Innovations in Cost and Efficiency Analyses for Consumer Electronics: A Technical Analysis of Display Components and Features

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ABSTRACT

Consumer electronics comprise a rapidly evolving market sector with shorter product cycles and faster changes in cost and energy consumption compared with those of traditional appliances such as white goods and lighting. This fast pace of product development, along with the associated changing costs over time and changes in duty cycle, necessitates a new and refined approach to policy development and program design for consumer electronics. In our paper, we describe a recent engineering analysis for consumer electronics.

Engineering analyses provide information to researchers, efficiency program designers and policy makers about how current and emerging technologies are expected to affect costs, product cycles and energy efficiency. Using computer displays as a case study, we show how engineering analyses for consumer electronics differ from those for traditional appliances and how our updated reverse engineering studies yield information on costs and efficiency changes over time. New methods for analysis include developing detailed power budgets at the component level, linking these components to a cost forecast model and identifying innovative technologies and best practices.

There are significant cost effective energy savings to be had in displays such as computer monitors—up to 50% on-mode power draw reductions for the market-representative models we evaluate. Our investigation shows there are ways to reduce energy use through more efficient backlighting, film stacks, LCD panels and power supplies, and by optimizing light output. Additionally, we examine promising emerging technologies that could save additional energy in the near future.

Introduction

Energy efficiency policy development for appliances has traditionally relied on energy use trends over time coupled with assumptions of relatively static technologies with a limited number of components. Costs of appliances are also relatively steady. Consumer electronics, by comparison, have very short consumer product cycles requiring constant innovation to develop new features and technologies to persuade consumers to consistently replace products. Trends in manufacturing consumer electronics components usually involve rapid maturation, including reduction of materials and increased process efficiency. These factors often result in reduced costs over time for consumer electronics. Falling consumer prices require more detailed review of costs and efficiencies to develop effective policies and programs that yield substantial energy savings. The following engineering analysis is an example of such a study conducted by Ecova on behalf of the California investor owned utilities to inform the California Energy Commission's policy development for computer monitors.

The primary factors that influence the price of monitors are length of time on the market and the "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, backlight technology, and film stack enables a direct link of efficiency improvements to bill of materials (BOM) incremental cost. Applying markups to that BOM yields a consumer incremental cost, which is required to demonstrate cost effectiveness for efficiency improvements.

Our approach for investigating displays differs from that of other electronics such as computers. The components of a display are often 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

The technical team studied the performance of three pairs of computer monitors. For each pair, we selected two models utilizing the ENERGY STAR Qualified Product list (QPL)[1]: one to represent the energy efficiency of an average display a consumer might purchase, and the second the most efficient model currently available on the market. Considerations were also given to representing a range of major display manufacturers. To isolate differences in reported power draw 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 QPL. The test units were 19, 22, and 27 inches viewable diagonal screen size, to represent a range of display usage from typical office computing to video viewing and gaming. These sizes are also among the most popular sizes sold today and in the near future (IHS iSuppli 2012).

On mode power testing was completed according to the ENERGY STAR test method with the display in its as-shipped condition with all user configurable options set to factory settings for default mode. The team also tested optional picture modes in default settings and with other picture features enabled to determine the relationship between non-default settings and power draw.

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 BOM 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)[2], and the panel drive electronics.[3]

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[1] This project was completed in two phases - one monitor pair's selection was based on an ENERGY STAR Qualified Product list from October, 2012, and the other pairs' selections were based on a list from January, 2013.

[2] For LCD displays, the backlight unit consists of the lamps and films needed to produce light that subsequently pass through the LCD panel to create an image.

[3] Panel drive electronics include the electronics required to interpret video signals and operate the opening and closing of pixels within the LCD panel.

We collected the following information:

- Detailed power budget: In-circuit power measurements were made using a multi-channel power meter spliced into the power distribution circuits of the display under test. See Figure 1 for a diagram of the components measured. Power measurements were made using the IEC video and Internet test clips such that the BLU, LCD panel and controller, main processor board (e.g. sensors, keypads, audio), and power supply losses could be measured separately.
- Film characterization: Identification of film types and the number of films in the stack[4].
- 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 has 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.
- Lamp count: The number and size of the LEDs in the display were recorded.
- 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).

