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Electronic Displays Technical Report - Engineering and Cost Analysis

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1 Executive Summary

The primary factors that influence the price of monitors are length of time on the market and "newness" of secondary functions incorporated into the monitor. Because features-related factors dwarf other price drivers including efficiency, studying the market price correlation with efficiency leads to inconclusive evidence regarding incremental cost of efficiency improvements. An alternative is to understand manufacturer's cost of incremental efficiency improvements. Opening up a computer monitor housing to study the electronics, back light technology, and film stack enables a direct link of efficiency improvements to bill of materials (BOM) incremental cost. Applying markups to that BOM can enable a consumer incremental cost required to demonstrate cost-effectiveness.

Our approach for investigating displays differs from that of other electronics such as computers. The components of a display are not interchangeable with components from a different model, even from the same manufacturer. In products like computers, we compare components by swapping them and observing the change in plug load. In highly integrated products like displays, we determine the energy efficiency of the components by measuring the input and output of the component while imbedded in the system. This involves careful non-destructive disassembly and cutting of conductors to allow measurement equipment to be inserted into the circuit. To evaluate the optical assembly of a display, we measure the light input and output of each layer separately.

Methodology

During this first phase of the project, the CASE Technical Team (referred to as "technical team" throughout this report) tested, analyzed and developed BOM costs for two 21.5" computer monitors to assess potential energy efficiency improvements and associated incremental costs. During the second phase of the project, the technical team repeated this process for two additional pairs of displays (18.5" and 27" viewable diagonal screen size).

The technical team studied the performance of three pairs of computer monitors. For each pair, two models were selected to represent the range of energy efficiency of displays currently on the market. To isolate differences in power due to energy efficient designs rather than other features and functionality, the technical team selected a pair of displays that had similar features but drew different amounts of power according to the ENERGY STAR® Qualified Product list (October 16, 2012 list for first phase and January 2, 2013 list for second phase). The test units were 18.5, 21.5 and 27 inches viewable diagonal screen size, to represent a range of display usage from typical office computing to video viewing and gaming (Table 5.3). These sizes are also among the most popular sizes sold today and in the near future (IHS iSuppli. 2012). The representative models were chosen to represent a display of average energy efficiency; the efficient models represented one of the most efficient models available at that time. Considerations were also given to representing a range of major display manufacturers.

On mode power testing was completed according to the ENERGY STAR test method using guidance from International Electrotechnical Commission (IEC) 62087, Ed. 2.0 with the display in its as-shipped condition with all user-configurable options set to factory settings for default mode. Optional picture modes in default settings and other picture features enabled were also tested.

The purpose of the teardown analysis was to investigate power and optical systems to determine which components and designs produce more efficient displays, as well as to collect a bill of materials for each display to be used in the subsequent incremental cost analysis. The technical team targeted components that together draw the majority of power in a display and that have energy efficiency improvement potential. These components include the power supply, the light processing components and lamps used in backlight units (BLUs) and the panel drive electronics.

The following information was collected:

- As-assembled and circuitry photographs: Documented the display and its components.
- Detailed power budget: Used invasive techniques, including modifying circuit boards, for in-circuit power measurements. A multi-channel power meter was spliced into the power distribution circuits of the display under test. Power measurements were made using the 10 minute IEC video test clip and the 10-minute IEC internet test clip such that the following loads could be measured separately:
    - BLU
    - LCD panel and controller
    - Main processor board and all other loads (e.g., sensors, keypads, audio)
    - AC plug load (total AC power draw of the display)
    - Power supply losses
- Film characterization: Identified film types and the number of films in the stack.
- Optical film stack and LCD panel transmittance: Transmittance as the amount of light normal to the display that passes through each layer was measured. Each film sheet and the LCD panel have a gain or loss. Loss through the entire optical system is assessed by comparing the transmittance of light out of the LCD panel (normal to the display) to the power into the BLU.
- Micrographs of optical films and LCD panel: Identified film and panel types using a 300X digital microscope to view internal structures.
- Lamp count: Recorded number and size of the LEDs in the display.
- Lamp efficacy: Each display's LED strip was removed to test lamp efficacy in an integrating sphere. Lamp efficacy is a measure of the efficiency with which a lamp converts electrical energy into light energy, expressed in lumens per watt (lm/W). All lamp efficacies were determined using a Sphere Optics Model SLM-20 integrating sphere. The lamps were prepared for testing by attaching leads so that four of the lamps could be powered in isolation. Prior to removal, the technical team determined the voltage per lamp that the display under test used to drive its BLU. The number of lamps energized was limited to prevent overheating with the lamp strip removed from its heat sink. The prepared LED assembly was placed in the integrating sphere with the lamps centered in the chamber. Lamp efficacy data were obtained while driving at the previously determined voltage per lamp and measuring the power input to the lamps being lit. Additional tests at lower driving voltages were also made to estimate what voltage produced the highest efficacy.

Test Results and Analysis

Displays shipped with a range of screen luminance (values resulting in a wide range of power draw values. For example, the representative 22" model had a default luminance of 275 cd/m^2 and corresponding power of 28.4 W. The efficient 22" model had a default luminance of 241 cd/m^2 and power of 18.9 W. The ENERGY STAR test method requires that screen luminance is calibrated to 200 cd/m^2 and average power measured over the 10-minute IEC video test clip. In this state, the 22" representative and efficient displays drew 21% and 11% less power, respectively, than in their as-shipped conditions.

Displays had user-selectable features that resulted in significantly lower power draw when enabled. For example, with its Dynamic Contrast feature enabled, the 22" representative model drew 35% less power than in its default Dynamic Contrast off state. In its "Eco" mode, the efficient display reduced its power by 20% compared to its default mode power.

In the teardown analysis, the technical team was able to identify specific efficiency improvements through the identification and measurement of individual components and systems such as the backlight, films, power supply and LCD panel.

Cost-Efficiency Analysis

Using the 19" pair as an example,

Figure 1.1 illustrates the relationship incremental consumer cost (BOM costs with retail markup) and energy efficiency for both test units, as well as several maximum technology scenarios that improve overall display efficiency using 2013 prices. The representative and efficient displays are shown in black. Maximum technology scenarios involving improved LED efficacy and reduction of backlight output are shown in red, and the addition of a more efficient power supply unit (PSU) and a reflective polarizer as well as the implementation of ABC are shown in orange. Emerging technology improvements including the use of thinner thin film transistors (TFTs) and quantum dots are shown in blue. A theoretical combination of the most efficient components from the representative and efficient displays is shown in green. Note that for this and other sizes analyzed, as display efficiency improves, the cost for additional efficiency improvement generally increases.

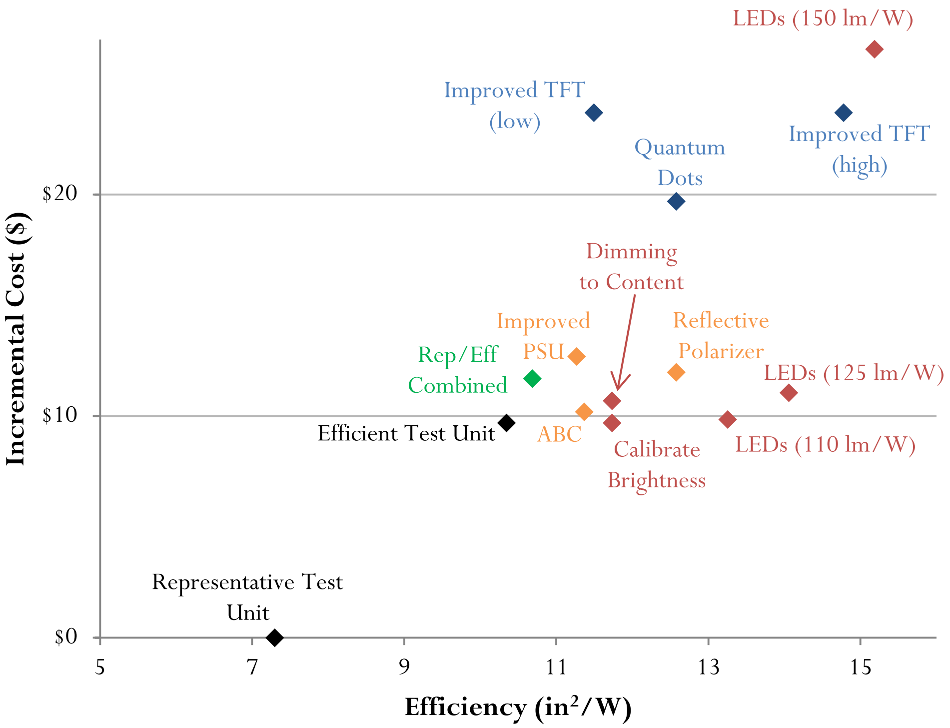

Figure 1.1 BOM cost in 2012 shown as a function of efficiency for both 19" test units (representative and efficient) as well as several maximum technology scenarios

Cost-Effective Approaches to Efficiency

Select individual efficiency measures shown above were combined to generate four cost-effective measures for each size analyzed (Figure 1.2). The label P_{ON_MAX} denotes the maximum power draw for the four scenarios within each size group. To determine if a scenario was cost effective, the technical team calculated the lifetime energy savings of the modeled more efficient display over the representative model and compared that to the incremental cost of the efficiency improvement. Costs effectiveness was calculated using 2013 costs. Costs generally decrease over time, making analyses of the same scenarios for future years result in even further cost effectiveness.

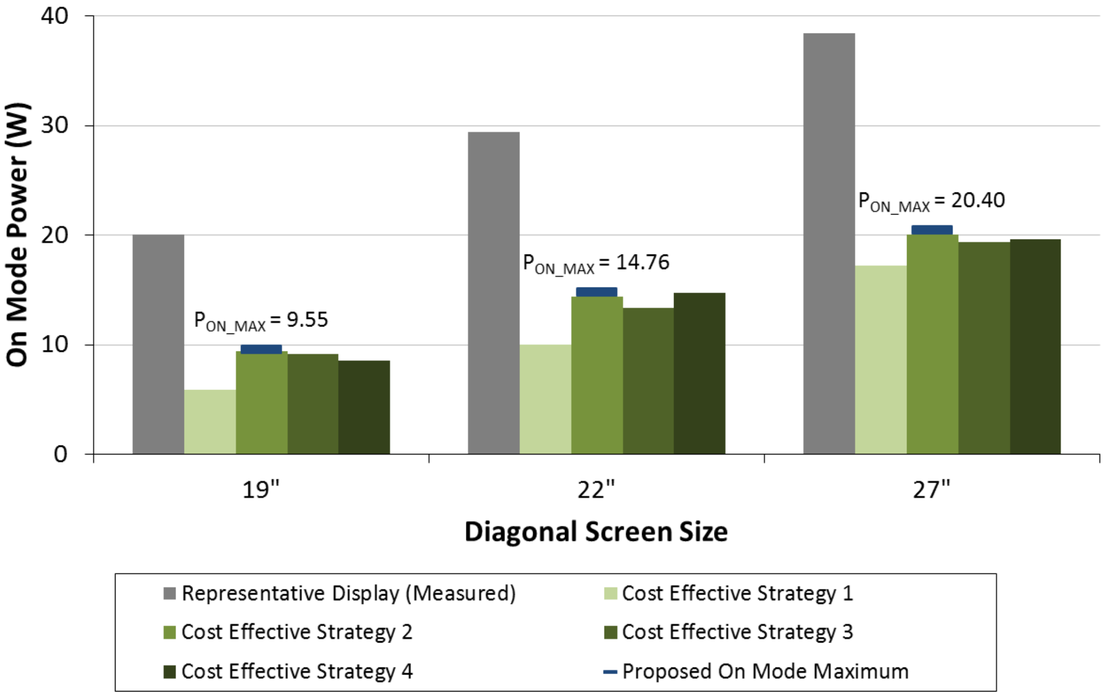

Figure 1.2 Cost-Effective Strategies – computer monitors. Representative display power measured in display's default luminance settings

Details regarding which efficiency measures we utilized for each scenario and the impact to on mode power draw are described in Table 5.1.

Conclusion

Through the testing and teardown analysis of a series of representative computer monitors, the technical team was able to demonstrate multiple paths to cost effectively reduce energy use. Approaches include more efficient film stacks, improved lamp efficacy, reducing default screen brightness, improved power supply efficiency, more common implementation of automatic brightness control and dimming screen brightness to video content. The technical team also found emerging technologies such as improved TFT technology and quantum dots to be cost effective, however, with less confidence in cost and efficiency estimates, prevented them from being included in the final analysis.

The power draw measurements of computer monitors in their default settings versus the ENERGY STAR test procedure method of calibrating screen brightness to 200 nits showed significant differences. Assuming that most users will not calibrate their monitors to such a precise brightness level, this suggests that strong consideration should be given to measuring monitors in their default brightness setting to more accurately reflect actual energy use.

2 Acronyms and Terminology

Table 5.3 lists the acronyms, and their definitions, used throughout this report.

Table 2.1 List and definitions of acronyms

Acronym	Expansion	Definition
ABC	Automatic brightness control	A technology used to adjust display brightness to room illumination
APL	Average picture level	The video signal level, during the active picture part of each horizontal line, is mathematically averaged over the period of a frame to come up with APL
BLU	Backlight unit	The assembly of lamps, reflectors, light guides and optical films used to convert electrical energy into a uniform source of light for an LCD display
BOM	Bill of materials	The list of all components and materials a manufacturer combines into an assembly
CCFL	Cold cathode fluorescent lamp	A tubular lamp that uses a discharge in mercury vapor to develop ultraviolet light, which in turn causes a fluorescent coating on the inside of the lamp to emit visible light
DP	DisplayPort	An interface for transferring digital video content
DVI	Digital visual interface	An interface for transferring digital video content
EPS	External power supply	A power adapter typically designed to convert ac power to dc power for use in electronics that is self-contained within its own housing outside the electronic device
HDMI	High-definition multimedia interface	An interface for transmitting uncompressed digital audio/video data
HD	High definition	Resolution of 720 progressively, 1,080 interlaced or 1,080 progressively scanned lines.
IEC	International Electrotechnical Commission	International standards and conformity assessment body for all fields of electrotechnology
IPS	Internal power supply	A power adapter typically designed to convert ac power to dc power for use in electronics that is contained within the electronic device
LCD	Liquid crystal display	A type of display technology using liquid crystals to control light
LED	Light emitting diode	A semiconductor light source that produces light through electroluminescence
LGP	Light guide plate	A plate used in edge lit BLUs to turn and distribute the light forward toward the LCD
OLED	Organic light emitting diode	An LED in which the emitting electroluminescent layer is a film of organic compounds
PCB	Printed circuit board	Insulating material with conductors on which electronic parts are mounted to provide support & electrical connectivity
RGB	Red green blue	May refer to sub-pixel color palette or may refer to a form of analog signal interface

3 Methodology

During this first phase of the project, the technical team tested, analyzed, and developed BOM costs for two 21.5" computer monitors to assess potential energy efficiency improvements and associated incremental costs. During the second phase of the project, the technical team repeated this process for two additional pairs of displays (18.5" and 27" viewable diagonal screen size).

The technical team uses teardown and engineering analysis to develop estimates of incremental BOM cost of displays as a function of efficiency. To enable California Energy Commission (CEC) to justify the energy consumption level that is most cost-effective at the time of compliance in this rapidly changing, innovative market, the technical team also forecasts these costs for the next four years. Costs of efficiency improvements are expected to continue to decline over time, enabling CEC to justify the most stringent standards level as shown in the shift below and to the right of the cost-efficiency curve in Figure 3.1. Driven by improvements in electronics and materials science, electronic displays become more efficient and less expensive more rapidly than products, like appliances, that have been regulated with mandatory standards. Because a display standard must be relevant for many years beyond its effective date, it is imperative to estimate changes in cost and efficiency through time in addition to cost estimates in the current market.

