applies to cabinet-based designs which dominate the market; standalone modules are excluded. All DVLED savings in this assessment are from non-active mode.

Active Mode efficiency: Technologies exist to improve DVLED Active Mode efficiency, including MicroLED with active matrix (TFT) backplanes that enable pixel-level power control. Research suggests these approaches could reduce active power consumption by 30%–50% compared to conventional passive matrix designs. However, a preliminary assessment indicates that manufacturing cost premiums for these technologies currently exceed lifetime electricity savings, making them not cost-effective for typical commercial installations. As manufacturing processes mature and costs decline, Active Mode efficiency improvements may become economically viable.

Given this technology trajectory, policymakers may wish to establish Active Mode efficiency requirements for DVLED after a period of information reporting and stakeholder engagement. This would allow time to gather market data on technology costs and performance, engage with manufacturers on feasible efficiency targets, and develop appropriate test procedures for Active Mode power measurement.

Computer Monitors and LCD Signage

These products already achieve low standby power under existing regulations. Savings potential is limited to active-mode efficiency improvements (8.6%).

Outdoor LCD signage: Outdoor LCD displays are currently out of scope for efficiency limits due to insufficient data to assess the suitability of TV-derived metrics for these products. Engineering differences, including active thermal management (heating and cooling), optical losses from protective enclosures and anti-glare treatments, and environmental sealing requirements, suggest caution in applying indoor-derived limits. However, PCL believes outdoor LCD has the same 8.6% Active Mode efficiency potential as other LCD display types. The savings shown in this assessment (0.4 TWh globally, 0.1 TWh EU) are contingent on development of appropriate outdoor-specific limits following a period of information reporting and stakeholder engagement.

Conclusion

Electronic displays consume approximately 582 TWh/year globally. In the long term, efficiency measures could reduce this by 63 TWh/year (11%), worth $7.5 billion annually and avoiding 31 million tonnes of CO_2 emissions. Globally, 62% of savings come from Active Mode improvements and 38% from Non-Active Mode improvements; in the EU, Non-Active Mode dominates at 73% due to higher smart wake penetration. The analysis supports prioritizing high-confidence interventions (standby power limits) while establishing measurement frameworks to enable future active-mode efficiency requirements.