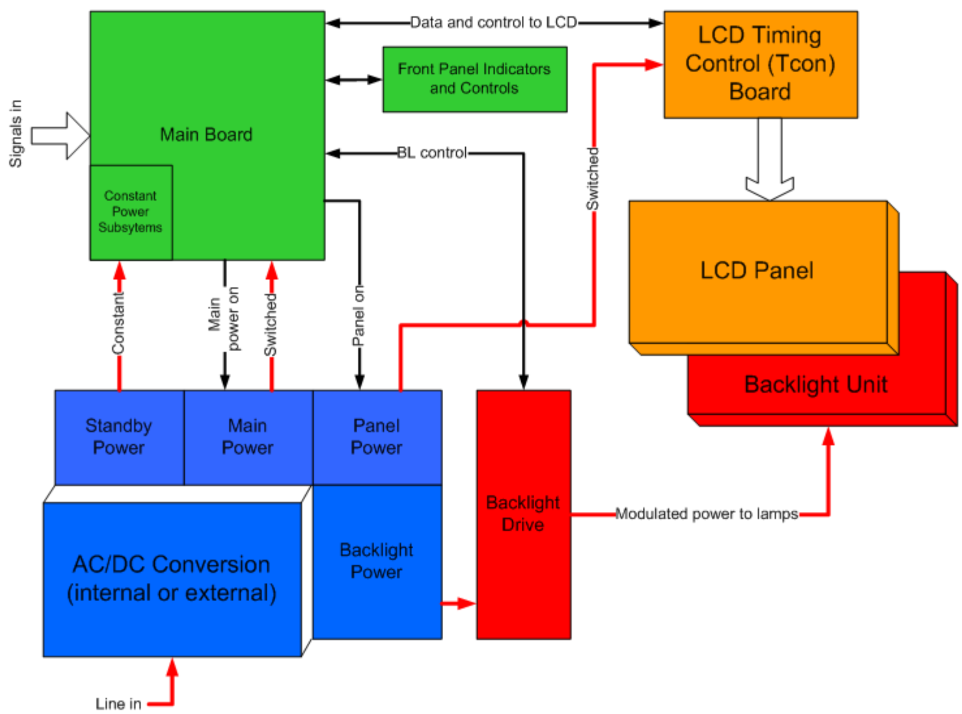

Figure 1. Electronic block diagram of a typical LCD display.

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

[4] LCD displays require a series of films to properly diffuse and direct light coming from the light source so that the viewer sees the video image with the overall brightness, consistency of brightness across the screen and from the range of viewing positions that the manufacturer intends.

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 in 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 (DisplaySearch 2013b), which also included the panel glass, polarizers, liquid crystals, drivers, inverters or LED controllers, and printed circuit boards (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, other electronics, and PCBs (DisplaySearch 2013c). The technical team then used the resulting BOM costs with a 30% 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 were 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.

Test Results and Analysis

Displays were shipped with a range of screen luminance values, resulting in a wide range of power draw values. For example, Table 1 shows that the market 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 18.8 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 with its default mode power.

Table 1. As-assembled power and luminance test results for 22” displays

Display ID	Test description	Display mode	Screen luminance[5] (cd/m^2)	Power (W)
D22-1 Representative	Default	Standard	275.4	28.4
	Default	ECO Optimize	202.8	23.1
	Default	ECO Conserve	129.6	17.2
	Dynamic Contrast enabled	Standard	184.0	18.4
	ENERGY STAR: calibrated luminance	Standard	202.5	22.5
	Max brightness	Standard	284.8	28.7
	Sleep (sleep signal source)	Standard		0.3
	Sleep (disconnect signal source)	Standard		0.3
	Auto-Power down enabled	Standard		0.2
D22-2 Efficient	Default	Standard	241.0	18.8
	Default	Scenery	225.0	18.4
	Default	Theater	220.0	18.3
	Default	Game	233.0	18.3
	Default	Night View	226.0	18.3
	Default	sRGB Mode	173.0	15.6
	ENERGY STAR: calibrated luminance	Standard	201.0	16.8
	Max brightness	Standard	247.0	18.6
	w/ Smartview enabled	Standard	245.0	18.3
	w/ ASCR enabled	Scenery	241.0	19.0
	w/ ECO Mode	Standard	167.0	15.1
	Sleep (sleep signal source)	Standard		0.2
	Sleep (disconnect signal source)	Standard		0.2
	Off	Standard		0.1

Figure 2 shows power draw and screen luminance (measured in candelas per square meter) for all test units in their various settings. This demonstrates that average power consumption increases approximately linearly with screen luminance. It also 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 with screen brightness, when the display is showing a picture.

[5] Screen luminance is measured using the IEC static 3-Bar pattern, while power is measured using the IEC video test clip (IEC 2011).