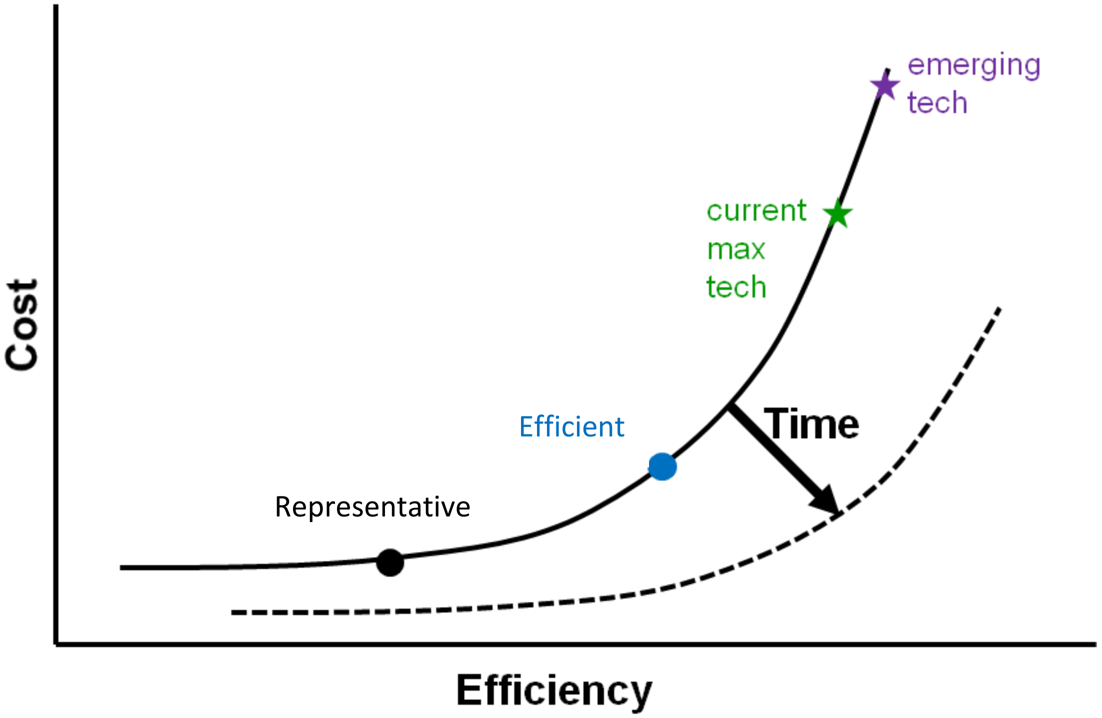

Figure 3.1 Conceptualized cost-efficiency curve

For three size categories, we tested and analyzed two displays – one market representative efficiency model and one highly efficient model – to estimate representative (black) and efficient (blue) energy efficiency (Figure 3.1). Based on the technical team's knowledge of current maximum and future emerging technology, efficiency was estimated for models on the upper right end of the curve. The technical team estimated cost for each display by developing a bill of materials for each model and leveraging market research data. As time passes, displays become more efficient and less expensive (dashed curve).

3.1 Test Unit Selection

To develop a cost-efficiency relationship for displays, the technical team studied the performance of three pairs of computer monitors. For each pair, two models were selected to represent the range of energy efficiency of displays currently on the market. To isolate differences in power due to energy efficient designs rather than other features and functionality, the technical team selected a pair of displays that had similar features but drew different amounts of power according to the ENERGY STAR Qualified Product list (October 16, 2012 list for first phase and January 2, 2013 list for phase 2). The test units were 18.5, 21.5 and 27 inches viewable diagonal screen size, to represent a range of display usage from typical office computing to video viewing and gaming (Table 3.1). These sizes are also among the most popular sizes sold today and in the near future (IHS iSuppli. 2012). The representative models were chosen to represent a display of average energy efficiency; the efficient models represented one of the most efficient model available at that time (Figure 3.2). Considerations were also given to representing a range of major display manufacturers.

In addition to these three pairs of displays, several other displays were studied for the energy impact of specific features and technologies. This included the examination of an OLED display, displays with ABC and touch screen capability, and an ultra-high resolution display.

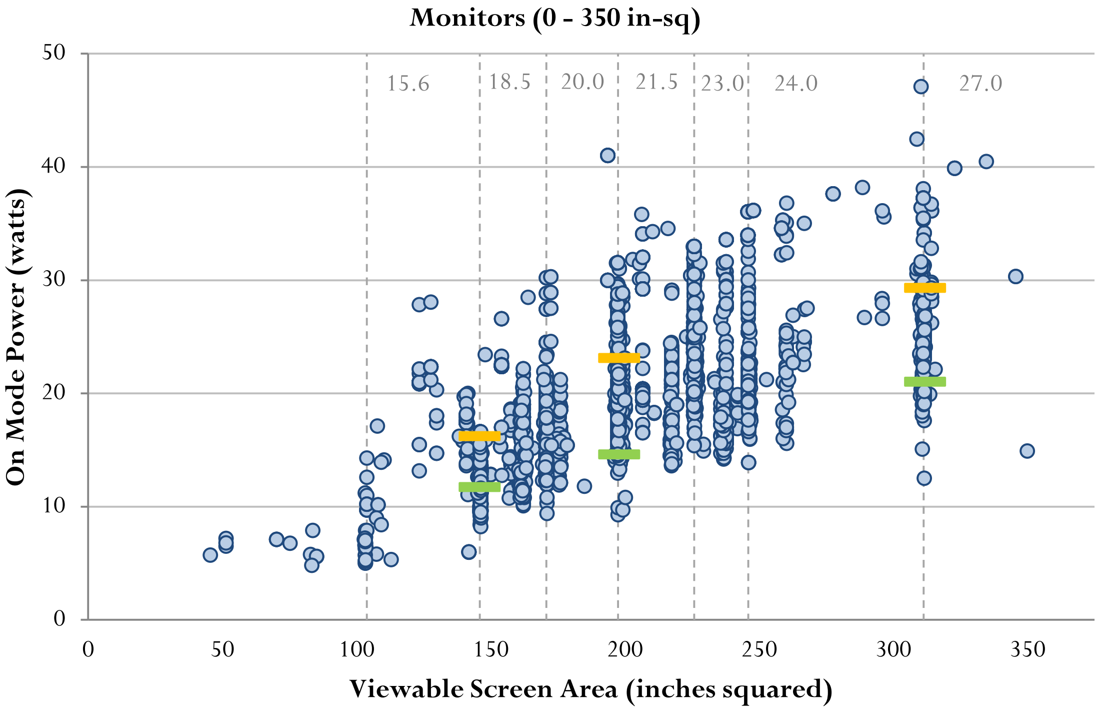

Figure 3.2 Measured On Mode Power of Tested Units Relative to Reported Power of Other Units

Source: CASE Team Analysis

Table 3.1 Features of Units Tested

Test Unit Description	Representative	Efficient	Representative	Efficient	Representative	Efficient
Test Unit ID	D19-1	D19-2	D22-1	D22-2	D27-1	D27-2
Diagonal Viewable Screen Size	18.5	18.5	21.5	21.5	27	27
Contrast Ratio	10,000:1	Not Listed	1000:1	1000:1	3,000:1	1000:1
Response Time (ms)	5	5	8	5	8	7
Power Supply	Internal	Internal	External	Internal	External	Internal
Panel Type	TN	TN	IPS	TN	TN	IPS
Weight (kg)	2.8	2	2.5	3.8	6.1	5.3
Video Ports	VGA	VGA	DVI, VGA	DVI, VGA, HDMI	DVI, VGA, DisplayPort	DVI, VGA, HDMI
Reported Brightness (cd/m^2)	200	250	250	250	300	270
Horizontal Viewing Angle (deg)	90	170	178	170	170	178
Vertical Viewing Angle (deg)	50	160	178	160	160	178
Network Ports	None	None	None	None	None	None
Backlight	CCFL Edge (top and bottom)	LED Edge (bottom)	LED Edge (bottom)	LED Edge (side)	LED Edge (bottom)	Led Edge (side)
ABC	No	No	No	No	Yes	No
Power scaling mode	Yes	Yes	Yes	Yes	No	Yes
ENERGY STAR Reported Power (W)	13.6	11.7	23.1	14.6	29.3	20.0

3.2 Efficiency Metric

For this analysis, the technical team chose to use an efficiency metric that relates a display's screen area to its power draw expressed in units of square inches per watt (in^2/W). Higher in^2/W indicates lower power draw, and therefore higher efficiency. This metric normalizes for size allows the technical team to compare the efficiency of displays across sizes and within size groups where there are often slight differences in screen area. Before deciding on that metric, other possibilities were examined for the efficiency metric that would incorporate screen brightness (both normal to the screen and off-axis) and contrast ratio, which may be expressed in terms of candelas per watt. However, these characteristics are often influenced by the market and measurement of them would increase the testing burden. Thus, the technical team did not work with metrics that include screen brightness and contrast ratio.

Note that the efficiency metric is used to compare energy performance of products tested in this cost-efficiency analysis. The power mode metrics used in the proposed standard levels are in watts.

3.3 As-Assembled Testing

The technical team performed testing according to the ENERGY STAR Program Requirements for Displays – Test Method (Version 6.0 – Final, Sep-2012) for input power, luminance, illuminance, ambient temperature, relative humidity, power meter specifications and measurement accuracy. To warm up and stabilize each display before testing, the IEC 62087 dynamic broadcast-content video signal was used, which has an average picture level (APL) of 34% for a minimum of one hour. Test signals were generated by a computer then input to the displays using an interface cable such as HDMI, DVI or VGA.

Instantaneous luminance measurements were collected using the 3-bar static test signal (Figure 3.3) in controlled darkroom conditions with the display in its as-shipped condition, with all user configurable options set to factory settings for default mode. Optional modes were tested in their default settings. Note that instantaneous power associated with each luminance measurement was logged, but used integrated power (described below) in the following analysis.

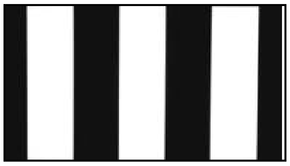

Figure 3.3 3-bar static test signal used for luminance testing

Source: IEC 62087, Ed. 2.0

The technical team performed on mode power testing according to the ENERGY STAR test method using guidance from IEC 62087, Ed. 2.0 with the display in its as-shipped condition with all user-configurable options set to factory settings for default mode. Since ENERGY STAR requires test units to be calibrated to 200 candelas per square meter (nits), each display was also tested in its default luminance settings to get a more accurate measurement of real world power draw as most models are brighter than 200 nits "out of the box" and end users are not likely to calibrate to 200 nits. Additionally, optional picture modes in default settings and other picture features enabled were tested. Line power was measured every second during the 10-minute IEC 62087 dynamic broadcast-content video signal (IEC test clip) and averaged those measurements to obtain average power consumption.

Sleep mode testing was performed at factory default settings using guidance from IEC 62301 Ed 1.0: Household Electrical Appliances – Measurement of Standby Power. Optional point-of-deployment (POD) modules were not installed and networking features deactivated (if applicable).

3.4 Teardown Analysis

The purpose of the teardown analysis was to investigate power and optical systems to determine which components and designs produce more efficient displays, as well as to collect a bill of materials for each display to be used in the subsequent incremental cost analysis. The technical team targeted components that together draw the majority of power in a display and that have energy efficiency improvement potential. These components include the power supply, the light processing components and lamps used in backlight units (BLUs) and the panel drive electronics.

The following information was collected:

- As-assembled and circuitry photographs: Documented the display and its components.
- Detailed power budget: Used invasive techniques, including modifying circuit boards, for in-circuit power measurements. A multi-channel power meter was spliced into the power distribution circuits of the display under test. Power measurements were made using the 10 minute IEC video test clip and the 10-minute IEC internet test clip such that the following loads could be measured separately:
    - BLU
    - LCD panel and controller
    - Main processor board and all other loads (e.g., sensors, keypads, audio)
    - AC plug load (total AC power draw of the display)
    - Power supply losses
- Film characterization: Identified film types and the number of films in the stack.
- Optical film stack and LCD panel transmittance: Transmittance as the amount of light normal to the display that passes through each layer was measured. Each film sheet and the LCD panel have a gain or loss. Loss through the entire optical system is assessed by comparing the transmittance of light out of the LCD panel (normal to the display) to the power into the BLU.
- Micrographs of optical films and LCD panel: Identified film and panel types using a 300X digital microscope to view internal structures.
- Lamp count: Recorded number and size of the LEDs in the display.
- Lamp efficacy: Each display's LED strip was removed to test lamp efficacy in an integrating sphere. Lamp efficacy is a measure of the efficiency with which a lamp converts electrical energy into light energy, expressed in lumens per watt (lm/W). All lamp efficacies were determined using a Sphere Optics Model SLM-20 integrating sphere. The lamps were prepared for testing by attaching leads so that four of the lamps could be powered in isolation. Prior to removal, the technical team determined the voltage per lamp that the display under test used to drive its BLU. The number of lamps energized was limited to prevent overheating with the lamp strip removed from its heat sink. The prepared LED assembly was placed in the integrating sphere with the lamps centered in the chamber. Lamp efficacy data were obtained while driving at the previously determined voltage per lamp and measuring the power input to the lamps being lit. Additional tests at lower driving voltages were also made to estimate what voltage produced the highest efficacy.

3.4.1 OLED Teardown

The OLED teardown methodology was somewhat different from that of the LCD displays due to the differences in technology. Specifically, OLED is an emissive technology, meaning it does not require a backlight for its pixels whose operation is controlled through an LCD controller. Instead, light production and pixel operation are controlled by the same system. Therefore, there is no film stack, BLU or LCD control power to compare directly with LCD measurements. The technical team did, however, gather power data for the display's main board and power supply losses which are comparable to an LCD display. To compare to an LCD's BLU power, the power delivered to the OLED panel that varies with light and dark images was isolated and measured. The rest of the power delivered to the panel was considered analogous to that of an LCD panel's LCD controller or the timing controller as it is often called.

3.5 Cost-Efficiency Analysis

To develop cost-efficiency relationships, BOM costs for the representative and efficient test units was first estimated. The technical team obtained cost information from DisplaySearch, a research company that analyzes the electronic display market and interviews manufacturers to develop quarterly cost estimates of typical display models by technology and size. DisplaySearch currently forecasts these costs through 2017. Using results from the teardown analysis, these costs were tailored to each test unit to develop a specific BOM cost using the following procedure. A retail markup factor to determine retail costs was then applied.

1. BLU cost: In its BLU cost report (DisplaySearch. 2013a), DisplaySearch listed costs for lamps (CCFL or LED), optical films, reflective sheets, diffusion boards or light guide plates and structural items such as the bezel and BLU frame for a typical display of a given size on the North American market. To modify DisplaySearch's costs to each test unit, the number of lamps and number and type of films were specified.
2. LCD module cost: DisplaySearch applied its BLU estimates to its LCD module costs (__. 2013b), which also included the panel glass, polarizers, liquid crystals, drivers, inverters or LED controllers and PCBs. In the technical team's teardown analysis, no atypical features (e.g., speakers, cameras) were found that would warrant changes to DisplaySearch's costs for typical models. Thus, the technical team simply changed the BLU cost estimated in step 1 for each teardown display and totaled LCD module costs.
3. LCD monitor cost: To estimate total display cost, DisplaySearch took the LCD module cost for the previous quarter (to account for LCD module production lag time), then added remaining items included in the BOM, such as power supplies, interfaces, cables, housing, and other electronics and PCBs (__. 2013c). The technical team then used the resulting BOM costs with a 30 percent retail markup in our cost-efficiency analysis. This markup is representative of both industry estimates and an average of DisplaySearch's markup across several screen sizes.

Finally, cost and efficiency was estimated for maximum technology scenarios to estimate the cost-efficiency relationship in the future display market. The technical team used results from the teardown analysis to identify current technologies that may be used to improve energy efficiency, as well as market research to identify emerging technologies that may be available for future energy efficiency improvements.

4 Test Results and Analysis

4.1 As-Assembled Test Results

4.1.1 19" Pair

Power and screen luminance test results for the two 19" test units are shown in Table 4.1. The representative model (D19-1) had a default luminance of 208 cd/m^2 and corresponding power of 19.2 W. The efficient model (D19-2) had a default luminance of 255 cd/m^2 and power of 14.0 W. The ENERGY STAR test method requires that screen luminance is calibrated to 200 cd/m^2 and average power measured over the 10-minute IEC video test clip. In this state, the representative and efficient displays drew less power than in their as-shipped conditions (Table 4.1).

Both displays had user-selectable features that resulted in significantly lower power draw when enabled. With its "Eco" mode selected, the representative model drew 25% less power than in its default standard mode. In its "Text" display mode, the efficient model reduced its power by 38% compared to its default mode power (Table 4.1).

In sleep mode, the representative and efficient displays drew about 0.3 W and 0.2 W, respectively. The representative model measured full power when it was disconnected from its source. This is due to the backlight remaining on to display a message to the user that the source has been disconnected.

Table 4.1 As-assembled power and luminance test results for 19" displays

Display ID	Input Port	Test Description	Display Mode	Screen Luminance (cd/m^2)	Power (W)
D19-1 Repre-sentative	VGA	Default	Standard	207.8	19.21
	VGA	Default	Graphics	210.6	19.12
	VGA	Default	Movie	180.6	17.16
	VGA	Default	Eco	137.8	14.48
	VGA	Default	User	208.9	19.30
	VGA	Color temp: cool	Standard	177.5	19.26
	VGA	ENERGY STAR: calibrated luminance	Standard	201.1	18.63
	VGA	Max brightness	Standard	212.9	19.25
	VGA	Sleep (sleep signal source)	Standard		0.30
	VGA	Sleep (disconnect signal source)	Standard		19.08
	VGA	Off	Standard		0.20
D19-2 Efficient	VGA	Default	Standard	254.8	14.02
	VGA	Default	Text	125.6	8.73
	VGA	Default	Internet	164.5	10.30
	VGA	Default	Game	202.4	11.68
	VGA	Default	Movie	293.3	13.34
	VGA	Default	Sports	279.7	15.05
	VGA	Color temp: Normal	Standard	252.3	14.04
	VGA	Color temp: Cool	Standard	219.8	14.06
	VGA	Color temp: sRGB	Standard	233.9	14.04
	VGA	ENERGY STAR: calibrated luminance	Standard	200.8	11.65
	VGA	Max brightness	Standard	275.6	14.96
	VGA	Sleep (sleep signal source)	Standard		0.20
	VGA	Sleep (disconnect signal source)	Standard		0.20
	VGA	Off	Standard		0.14

4.1.2 22" Pair

Power and screen luminance test results for the two 22" test units are shown in Table 4.2. Both displays shipped with relatively high screen luminance ("Standard" modes). The representative model (D22-1) had a default luminance of 275 cd/m^2 and corresponding power of 28.4 W. The efficient model (D22-2) had a default luminance of 241 cd/m^2 and power of 18.9 W. With luminance calibrated for the ENERGY STAR test procedure, the representative and efficient displays drew 21% and 11% less power, respectively, than in their as-shipped conditions (Table 4.2).

Both displays had user-selectable features that resulted in significantly lower power draw when enabled. With its Dynamic Contrast feature enabled, the representative model drew 35% less power than in its default Dynamic Contrast off state. In its Eco mode, the efficient model reduced its power by 20% compared to its default mode power (Table 4.2).

In sleep mode, the representative and efficient displays drew about 0.3 W and 0.2 W, respectively. The representative model had an auto power-down mode in which it drew 0.2 W. The efficient display had an off mode and in which it drew 0.1 W (Table 4.2).

Table 4.2 As-assembled power and luminance test results for 22" displays

Display ID	Input Port	Test Description	Display Mode	Screen Luminance (cd/m^2)	Power (W)
D22-1 Repre-sentative	DVI	Default	Standard	275.4	28.42
	DVI	Default	Eco Optimize	202.8	23.06
	DVI	Default	Eco Conserve	129.6	17.23
	DVI	Dynamic Contrast enabled	Standard	184.0	18.43
	DVI	ENERGY STAR: calibrated luminance	Standard	202.5	22.46
	DVI	Max brightness	Standard	284.8	28.69
	VGA	Default	Standard	270.3	28.25
	VGA	ENERGY STAR: calibrated luminance	Standard	202.3	22.27
	VGA	Max brightness	Standard	274.5	28.53
	DVI	Sleep (sleep signal source)	Standard		0.28
	DVI	Sleep (disconnect signal source)	Standard		0.26
	DVI	Auto-Power down enabled	Standard		0.20
D22-2 Efficient	HDMI	Default	Standard	241.0	18.76
	HDMI	Default	Scenery	225.0	18.38
	HDMI	Default	Theater	220.0	18.34
	HDMI	Default	Game	233.0	18.29
	HDMI	Default	Night View	226.0	18.31
	HDMI	Default	sRGB Mode	173.0	15.57
	HDMI	ENERGY STAR: calibrated luminance	Standard	201.0	16.82
	HDMI	Max brightness	Standard	247.0	18.64
	HDMI	w/ Smartview enabled	Standard	245.0	18.30
	HDMI	w/ ASCR enabled	Scenery	241.0	19.03
	HDMI	w/ Eco Mode	Standard	167.0	15.08
	DVI	Default	Standard	246.0	18.71
	VGA	Default	Standard	246.0	18.50
	HDMI	Sleep (sleep signal source)	Standard		0.16
	HDMI	Sleep (disconnect signal source)	Standard		0.16
	HDMI	Off	Standard		0.12

4.1.3 27” Pair

Power and screen luminance test results for the two 27” test units are shown in Table 4.3. The monitors were shipped with very different screen luminance values (“Standard” mode). The representative model (D27-1) had a default luminance of 400 cd/m^2 and corresponding power of 38.6 W. The efficient model (D27-2) had a default luminance of 171 cd/m^2 and power of 21.8 W. With luminance calibrated for the ENERGY STAR test procedure (200 cd/m^2) the representative display drew 40% less power than in its as-shipped condition while the efficient display drew 16% more power than in its as-shipped condition (Table 4.3).

Both displays had user-selectable features that resulted in significantly lower power draw when enabled. With its “Eco Saving” feature enabled, the representative model drew 65% less power than in its default (as-shipped) state. In its energy smart feature enabled, the efficient display reduced its power by 48% compared to its default mode power (Table 4.3).

In sleep mode, both displays drew about 0.3 W (Table 4.3).

Table 4.3 As-assembled power and luminance test results

Display ID	Input Port	Test Description	Display Mode	Screen Luminance (cd/m^2)	Power (W)
D27-1 Repre-sentative	DP*	Default	Custom	400.8	38.56
	DP	Default	Standard	203.9	22.96
	DP	Default	Game	400.7	38.47
	DP	Default	Cinema	400.4	38.41
	DP	Default	Dyn. Contrast	400.3	34.69
	DP	Magic color: Full	Custom	400.7	38.39
	DP	Magic color: intelligent	Custom	401.0	38.37
	DP	Response time: normal	Custom	400.3	38.33
	DP	Response time: fastest	Custom	400.2	38.34
	DP	Eco Saving: 50%	Custom	142.1	18.23
	DP	Eco Saving: 75%	Custom	269.2	27.91
	DP	ENERGY STAR: calibrated luminance	Custom	199.2	22.99
	DP	Max brightness	Custom	402.3	38.47
	DVI	Default	Custom	397.6	38.41
	VGA	Default	Custom	379.6	38.43
	DP	Sleep (sleep signal source)	Custom		0.34
	DP	Sleep (disconnected signal source)	Custom		0.34
	DP	Off by timer (1 hour)	Custom		0.33
	DP	Off	Custom		0.33
D27-2 Efficient	HDMI	Default	Standard	170.9	21.77
	HDMI	Default	Multimedia	154.4	23.51
	HDMI	Default (dyn. contrast enabled)	Movie	168.9	25.93
	HDMI	Default	Game	166.6	23.48
	HDMI	Default	Text	128.5	17.48
	HDMI	Default	Warm	170.5	23.56

Display ID	Input Port	Test Description	Display Mode	Screen Luminance (cd/m^2)	Power (W)
	HDMI	Default	Cool	163.3	23.28
	HDMI	ENERGY STAR: calibrated luminance	Standard	200.1	25.23
	HDMI	Max brightness	Standard	247.3	25.84
	HDMI	w/ Image enhance enabled	Standard	171.5	21.79
	HDMI	Dynamic contrast disabled	Movie	152.6	23.53
	HDMI	w/ energy smart enabled	Standard	89.3	12.88
	DVI	Default	Standard	202.4	21.64
	VGA	Default	Standard	186.5	21.17
	HDMI	Sleep (sleep signal source)	Standard		0.28
	HDMI	Sleep (disconnect signal source)	Standard		0.29
	HDMI	Off	Standard		0.24

*DisplayPort

Average power consumption increased approximately linearly with screen luminance (Figure 4.1). This suggests that the majority of power draw variability is related to producing light and generating an image on the screen. Signal processing and other functions draw relatively constant power, as compared to screen brightness, when the display is showing a picture.

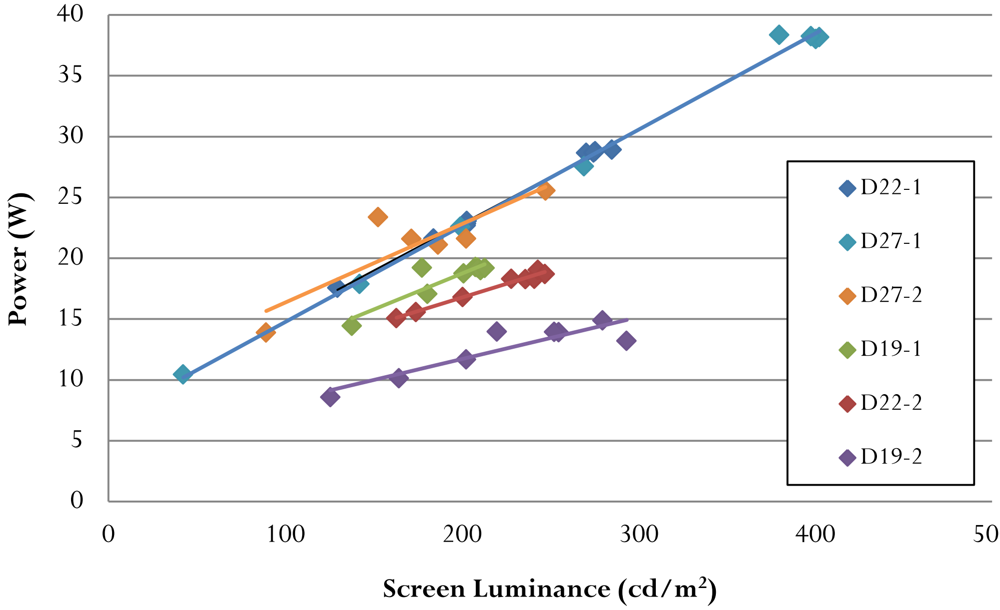

Figure 4.1 Screen luminance versus power for the representative and efficient test units (lines are linear fits to the data)

4.1.4 Touch Screen

To determine the power draw impact of touch screen, the technical team tested a touch screen capable monitor both with and without the touch screen capability enabled (enabled via a USB connection). In addition to testing using the IEC video test clip, a two minute sequence of operations first using the touch screen interface, then using the keyboard and mouse were conducted. In each case, the monitor used approximately one additional watt of power with touch screen enabled (Table 4.4).

Table 4.4 Touch screen power test results

Display ID	Test	Input Port	Test Description	Display Mode	Power (W)
D22-3 Touch Screen	IEC video clip	DVI	Default	Standard	17.08
	IEC video clip	DVI	Default, USB plugged in	Standard	18.04
	Web browsing sequence	VGA	Touch screen interface	Standard	17.62
	Web browsing sequence	VGA	Keyboard and mouse interface	Standard	17.61
	Web browsing sequence	VGA	Keyboard and mouse interface, USB unplugged	Standard	16.67

4.1.5 Automatic Brightness Control

To test the power draw impact of automatic brightness control (ABC), power and luminance testing were conducted according to the same ENERGY STAR test procedure applied to other models tested. The ENERGY STAR procedure includes power measurements at a range of room lighting levels (10 and 300 lux). In addition to these points, power at additional lighting levels of 0, 30, 50, 100 and 200 lux were measured (Table 4.5, Figure 4.2).

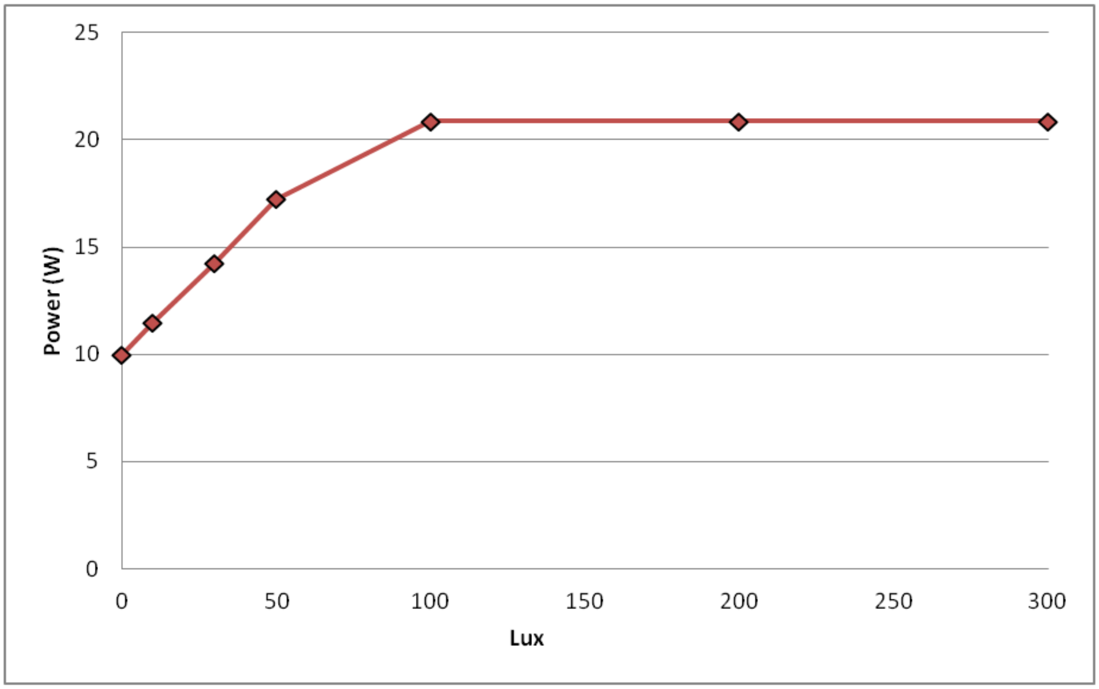

Figure 4.2 Relationship between room brightness (lux) and power draw for ABC enabled monitor (D19-3)

ABC enabled in low room lighting conditions resulted in significantly lower power draw. This model drew about 50% less power in low light conditions (0-10 lux) than in its default state with ABC turned off (Figure 4.2).