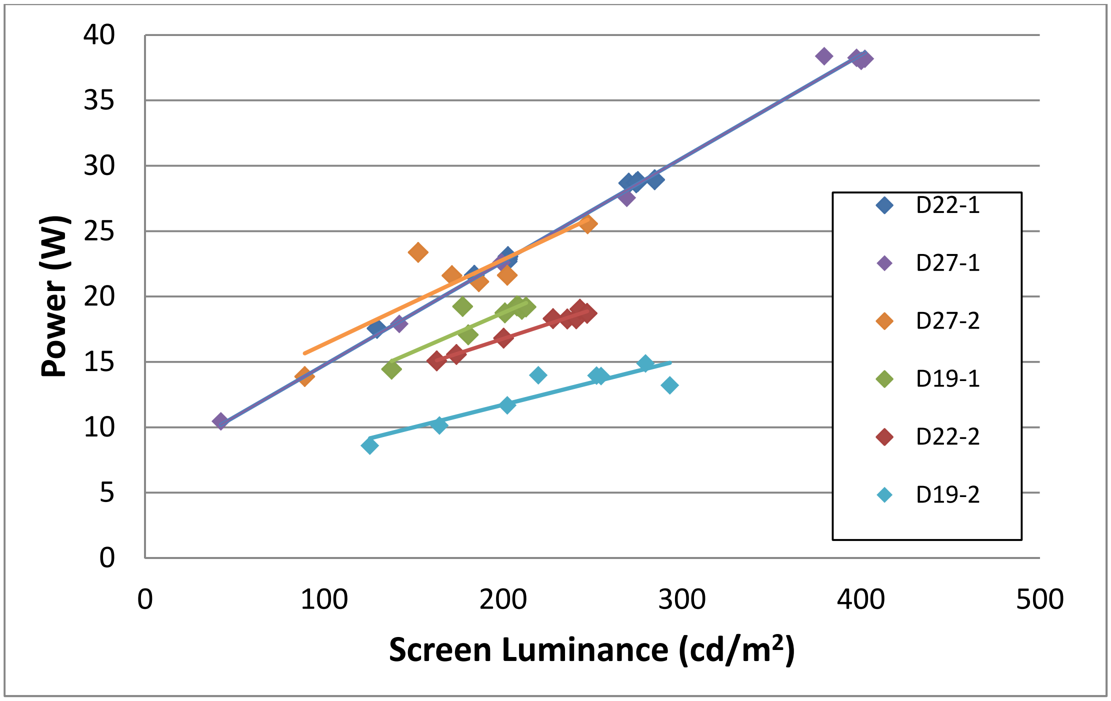

Figure 2. Screen luminance versus power for the representative and efficient test units (lines are linear fits to the data).

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.

Instantaneous power measured during the test clips shows how power of the backlight and other components scale to the content displayed. For example, Figure 3 shows power logs for the 22" 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. We define power scaling mode as a setting in which the unit shows reduced average power draw such as in an "eco" or other setting. When available, we select a setting that increases or decreases the monitor's backlight power according to the brightness of the content on the screen. This is also known as dynamic contrast. Later, in Figure 4, this is referred to as "Dimming to Content."

In its default mode, backlight unit power of the 22" representative model was constant; it did not scale power to picture content (Figures 3A 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 (Figures 4.4C and D, top row).

The backlight power of the 22" efficient model similarly did not scale to content in default mode (Figure 3A 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 3C, 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 3D, bottom row).