Table 4.5 As-assembled power and luminance test results for ABC enabled monitor (D19-3)

Display ID	Input Port	Test Description	Display Mode	Screen Luminance (cd/m^2)	Power (W)
D19-3 ABC	DP*	ABC off	Standard	242.4	20.82
	DP	ABC off	Movie	248.2	23.57
	DP	ABC off	Photo	248.8	23.69
	DP	ABC off	Text	244.1	23.79
	DP	ABC off	Gaming	252.1	23.50
	DP	ABC off	Dynamic	95.6	12.11
	DP	ENERGY STAR: calibrated luminance	Standard	200.5	21.02
	DP	Max brightness	Standard	245.4	23.68
	DVI	ABC off	Standard	238.1	24.09
	VGA	ABC off	Standard	233.7	24.61
	DP	ABC on, Illuminance = 0 lux	EcoMode1**		9.99
	DP	ABC on, Illuminance = 10 lux	EcoMode1		11.48
	DP	ABC on, Illuminance = 30 lux	EcoMode1		14.23
	DP	ABC on, Illuminance = 50 lux	EcoMode1		17.23
	DP	ABC on, Illuminance = 100 lux	EcoMode1		20.86
	DP	ABC on, Illuminance = 200 lux	EcoMode1		20.86
	DP	ABC on, Illuminance = 300 lux	EcoMode1		20.85
	DP	ABC on, Illuminance = 10 lux	EcoMode2		11.45
	DP	ABC on, Illuminance = 300 lux	EcoMode2		14.01
	DP	Auto brightness 2 (white content, no ABC)	Standard		21.50
	DP	ABC on, Illuminance = 0 lux	EcoMode1, auto brightness 3		15.53
	DP	ABC on, Illuminance = 10 lux	EcoMode1, auto brightness 3		16.27
	DP	ABC on, Illuminance = 30 lux	EcoMode1, auto brightness 3		17.68
	DP	ABC on, Illuminance = 50 lux	EcoMode1, auto brightness 3		19.07
	DP	ABC on, Illuminance = 100 lux	EcoMode1, auto brightness 3		20.85
	DP	ABC on, Illuminance = 200 lux	EcoMode1, auto brightness 3		20.84
	DP	ABC on, Illuminance = 300 lux	EcoMode1, auto brightness 3		20.83
	DP	Sleep (sleep signal source)	Standard, ABC off		1.25
	DP	Sleep (disconnected signal source)	Standard, ABC off		0.31
	DP	Off by timer (1 hour)	Standard, ABC off		0.29
	DP	Off	Standard, ABC off		0.29

*DisplayPort   **EcoMode1 and ABC enabled is unit's default setting.

4.2 Teardown Analysis

The circuitry of an LCD display is described in Figure 4.3. The technical team isolated and tested power for the following components:

- Backlight unit (red)
- LCD panel and timing controller (orange)
- Other electronics: main processor board and all other loads such as keypads, audio and indicators (green)
- Ac plug load: total ac power draw of the display
- Power supply losses (blue)

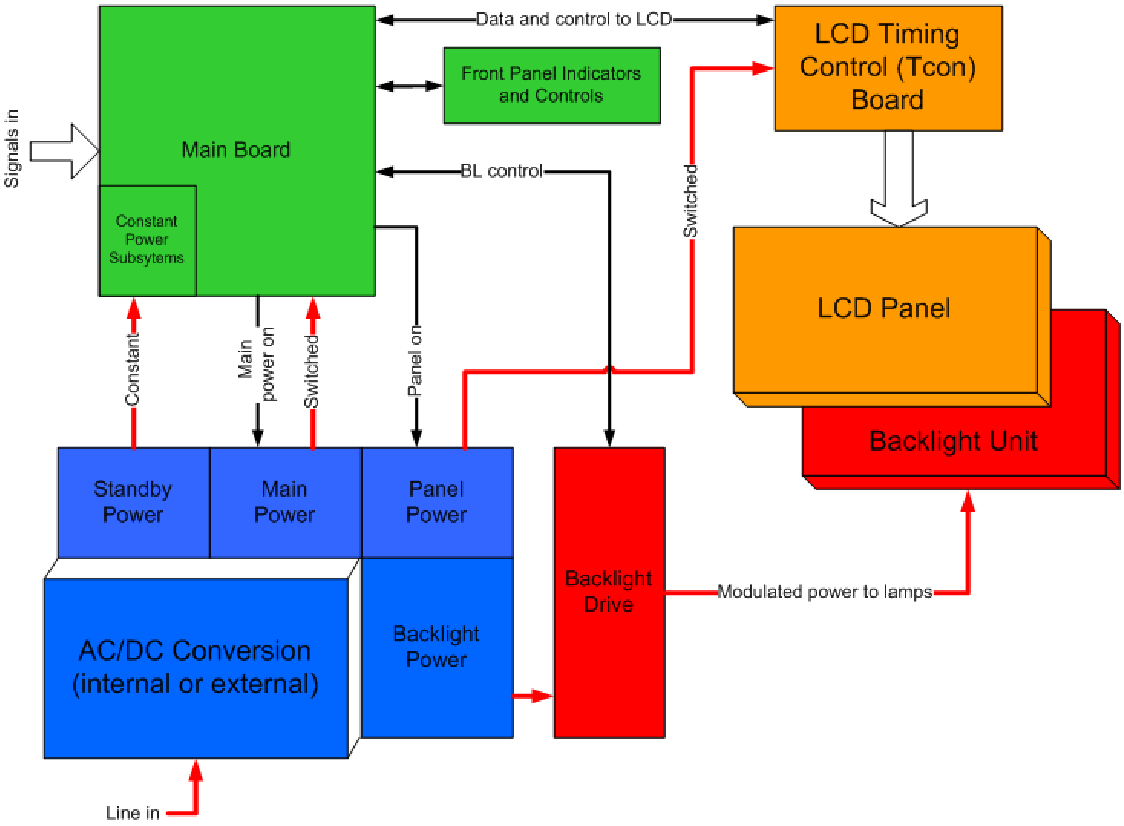

Figure 4.3 Electronic block diagram of a typical LCD display

Source: Ecova

4.2.1 Power Budget

The technical team developed component-level power budgets for each display in its default and power scaling (power saving) mode by logging component-level power during the IEC video and internet test clips. Average power budgets are shown in Figure 4.4, Figure 4.5, and Figure 4.6. The backlight unit accounts for the majority of a display's power budget with more efficient designs reducing the percent of power draw used by the backlight.

For example, the 22" pair's representative model's backlight unit accounted for 47% to 58% of the total power budget. The efficient display's backlight unit was more efficient using 39% to 51% for the display's total budget (Figure 4.5).

D19-1, D19-2, D22-2 and D27-1 utilized twisted nematic (TN) LCD panels, the most common type of panel used in monitors today. When no voltage is applied across a pixel on a TN panel, the pixel is open and light passes through it. To darken the pixel, a voltage is applied to close it. Thus TN panels use less power to display the mostly white images shown on monitors when they are used to display web content, word processing and other non-video content. TN panels use more power to display video, which has a darker average pixel level. This behavior is shown in the comparison between D22-2's LCD power measurements using the video (darker APL, higher LCD power) and internet (brighter APL, lower LCD power) test clips (Figure 4.5).

In contrast, the 22" representative (D22-1) and 27" efficient (D27-2) models have In-plane switching (IPS) LCD panels. Pixels in an IPS panel are closed under no load, and open when a voltage is applied. Thus IPS panels use less power the dimmer the image displayed. This makes them a good choice for monitors that are used primarily for gaming or other video content. D22-1's and D27-2's LCD panels used more power for the brighter internet test clip than for the dimmer internet clip (Figure 4.5 and Figure 4.6).

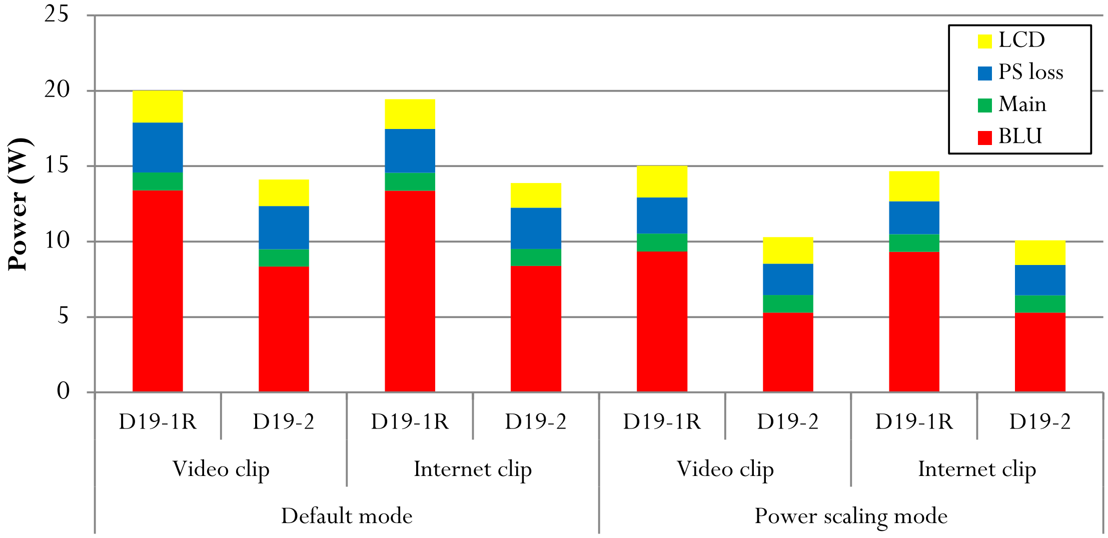

Figure 4.4 Average power for 19" test units in default and power scaling modes, with the IEC video and internet test inputs

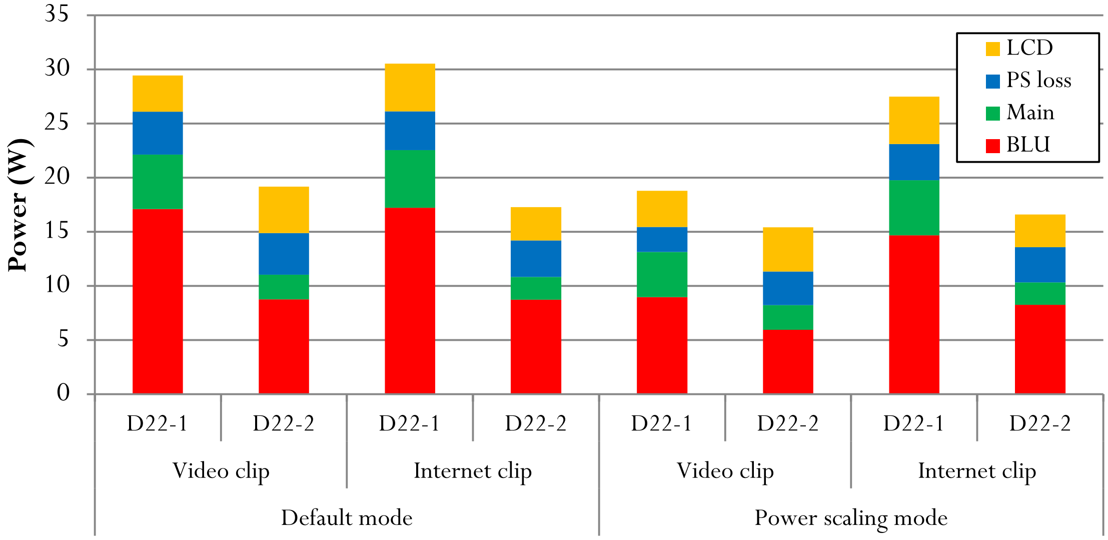

Figure 4.5 Average power for 22" test units in default and power scaling modes, with the IEC video and internet test inputs

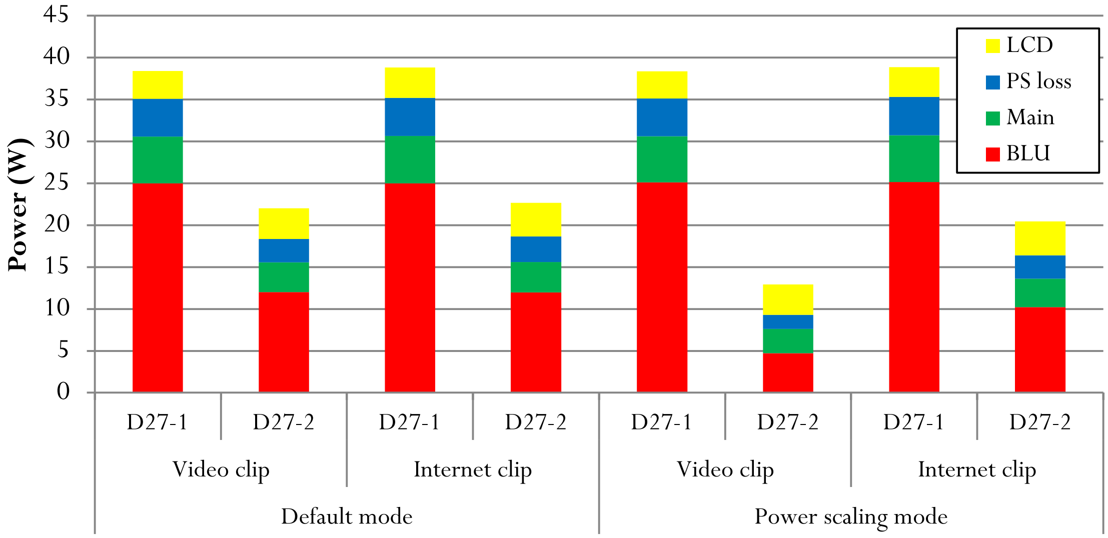

Figure 4.6 Average power for 27" test units in default and power scaling modes, with the IEC video and internet test inputs

Instantaneous power measured during the test clips shows how power of the backlight and other components scales to the content displayed. Figure 4.7, Figure 4.8, and Figure 4.9 how power logs for the representative (top row) and efficient (bottom row) models in (A) default mode with the video clip, (B) in default mode with the internet clip, (C) in power scaling mode with the video clip and (D) in power scaling mode with the internet clip.

19" Pair. In both default and power scaling modes, neither display scaled its backlight to the content displayed (Figure 4.7). The power reduction in power scaling mode for both displays was the result of a simple, overall dimming of the backlight.

22" Pair. In its default mode, the backlight unit of the representative model was constant; it did not scale power to picture content (Figure 4.8A and B, top row). In power scaling mode, however, backlight power scaled to average picture level of the test clip, reducing power by 10 and 35% when playing the internet and video clips, respectively (Figure 4.8C and D, top row).

Backlight power of the efficient model similarly did not scale to content in default mode (Figure 4.8A and B, bottom row). In power scaling mode and playing the video clip, power was lower than in default mode, increasing only for the brightest scenes and reducing power by 20% (Figure 4.8C, bottom row). In power scaling mode and playing the internet clip, however, power was usually the same as in default mode, decreasing only for the darkest scenes, reducing power by 4% (Figure 4.8D, bottom row).

27" Pair. In its default and power scaling modes, the backlight unit of the representative model was constant; it did not scale power to picture content (Figure 4.9A, B, C and D, top row). Similar to the 19" displays, the backlight was simply dimmed to achieve energy savings in its energy saving mode.

Backlight power of the efficient model did not scale to content in default mode (Figure 4.9A and B, bottom row). In power scaling mode, however, backlight power scaled to average picture level of the test clip, reducing power by 10 and 40% when playing the internet and video clips, respectively (Figure 4.9C and D, bottom row).

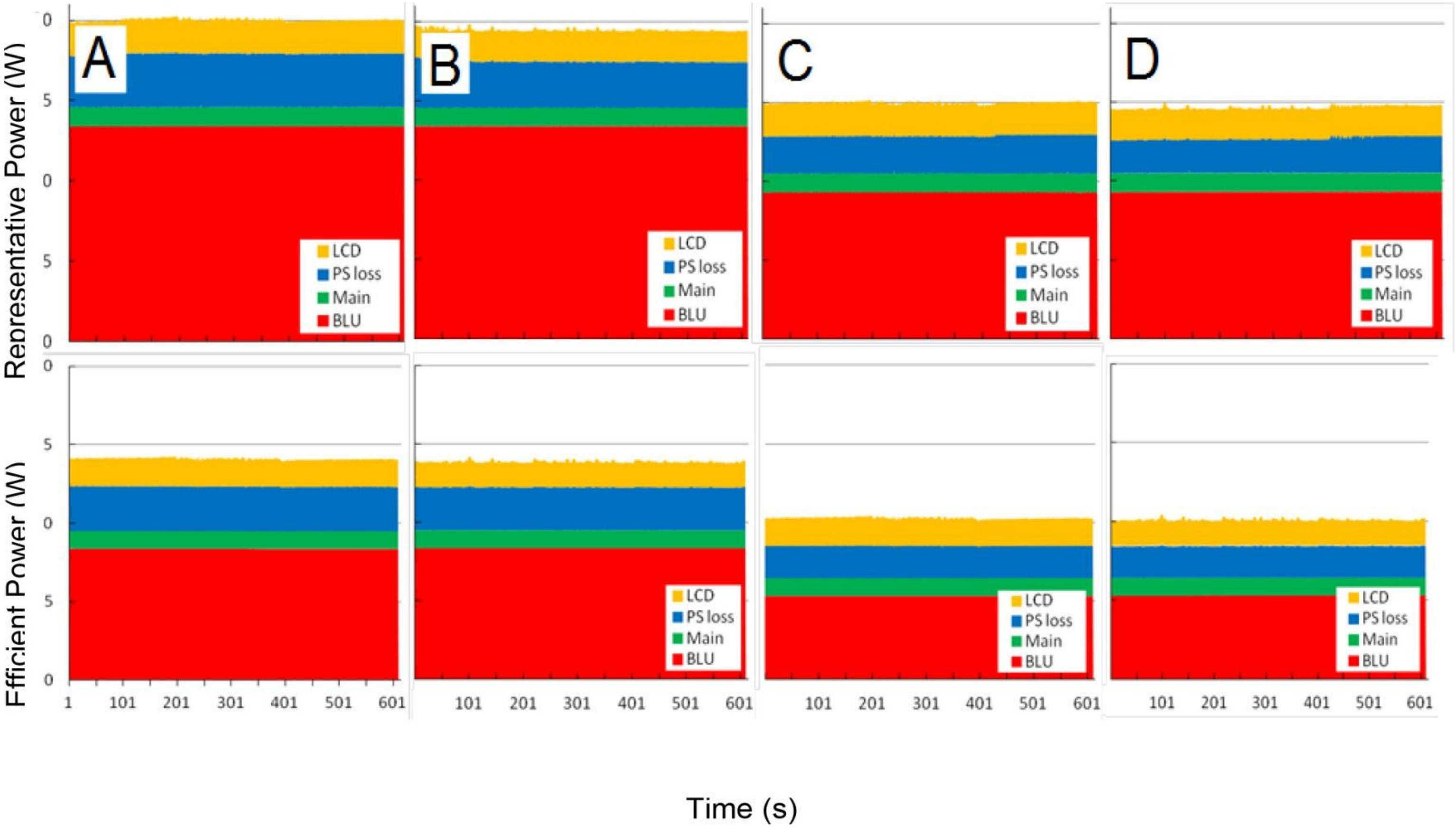

Figure 4.7 Instantaneous power over the 10-minute IEC test clip for the representative (D19-1, top row), and efficient (D19-2, bottom row) models (A) IEC video test clip, default mode (B) IEC internet test clip, default mode (C) IEC video test clip, power scaling mode (D) IEC internet test clip, power scaling mode

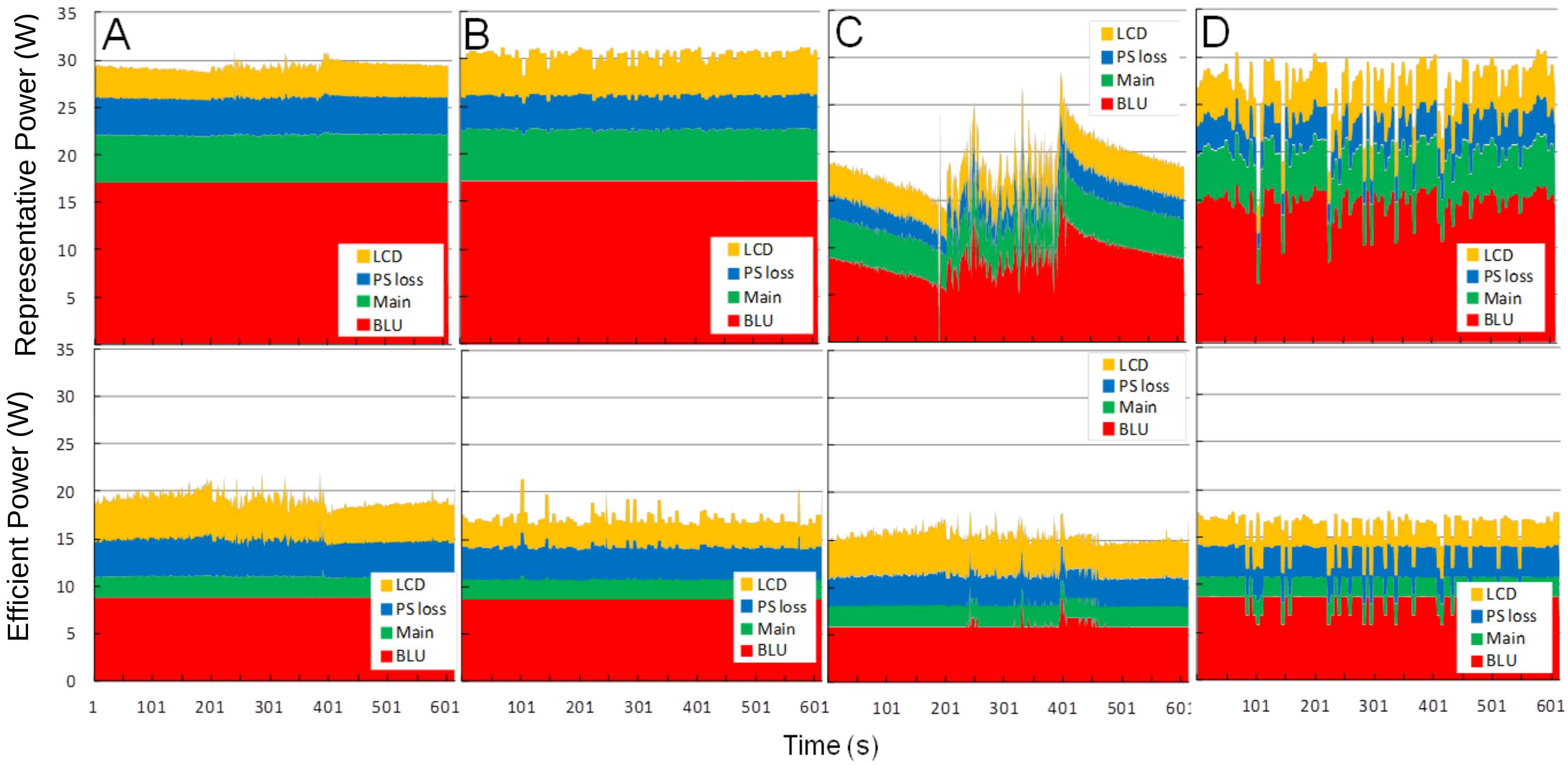

Figure 4.8 Instantaneous power over the 10-minute IEC test clip for the representative (D22-1, top row), and efficient (D22-2, bottom row) models (A) IEC video test clip, default mode (B) IEC internet test clip, default mode (C) IEC video test clip, power scaling mode (D) IEC internet test clip, power scaling mode

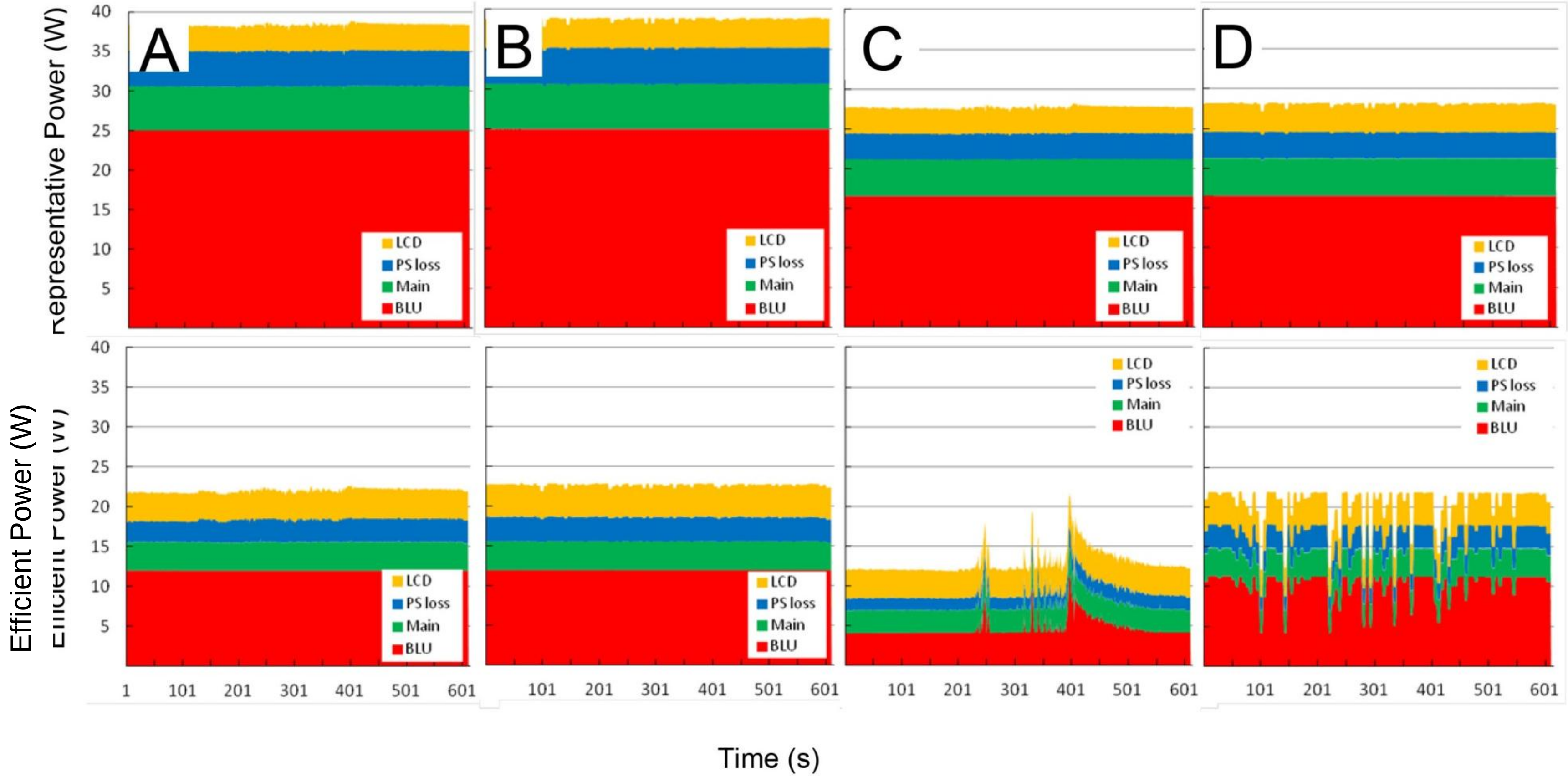

Figure 4.9 Instantaneous power over the 10-minute IEC test clip for the representative (D27-1, top row), and efficient (D27-2, bottom row) models (A) IEC video test clip, default mode (B) IEC internet test clip, default mode (C) IEC video test clip, power scaling mode (D) IEC internet test clip, power scaling mode

4.2.2 Power Supply Efficiency

Like most electronics, displays receive ac power and convert it through a power supply stage to reduced voltage dc before it can be used by other components. Power supply efficiency is the ratio of dc power output from the power supply over ac power input to the power supply. Higher power supply efficiency indicates less power loss in the power supply.

Power supplies for the 19” and 27” pairs showed slight differences with regards to efficiency. Within the 22” pair, the representative display contained an external power supply (EPS) with a measured power supply efficiency of 87%, while the efficient model contained an internal power supply (IPS) with a measured power supply efficiency of 80% (Table 4.6).

Table 4.6 Component efficiencies for representative and efficient test units

Test Unit Description	**Rep**	**Eff**	**Rep**	**Eff**	**Rep**	**Eff**
Test Unit ID	D19-1	D19-2	D22-1	D22-2	D27-1	D27-2
Power supply type	internal	internal	external	internal	external	external
Power supply efficiency (%)	83	80	87	80	88	87
Number of LED lamps	2 (CCFL)	48	48	44	64	42
Lamp efficacy (lm/W)	47	69	105	104	87	107
BLU on-axis efficiency (cd/W)	24	27	18	48	34	41
LCD panel transmissivity (%)	6	6	11	7	7	9

Source: CASE Team Testing and Analysis

4.2.3 Lamp Efficacy

The first step to producing an image on the screen of an electronic display is to produce light. How efficiently it produces this light has a significant effect on the overall efficiency of the display. Lamp efficacy is measured as a ratio of light output in lumens to electric power input in watts. The two test units within the 22” size group had comparable lamp efficacy, both measuring about 105 lm/W (Table 4.6). There were more significant differences in the other sizes. As expected, the LED lamps outperformed the CCFL lamps in the 19” size group (47% higher efficacy), however, those LEDs were a much lower level of efficacy than the best LEDs tested, such as the 107 lm/W LEDs found in test unit D27-2.

Market analysts have predicted a continued trend toward higher efficacy LEDs. The technical team has noticed an improvement in display LED efficacy from about 80 lm/W in 2010 to greater than 100 lm/W measured in this analysis. This trend is expected to continue in coming years.

4.2.4 Backlight Unit On-Axis Efficiency

Once the light is produced and directed normal to the display by the light guide plate, usable light gain is achieved by passing the light through the optical film stack. As noted previously, usable light is measured as the luminance of light directed normal to the display’s screen. As light passes through a display’s optical components, it is focused and oriented to be usable once it hits the LCD panel. Figure 4.10, Figure 4.11 and Figure 4.12 illustrate light gains and losses through the film stack of the test units. Screen-normal gain is presented as the gain through both an individual layer (black and blue columns) and cumulatively as light passes through the film layers (black and blue lines). The data for the representative and efficient models are shown in black and blue, respectively.

Both 22” displays had two diffusers, one as the bottom layer of the film stack and a second as the middle or top layer (Figure 4.11). The diffusers scatter light for even brightness across the screen area and, to a lesser degree, direct the light normal to the screen. The diffusers in the representative model achieved more screen-normal gain than those in the efficient model.

Both 22” displays also had a horizontal prism film. The prism film in the representative model was the top layer of the film stack, whereas the film in the efficient model was the middle layer. Horizontal prism film directs light normal to the screen that would otherwise spread vertically. The efficient display’s prism film achieved almost twice the screen-normal gain that the representative model’s prism did (Figure 4.11).

High-gain film stacks, such as those found in both 27” models (Figure 4.12), use as a top layer a reflective polarizer, which passes light of one polarization to the back of the LCD panel and reflects the rest of the light back toward the lamps to be recycled through the film stack. None of the 19” or 22” displays tested included a reflective polarizer in its film stack.

Although we describe the screen-normal gain for each layer in the film stack, it is important to note that the films interact with each other. Thus the gain measurements for the middle and top film of each display may be different if we measured them without the films below them in place.

The cumulative screen-normal gain as light passes through each layer is shown as lines in Figure 4.11 and Figure 4.12. Looking at the 22” pair, the film stack of the efficient display had a slightly higher gain than that of the representative model. The gain of the 19” and 27” film stacks were quite similar with each size group. We calculated backlight unit on-axis efficiency as the screen-normal light output divided by the backlight power input. Because it had both a lower input power and a higher gain film stack, the 22” pair’s efficient display had a backlight unit on-axis efficiency that was more than twice that of the representative model (Table 4.6).

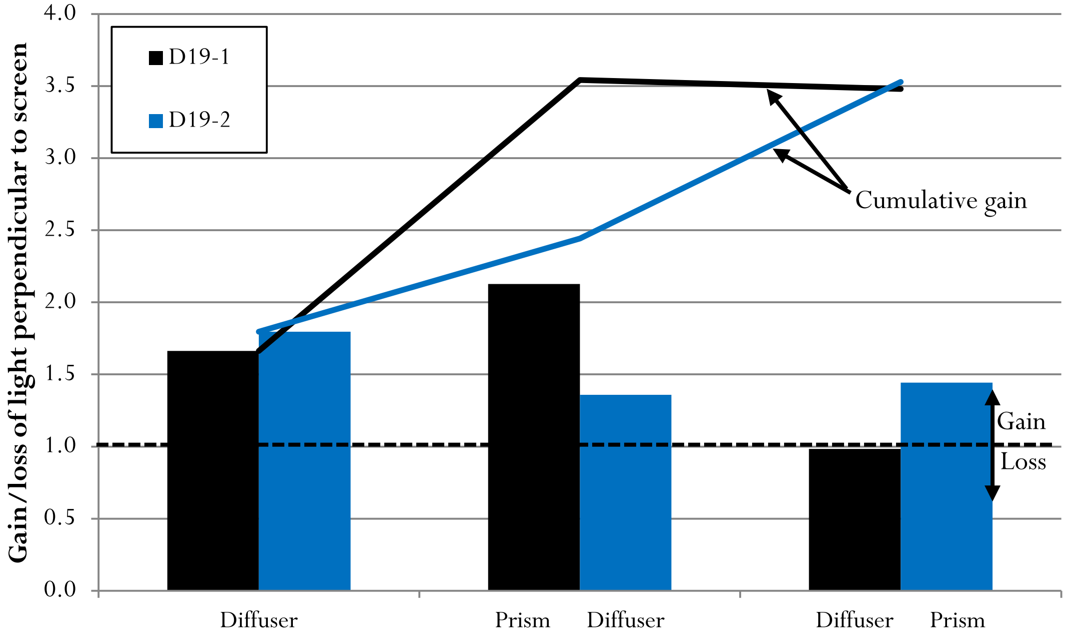

Figure 4.10 19" pair gain (or loss) of light normal to display, measured as the luminance out of a layer over luminance into a layer

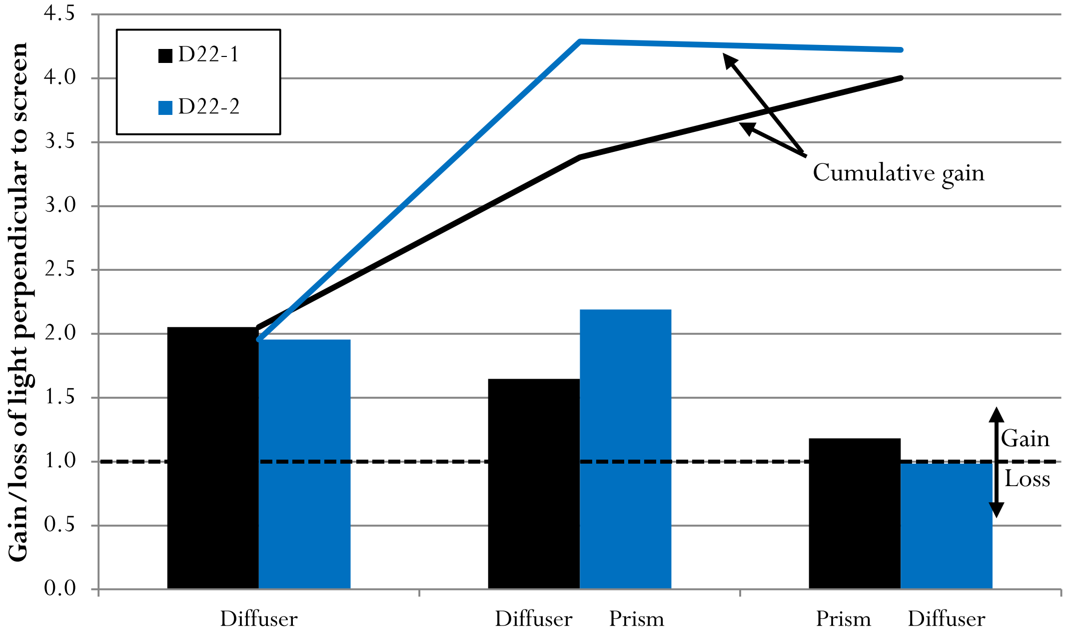

Figure 4.11 22" pair gain (or loss) of light normal to display, measured as the luminance out of a layer over luminance into a layer

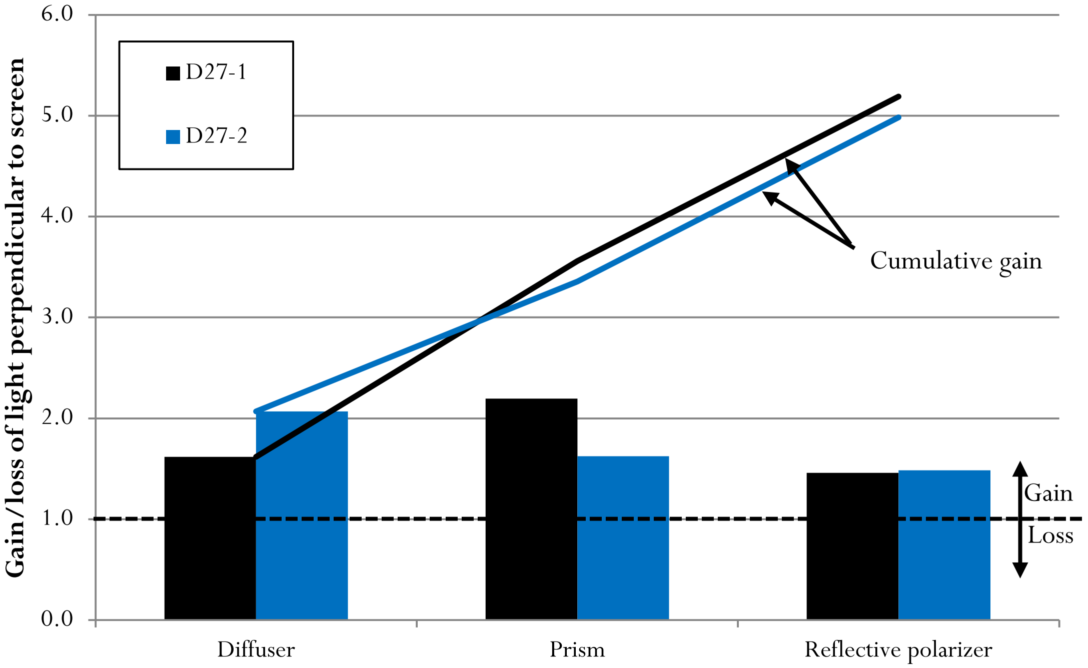

Figure 4.12 27" pair gain (or loss) of light normal to display, measured as the luminance out of a layer over luminance into a layer

4.2.5 LCD Transmissivity

LCD transmissivity is the ratio of screen-normal light measured out the front of the LCD panel to the screen-normal light measured out the front of the film stack. The 22" representative model LCD panel, which uses in-plane switching (IPS) technology, transmitted over 50% more light than the 22" efficient panel, which uses twisted nematic (TN) technology (Table 4.6). The 27" efficient model panel also uses IPS technology and transmitted almost 30% more light than the 27" representative model which uses a TN panel. Both of the 19" test units incorporated TN panels and measured very similar panel efficiency (Table 4.6).

4.2.6 OLED Teardown

In addition to the teardown of the dominant panel display technology, LCD, the technical team also examined in detail an OLED display to investigate the energy implications of this technology in the event it gains a significant market share as many industry analysts expect. Smaller OLED displays are already common in the smart phone space, however, only a handful of OLED displays have become available in the consumer and commercial TV and computer monitor markets.

Since there were no available consumer grade OLED computer monitors available on the market at the time of procurement for test units for this analysis, a 25" professional grade monitor intended for video editing and other applications that require high quality color reproduction and off-axis color stability was selected.

The OLED teardown methodology was somewhat different from that of the LCD displays due to the differences in technology. Specifically, OLED is an emissive technology, meaning it does not require a backlight for its pixels whose operation is controlled through an LCD controller. Instead, light production and pixel operation are controlled by the same system. Therefore, there is no film stack, BLU or LCD control power to compare directly with LCD measurements. The technical team did, however, gather power data for the display's main board and power supply losses which are comparable to an LCD display (Table 4.7). To compare to an LCD's BLU power, the power delivered to the OLED panel that varies with light and dark images (BLU equivalent in Table 4.7) were isolated and measured. The rest of the power delivered to the panel was considered analogous to that of an LCD panel's LCD controller or the timing controller as it is often called (Tcon equivalent in Table 4.7).

Table 4.7 OLED Display Power Budget

Component	Power (W)
BLU equivalent	17.9
Tcon equivalent	11.6
Main + PS	29.2
Line (total)	**58.7**

4.2.7 USB Charging Power Draw

For two monitors with USB charging capability, a dummy load (fixed resistor) of 2.25 W was used to represent a charging device. The resulting plug load impact was around 3 watts. For these tests, the monitors displayed the 3 bar luminance test pattern.

Table 4.8 USB Charging Power Draw

Monitor	Plug Load Power Draw (W)	Plug Load Power Draw with 2.25W Charging Load (W)
D27-2	22.4	25.3
D22-3	19.6	22.8

4.2.8 Summary

19" Pair. The efficient display was equipped with LED backlighting while the representative display used CCFLs. This is the key difference that accounts for the difference in energy use as the film stacks, power supply efficiencies and panel efficiency were similar. However, the difference could have been much greater given the relatively low efficacy of the LEDs in the efficient display. The LEDs were measured at 69 lumens/watt while the LEDs measured from other displays averaged more than 100 lumens/watt (Table 4.6). Additionally, the efficient display's default screen brightness was approximately 20% higher than the representative model (Table 4.1), making its out of the box power draw higher than it would be if its luminance was set to the same level as that of the representative display.

22" Pair. Although the efficient display was overall more efficient than the representative model, the representative model did have a much more efficient LCD panel. The efficient display, however, had a more efficient backlight unit because it used fewer LEDs and had a higher film stack gain. Both displays had LEDs with efficacy of about 105 lm/W, which is much higher than the 80 lm/W the technical team observed in previous work on 2010-11 model year displays. Neither display included a reflective polarizer, which can increase film stack efficiency by 50% or more (3M 2008). The technical team examines efficiency improvements, including a scenario in which the efficient display has a reflective polarizer and a more efficient LCD panel, in the following Cost-Efficiency Analysis section (Section 5).

27" Pair. The efficient display's BLU was measured to be approximately 20% more efficient than the representative display BLU due to a more efficient panel and higher efficacy LEDs. Both display stacks contained a reflective polarizer and the power supply efficiencies were very similar. When calibrated to the ENERGY STAR test procedure prescribed luminance level of 200 nits, the displays are relatively close in terms of on mode power, in fact, the efficient models draws about 10% more. However, in their "out-of-the-box" state, the representative display draws almost 80% more power due to its high screen luminance (400 nits vs. 170 nits for the efficient display) (Table 4.3).

4.3 Resolution Analysis

For LCD displays, higher resolution to increase power draw, all other aspects being equal (e.g. size, brightness, panel technology etc.) is expected. Higher resolution means more pixels which increase the area of the electronics that control pixel operation, reducing the transmissivity of the panel. To maintain screen luminance, this requires increased output from the backlight which correlates to increased display power (Figure 4.1).

To determine the degree to which increased resolution affects display on mode power draw, the technical team analyzed data from three different sources. First, the power differences allowed under the ENERGY STAR Version 6 specification was calculated. Given the highly vetted nature of the ENERGY STAR specification process, this allowance was assumed to be deemed reasonable by ENERGY STAR partners. Second, an ENERGY STAR qualified product list (QPL) from May 2013 was analyzed to determine the relationship between power and resolution in the current marketplace. Finally, the technical team tested two computer monitors of the same size, brand and LCD structure, but with different resolutions to estimate a power difference if all other elements are held equal.

Table 4.9 compares the power calculated from the ENERGY STAR specification and the analysis of the May 2013 QPL across three resolutions for four different display sizes. The percent power columns compare the power draw of the lower resolution display of the same size. For example, using the ENERGY STAR specification, the calculated on mode power for a 15" display is 48% more when going from a resolution of 1.05 MP to 2.07 MP. Similarly, the same increase in resolution for a 15" display using the trends[1] found in the ENERGY STAR QPL resulted in an increase in power draw of 46%. Although there are differences in power increases across methods, the values are relatively close and show that resolution likely has a significant impact on power draw.

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[1] We determined the trends of the QPL by examining increases in resolution and power within several screen sizes and calculating the ratio between the average increase in power to the average increase in resolution. From this ratio, we calculated an exponent (0.56) used to determine expected on mode power in Table 4.9. For example, to estimate the power draw that results from increasing the resolution of a 15" display from 1.05 to 2.07 MP, the ratio of the resolutions (2.07/1.05) are raised to the 0.56 exponent. This results in a 1.46 multiplier which is then applied to the original power draw of 12.8 watts to calculate a value of 18.8 watts at a resolution of 2.07 MP.

Table 4.9 Comparison of power draw increase with increase in resolution across common display sizes

Diagonal Screen Size (in)	Screen Area (sq in)	Resolution (MP)	ENERGY STAR Specification Calculation		Analysis of ENERGY STAR QPL	
			Max On Mode Power (W)	% Power Increase from Low to High Resolution	On Mode Power (W)	% Power Increase from Low to High Resolution
15	103	1.05	12.8	-		-
	103	2.07	19.0	48%	18.8	46%
	103	3.69	28.6	51%	26.2	38%
18.5	146.5	1.05	13.7	-		-
	146.5	2.07	19.8	45%	20.0	46%
	146.5	3.69	29.5	49%	27.3	38%
21.5	198	1.05	14.9	-		-
	198	2.07	21.1	41%	21.9	46%
	198	3.69	30.8	46%	29.1	38%
27	311	1.05	22.9	-		-
	311	2.07	29.0	27%	33.5	46%
	311	3.69	38.7	33%	40.1	38%

Testing confirmed the relative impact of resolution on power draw found in the above analyses. Comparing the power draw of two 27" LCD monitors with IPS panels, a 2.07 megapixels (1920 pixels horizontal by 1080 pixels vertical) panel and the other with a 3.69 megapixels (2560 pixels horizontal by 1440 pixels vertical) panel, we found a more than 50% increase in plug load after normalizing for other components. We assumed an increase in pixels results in increased power draw from various components including:

- Backlight unit (BLU) – More pixels mean more blocking of light by TFTs which supply power to sub pixels. Therefore, in order to pass through the same amount of light as a panel of the same size with fewer pixels, a higher resolution monitor will need more light output from its BLU.
- LCD controller – Extra power is needed secondarily in the LCD panel to control extra pixels.
- Signal processing – A small amount of extra power is needed for extra signal processing on the monitor's main board.

Given the above investigation and analyses, for computer monitors, the technical team believes that for computer monitors, it is reasonable to add extra on mode power allowance for higher resolutions.

5 Cost-Efficiency Analysis

5.1 19" Pair – Incremental Cost of Efficiency Improvements

Figure 5.1 illustrates the relationship between incremental consumer cost (BOM costs with retail markup) and energy efficiency for the test units, as well as several maximum technology and emerging technology scenarios that improve overall display efficiency using 2013 prices. The representative and efficient displays are shown in black. Maximum technology scenarios involving improved LED efficacy and reduction of backlight output are shown in red, and the addition of a more efficient PSU and a reflective polarizer as well as the implementation of ABC are shown in orange. Emerging technology improvements including the use of thinner TFTs and quantum dots are shown in blue. A theoretical combination of the most efficient components from the representative and efficient test unit displays is shown in green in Figure 5.1. Details regarding the assumptions and sources behind the cost and efficiency estimates for all three pairs of displays can be found in the Efficiency Improvement Measures section (Section 5.4). Note that for this and other sizes analyzed, as display efficiency improves, the cost for additional efficiency improvement generally increases. Table 5.1 summarizes the resulting efficiency and incremental cost for each of these measures and the relative improved efficiency and cost beyond the representative test unit.

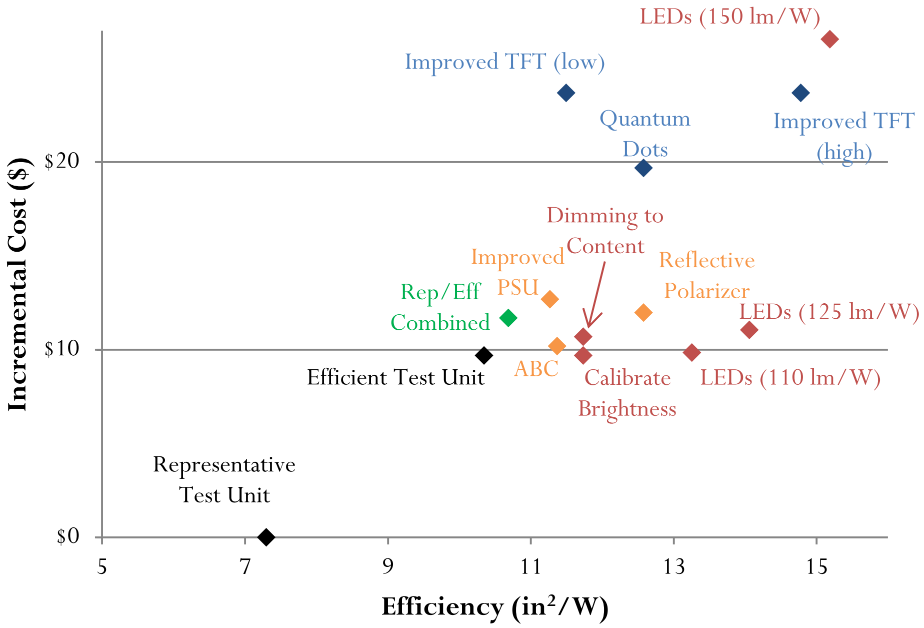

Figure 5.1 19" computer display incremental consumer cost in 2013 shown as a function of efficiency for both test units (representative and efficient) as well as several maximum technology and emerging technology scenarios

Table 5.1 Summary of efficiency measures relative to representative test unit efficiency

Measure	Efficiency (in^2/W)	Efficiency Improvement over Representative Test Unit
Representative Test Unit	7.30	-
Efficient Test Unit	10.34	42%
Technology Scenarios		
Rep/Eff Combined	10.69	46%
Improved PSU	11.27	54%
ABC	11.37	56%
Dimming to content	11.73	61%
Calibrate Brightness	11.73	61%
Reflective Polarizer	12.58	72%
LEDs (110 lm/W)	13.25	82%
LEDs (125 lm/W)	14.06	93%
LEDs (150 lm/W)	15.19	108%
Improved TFT (low)	11.49	58%
Improved TFT (high)	14.78	103%
Quantum dots	12.58	72%

The incremental cost between the representative and efficient test units is significant due to the shift from a CCFL to an LED-based backlight unit. Implementing more efficient LEDs (110 lm/W) results in an even more significant jump in efficiency since the efficient units was equipped with relatively low performing LEDs (69 lm/W).

5.2 22” Pair – Incremental Cost of Efficiency Improvements

Figure 5.2 illustrates the relationship between incremental consumer cost (BOM costs with retail markup) and energy efficiency for both test units, as well as several maximum technology scenarios that improve overall display efficiency using 2013 prices. The representative and efficient displays are shown in black. Maximum technology scenarios involving improved LED efficacy and reduction of backlight output are shown in red, and the addition of a more efficient PSU and a reflective polarizer as well as the implementation of ABC are shown in orange. A theoretical combination of the most efficient components from the representative and efficient displays is shown in green. Emerging technology improvements including the use of thinner TFTs and quantum dots are shown in blue. Table 5.2 summarizes the resulting efficiency from each of these measures and the relative improved efficiency beyond the representative test unit.

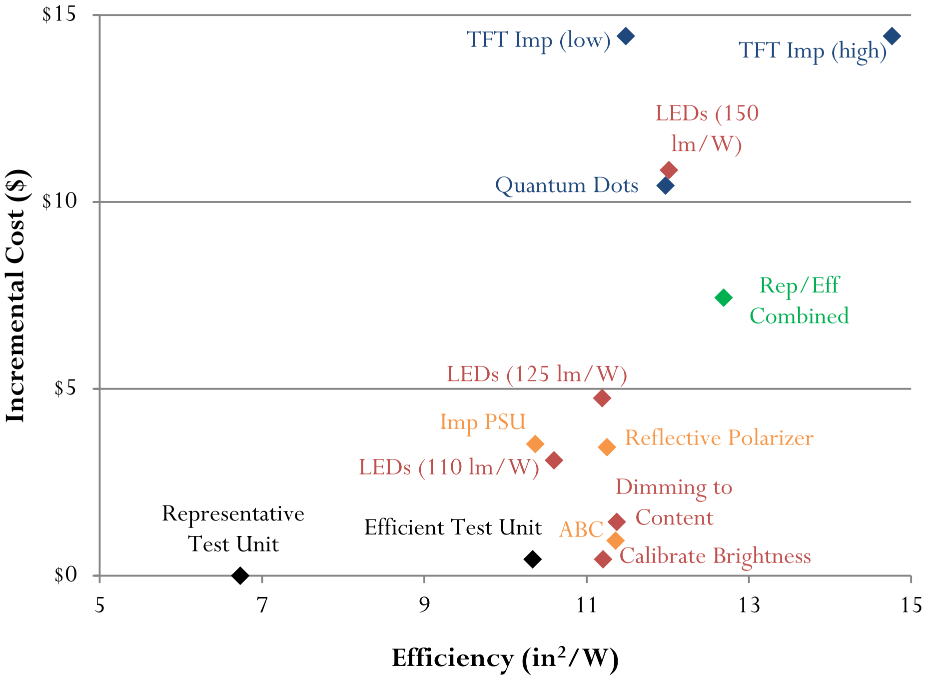

Figure 5.2 22" computer display incremental consumer cost in 2013 shown as a function of efficiency for both test units (representative and efficient) as well as several maximum technology scenarios

Table 5.2 Summary of efficiency measures relative to representative test unit efficiency

Measure	**Efficiency (in^2/W)**	**Efficiency Improvement over Representative Test Unit**
Representative Test Unit	6.73	-
Efficient Test Unit	10.33	54%
Technology Scenarios		
Rep/Eff Combined	12.69	89%
Reflective Polarizer	10.37	54%
LEDs (110 lm/W)	10.60	57%
LEDs (125 lm/W)	11.19	66%
LEDs (150 lm/W)	12.01	78%
Calibrate Brightness	11.20	66%
Improved PSU	11.25	67%
ABC	11.36	69%
Dimming	11.37	69%
Quantum Dots	11.97	78%
Improved TFT (low)	11.48	71%
Improved TFT (high)	14.76	119%

The incremental cost between the representative and efficient displays was minimal for an efficiency improvement of 54%. Despite being less efficient overall, the representative model had a more efficient LCD panel than the efficient model, so we performed a theoretical combination of the most efficient components from the representative and efficient displays identified during the teardown analysis (shown in green as Rep/Eff Combined in Figure 5.2).

5.3 27" Pair – Incremental Cost of Efficiency Improvements

Figure 5.3 illustrates the relationship between incremental consumer cost (BOM costs with retail markup) and energy efficiency for both test units, as well as several maximum technology scenarios that improve overall display efficiency using 2013 prices. The representative and efficient displays are shown in black. Maximum technology scenarios involving improved LED efficacy and reduction of backlight output are shown in red, and the additions of a more efficient PSU as well as the implementation of ABC are shown in orange. Emerging technology improvements including the use of thinner TFTs and quantum dots are shown in blue. Table 5.3 summarizes the resulting efficiency from each of these measures and the relative improved efficiency beyond the representative test unit.

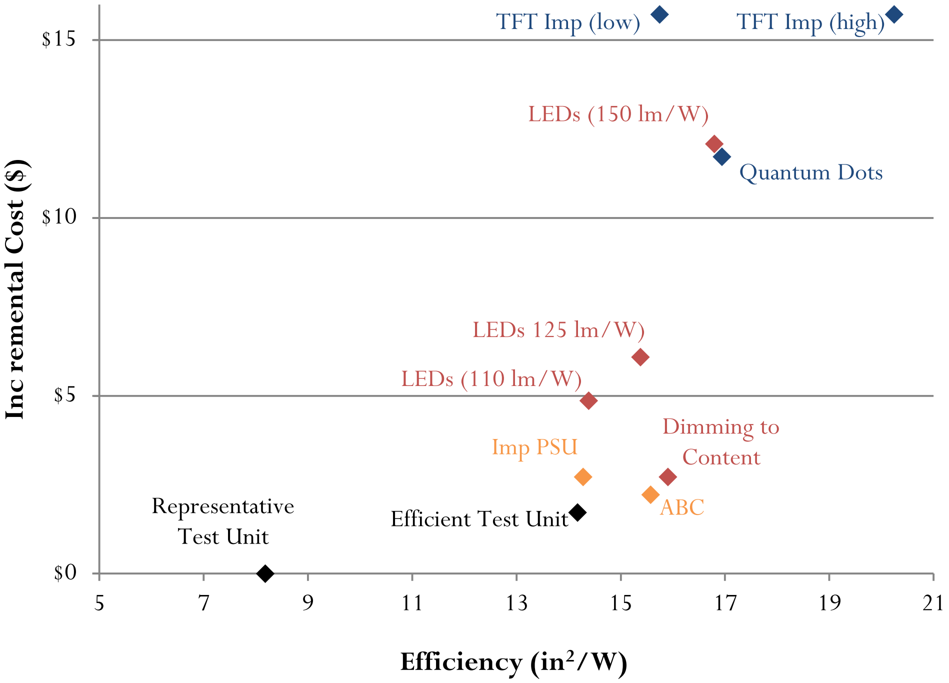

Figure 5.3 27" computer display incremental consumer cost in 2013 shown as a function of efficiency for both test units (representative and efficient) as well as several maximum technology scenarios

Table 5.3 Summary of efficiency measures relative to representative test unit efficiency

Measure	Efficiency (in^2/W)	Efficiency Improvement over Representative Test Unit
Representative Test Unit	8.18	-
Efficient Test Unit	14.17	73%
Technology Scenarios		
Improved PSU	14.28	75%
LEDs (110 lm/W)	14.38	76%
LEDs (125 lm/W)	15.38	88%
LEDs (150 lm/W)	16.80	105%
ABC	15.57	90%
Dimming	15.90	94%
Improved TFT (low)	15.75	92%
Improved TFT (high)	20.24	147%
Quantum Dots	16.94	107%

In this case, the difference in efficiency between the representative and efficient test units is significant (73%) due to the more efficient components contained within the efficient unit. These include a more transmissive LCD panel, LEDs with higher efficacy, and fewer LED lamps.

5.4 Efficiency Improvement Measures

5.4.1 LED Improvements

The technical team performed calculations for three scenarios representing improvements in LED lamp efficacy for each monitor pair: modeling increased lamp efficacy to 110 lumens per watt (lm/W), 125 lm/W and 150 lm/W. Improving to 110lm/W is slightly better than current typical display lamp efficacy (95-100 lm/W according to discussions with industry experts). Increases in overall display efficiency of the best-on-market models ranged from 1% in the case of the 27" which already had efficient lamps (107 lm/W) to 22% in the case of the 19" model. Costs for these lamps were estimated from discussions with industry experts based on DisplaySearch costs for slightly lower performance lamps. Further increasing lamp efficacy to 125lm/W and 150 lm/W increased total display efficiencies significantly (8% to 30%) while only moderately increasing costs. The reason for this stems from using more efficacious lamps to produce the same amount of backlight, which allows manufacturers to build displays with fewer lamps. Costs for the 125lm/W and 150lm/W lamps were conservatively estimated to be considerably higher (two times and eight times respectively) than the cost of typical lamps found in current displays.

5.4.2 Reflective Polarizing Film

In the case of the 19" and 22" pairs, neither the representative nor the efficient test units contained a reflective polarizer which is a low cost means to recycle improperly polarized light rather than letting it be lost as absorbed heat. This improvement increases LCD transmissivity which enables the use of a less powerful BLU. When a reflective polarizer was theoretically added to the 19" and 22" best-on-market models, it increased overall efficiency by 10% and15% respectively. This estimate is based on component manufacturer estimates for BLU improvements (HDTVExpert.com 2012, 3M 2013). Cost estimates are based on data supplied by DisplaySearch's BLU Cost Model. Both of the 27" models already contained a reflective polarizing film and therefore this efficiency improvement was not considered for the 27" pair analysis.

The market for reflective polarizing film has been dominated by 3M. Although 3M's patent has expired, other market players have yet to attain a significant market share.2 For this reason, the technical team has included the use of reflective polarizing as only one of several paths to our proposed efficiency levels. Our proposed limits do not require the use of reflective polarizing film.

5.4.3 Power Supply Improvements

For the 22" pair, the best-on-market display included an internal power supply with a measured power supply efficiency of 80%. Recent improvements in power supply topologies have enabled more efficient power supplies to be developed and included in electronic devices. The existing power supply was theoretically replaced with an 88% efficient power supply (the efficiency of the best power supply we tested) in the best-on-market model; it increased overall efficiency by nearly 8% at an estimated incremental cost of about $3.00. The 19" best-on-market display showed a similar level of improvement while the 27" display demonstrated only a modest efficiency improvement (1%) since its power supply was already quite efficient (87%).

5.4.4 Automatic Brightness Control (ABC)

ABC is a method for adjusting a display's brightness to increase in bright ambient conditions and decrease in more dimly lit conditions. Reducing screen brightness in darker conditions reduces eye strain and also reduces BLU power. In order to account for energy savings, an estimate for time spent in dim and bright conditions is needed. For the purposes of this analysis, we estimated a split of 80% of on mode time in a bright room, such as an office and 20% of the time spent in more dim conditions. Although no field data was found to determine this split of time between different viewing environments, it was deemed reasonable given that most computer monitor time is likely in an office setting with an increasing amount of time being spent in more dim conditions associated with gaming or video viewing as evidenced by the increase in shipments of larger sized computer monitors (IHS iSuppli. 2012). ENERGY STAR also used this ratio of bright and dark viewing conditions for calculating on mode power for its version 5.0 displays specification. Using ENERGY STAR's current power measurement points of 10 lux and 300 lux, a 9% savings in on mode power on the unit we tested equipped with ABC was found. The technical team calculated the same percent savings when using DOE's test results of ABC enabled TVs ([DOE]). This report also states that three field studies showed a significant amount of TV viewing occurred between 10 and 15 lux, making the 10 lux power measurement a reasonable level to approximate residential, non-office environment viewing. Although a power saving credit of 9% was used in the cost analysis, this method is in line with ENERGY STAR's approach in its Version 6 specification for monitors. ENERGY STAR uses a 10% adder to the allowable on-mode power for monitors that meet its criteria for implementing ABC (ENERGY STAR 2013).

The cost associated with implementing ABC are based on three basic required components: (1) the ability of a display to dim its backlight, (2) an ambient light sensor that measures lighting levels, and (3) the software to interpret the light levels and translate them to a particular display brightness. All displays tested had the ability to dim their backlight, so costs for this component were not considered. Conversations with sensor manufacturers have revealed that the sensors typically cost between 10 and 25 cents each. Finally, the cost of the software to communicate light levels to a display's backlight was estimated to be minimal when implemented in mass production, giving a total incremental cost of approximately 50 cents to implement ABC in a display.

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[2] Example of another manufacturer of reflective polarizing film: http://www.nittousa.com/files/ProductDetails.aspx?PId=447

5.4.5 Backlight Dimming to Video Content

Similar to ABC, dimming (also referred to as global dimming) reduces the light output and therefore power of a display. However, the degree to which the backlight dims depends on the brightness of the video content instead of the brightness of the room. Two of the units tested incorporated dimming (22" representative and 27" efficient models, see Figure 4.8 and Figure 4.9, however, they were not enabled by default. Power savings with dimming enabled using the IEC video clip were 35% and 40% for the 22" and 27" models respectively. For this analysis, a conservative power reduction of 30% was used and applied to all efficient units.

Through consultation with industry experts, costs for dimming to video content were estimated to be similar to those for ABC. The need to interpret signal picture levels and apply them to backlight output may require a slightly higher processing capability, so an incremental cost of $1 was used for implementation of dimming to content.

5.4.6 Limit Screen Brightness (Calibration)

In its testing, the technical team found a wide range of screen brightness values in default mode which has a significant impact on BLU power (see Figure 4.1). Although the ENERGY STAR test procedure requires calibration of units to 200 nits (candelas per square meter), our test data shows that this method is not representative of real world power usage. For example, the best-on-market 22" monitor had a default luminance value of 255 nits and a corresponding on mode power of 14 watts (Table 4.1). Reducing the default brightness to 200 nits results in an on mode power of just under 12 watts, a 15% reduction in power with zero incremental cost.

5.4.7 Emerging Technology Options

It is important to note that for the cost-effective analysis (Section 5.6) the technical team did not include scenarios including the following emerging technology options as there was less confidence in the cost and efficiency estimates. However, the technical team analyzed these emerging technology options for each size pair for illustrative purposes only and found at least one cost-effective option for each size group (18.5, 21.5 and 27 inch). This is significant given likely future cost reductions would create even greater energy efficiency improvements in the coming years.

5.4.7.1 Quantum Dots

Quantum dots are very tiny particles that can emit light at very specific wavelengths. Used in conjunction with an LCD panel's color filter, they can theoretically produce red, blue and green light more efficiently and with a greater color gamut than current displays (LEDs Magazine. 2011). The increased efficiency comes in part from using current (blue light emitting) LEDs without a phosphor coating that creates white light. At least one manufacturer has begun implementing this technology and offered currently by multiple suppliers: QD Vision and 3M (CNET. 2013a; QD Vision 2013; 3M. 2013).

5.4.7.2 Higher LCD Panel Transmissivity

Efficient approaches to reduce backlight demand include increasing pixel effective area by reducing the area of TFTs that block light (Figure 5.4). Sharp has introduced its indium gallium zinc oxide (IGZO) TFT technology which takes up less space than traditional amorphous silica TFTs (Gizmag. 2013). In addition, this technology reportedly saves energy through the reduction of screen refreshes required for still images when compared to amorphous silica TFT technology (CNET. 2013b).

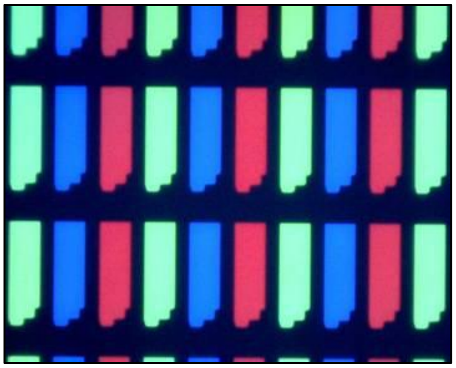

Figure 5.4 Micrograph of a twisted nematic LCD panel, an LCD type that is commonly used in computer monitors[3]

Another potential method to reduce backlight demand includes adding additional sub-pixel colors beyond red, green and blue In TVs, some manufacturers have implemented yellow or white sub-pixels to create a panel that reportedly transmits light more efficiently (Sharp (Europe). 2010). The technical team would expect this approach could be adapted for computer monitors as well.

Matching LCD technology to content and application is another way to increase panel transmissivity. IPS panels align liquid crystals to an open position when voltage is applied, while TN panels will remain open until a voltage is applied, blocking light from passing through. Using a test clip with more dark images than light images (such as the IEC video test clip) provides an advantage to the IPS technology. Additionally, TN panels have a narrower viewing angle which works well for an individual at a workstation, but is less optimal when a monitor is used as a television with multiple viewers. Therefore, matching IPS LCD technology to larger monitors intended for more television type usage (darker images, wider viewing angle) and TN technology to other monitors intended for more traditional computing type usage (white backgrounds, smaller viewing angle) makes sense from an energy standpoint.

5.4.7.3 Organic Light Emitting Diode (OLED)

Because they do not require a backlight or filters, OLED displays theoretically have the potential to use less energy than LCD displays. Our testing of an available 25” OLED monitor showed much higher average plug load power draw than the highly efficient 27” LED-LCD tested (58W vs. 22W). This was expected as the OLED display was an early generation model, not the product of a mature and efficient manufacturing process such as that of the 27” LED-LCD. In addition, the OLED display was designed for professional editing usage, incorporating fans and other heat protecting features to account for a duty cycle with greater time spent in active mode. To account for these differences, the technical team compared component level measurements between the two monitors and estimated the power draw of an OLED with more efficient processing and display controls that would be in line with a more mass produced product that is also designed for a more typical consumer duty cycle. This results in a modeled OLED display that uses 2 to 3 more watts than the LED-LCD display. With future improvements in the manufacturing process and OLED lighting efficiency, it is possible OLED displays will achieve the theoretical energy use advantage over LCDs.

5.5 Incremental Cost Reduction Over Time

DisplaySearch forecasts a logarithmic decline in display component and manufacturing costs over time following the initial date of mass production for any given model. This cost reduction has the effect of closing the incremental cost gap between market available (i.e. representative and efficient) displays and

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[3] Each green, blue and red block is a subpixel that, when open, lets colored light out of the front of the display. Black areas are TFTs and structural material. The less space occupied by TFTs and structural material, the more light passes through the panel.

displays with maximum technology energy efficiency improvements, increasing cost effectiveness over time. Figure 5.5 shows the decrease in incremental cost between 2013 and 2016 for some of the efficiency measures for the 22” screen size.

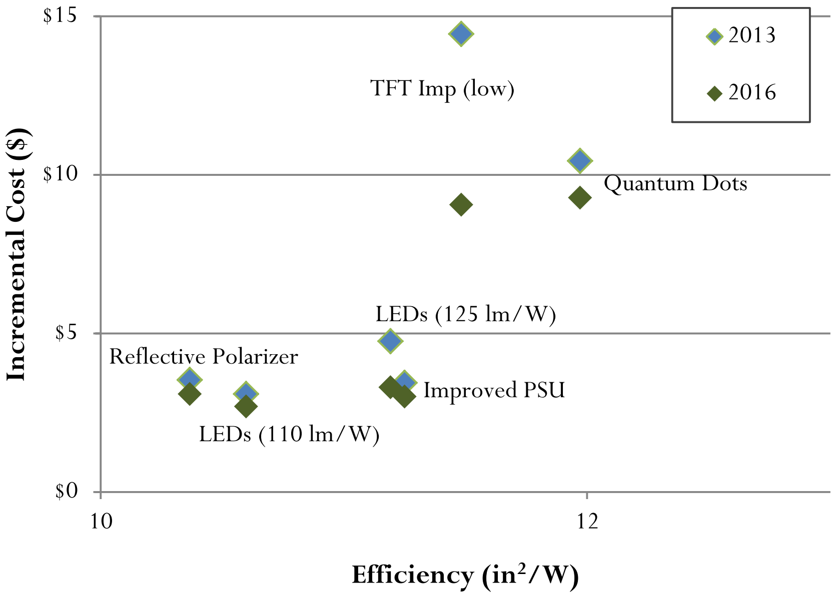

Figure 5.5 Incremental cost by efficiency measure showing the decrease in incremental cost from 2013 to 2016 for the 22” screen size

5.6 Cost-effective Approaches to Efficiency

The select individual efficiency measures described above were combined to generate four cost-effective measures for each size analyzed (Figure 5.6). The label PON_MAX denotes the maximum power draw for the four scenarios within each size group. To determine if a scenario was cost effective, the technical team calculated the lifetime energy savings of the modeled more efficient display over the representative model and compared that to the incremental cost of the efficiency improvement. Cost effectiveness was calculated using 2013 costs. As noted earlier (Section 5.5), costs generally decrease over time, making analyses of the same scenarios for future years result in even further cost effectiveness.

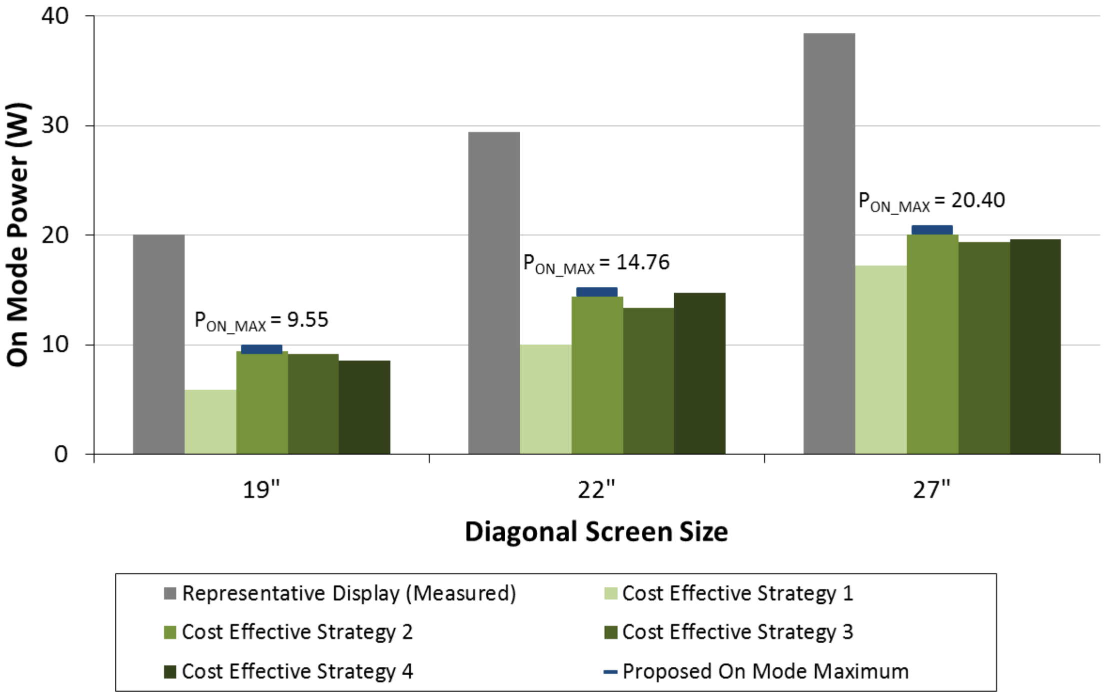

Figure 5.6 Cost-Effective Strategies – computer monitors. Representative display power measured in display's default luminance settings

Details regarding which efficiency measures we utilized for each scenario and the impact to on mode power draw are described in Table 5.4.

Table 5.4 Descriptions of Cost-Effective Strategies

Diagonal Screen Size	Representative Display (Measured)	Cost Effective Strategy 1	Cost Effective Strategy 2	Cost Effective Strategy 3	Cost Effective Strategy 4
19"	On Mode: 20.01W PSU: 80% Reflective Polarizer: None Lamp Efficacy (CCFL): 47lm/W Screen Brightness: 255 nits Global Dimming: None ABC: None	On Mode: 5.9W PSU: 88% Reflective Polarizer: Yes Lamp Efficacy (LED): 110lm/W Screen Brightness: 200 nits Global Dimming: Yes ABC: Yes	On Mode: 9.44W PSU: 88% Reflective Polarizer: None Lamp Efficacy (LED): 110lm/W Screen Brightness: 255 nits Global Dimming: Yes ABC: None	On Mode: 9.16W PSU: 88% Reflective Polarizer: None Lamp Efficacy (LED): 110lm/W Screen Brightness: 200 nits Global Dimming: None ABC: None	On Mode: 8.55W PSU: 83% Reflective Polarizer: Yes Lamp Efficacy (LED): 125lm/W Screen Brightness: 255 nits Global Dimming: None ABC: None
22"	On Mode: 29.42W PSU: 87% Reflective Polarizer: None Lamp Efficacy (LED): 105lm/W Screen Brightness: 275 nits Global Dimming: Not enabled by default ABC: None	On Mode: 13.78W PSU: 88% Reflective Polarizer: Yes Lamp Efficacy (LED): 110lm/W Screen Brightness: 200 nits Global Dimming: Enabled by default ABC: Yes	On Mode: 14.34W PSU: 87% Reflective Polarizer: None Lamp Efficacy (LED): 110lm/W Screen Brightness: 241 nits Global Dimming: Enabled by default ABC: None	On Mode: 13.33W PSU: 87% Reflective Polarizer: Yes Lamp Efficacy (LED): 105lm/W Screen Brightness: 241 nits Global Dimming: Enabled by default ABC: None	On Mode: 14.73W PSU: 87% Reflective Polarizer: None Lamp Efficacy (LED): 125lm/W Screen Brightness: 241 nits Global Dimming: Not enabled by default ABC: None
27"	On Mode: 38.38W PSU: 88% Reflective Polarizer: Yes Lamp Efficacy (LED): 87lm/W Screen Brightness: 400 nits Global Dimming: None ABC: None	On Mode: 17.25W PSU: 88% Reflective Polarizer: Yes Lamp Efficacy (LED): 110lm/W Screen Brightness: 170 nits* Global Dimming: Yes ABC: None Improved TFT (low)	On Mode: 20.04W PSU: 88% Reflective Polarizer: Yes Lamp Efficacy (LED): 107lm/W Screen Brightness: 170 nits Global Dimming: None ABC: Yes	On Mode: 19.36W PSU: 88% Reflective Polarizer: Yes Lamp Efficacy (LED): 110lm/W Screen Brightness: 170 nits Global Dimming: Yes ABC: None	On Mode: 19.62W PSU: 88% Reflective Polarizer: Yes Lamp Efficacy (LED): 107lm/W Screen Brightness: 170 nits Global Dimming: Yes ABC: None

5.7 Conclusion

Through the testing and teardown analysis of a series of representative computer monitors, the technical team was able to demonstrate multiple paths to cost effectively reduce energy use. Approaches include more efficient film stacks, improved lamp efficacy, reducing default screen brightness, improved power supply efficiency, more common implementation of automatic brightness control and dimming screen brightness to video content. The technical team also found emerging technologies such as improved TFT technology and quantum dots to be cost effective, however, with less confidence in cost and efficiency estimates, prevented them from being included in the final analysis.

The power draw measurements of computer monitors in their default settings versus the ENERGY STAR test procedure method of calibrating screen brightness to 200 nits showed significant differences. Assuming that most users will not calibrate their monitors to such a precise brightness level, this suggests that strong consideration should be given to measuring monitors in their default brightness setting to more accurately reflect actual energy use.

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