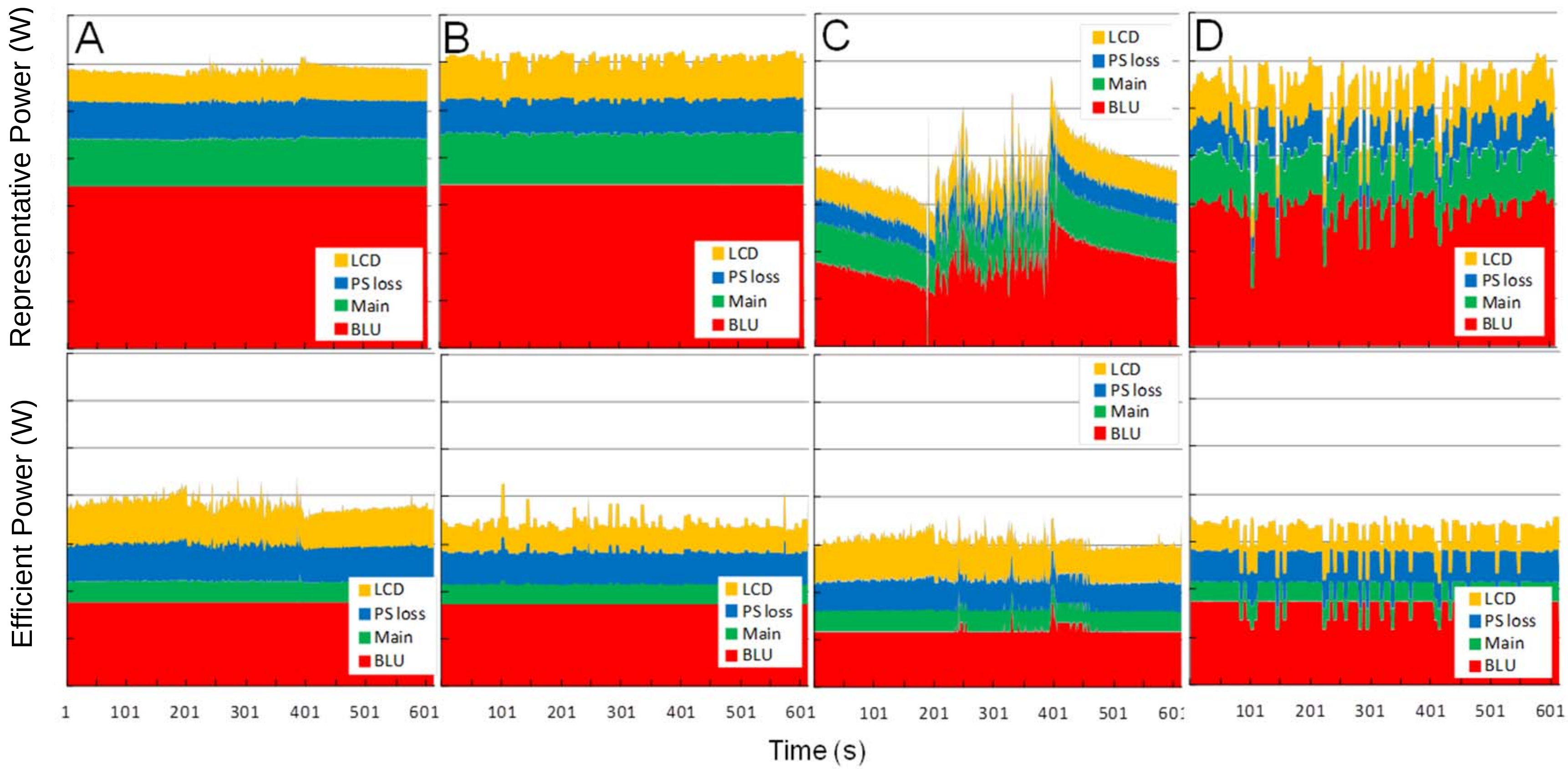

Figure 3. Instantaneous power over the 10 minute IEC test clip for the representative (D22-1, top row), and efficient (D22-2, bottom row) models. (A) IEC video test clip, default mode (B) IEC Internet test clip, default mode (C) IEC video test clip, power scaling mode (D) IEC Internet test clip, power-scaling mode.

As mentioned in the methodology section, we also measured power supply efficiency, lamp efficacy, number of lamps, backlight unit efficiency, and LCD panel transmissivity for all six monitors. Table 2 summarizes those results.

Table 2. 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

19” Pair. The efficient display was equipped with LED backlighting while the representative display used CCFLs. This is the key factor 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 – measured at 69 lumens/watt while the LEDs measured from other displays averaged more than 100 lumens/watt. Additionally, the efficient display’s default screen brightness was approximately 20% higher than the representative model, making its out-of-the-box power draw higher than it would be if its luminance was set to the same level as the representative display.

22” Pair. Although the efficient display was overall more efficient than the representative model, the representative model had 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 highly efficient LEDs, 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 significantly (Green Tech World 2010).

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 very similar power supply efficiencies. 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 draw 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 cd/m^2 vs. 170 cd/m^2 for the efficient display).

Cost Efficiency Analysis

Through the identification of best practices found from the results, above, along with industry research, we calculated the incremental cost between each market representative test unit and individual improvements in efficiency. A summary of the sources of our calculations are listed in Table 3, below.

Table 3. Source of efficiency improvements and costs

Efficiency improvement	Source of efficiency improvement	Source of cost estimates calculation
LED efficacy	Measured best practice, market trends, and industry expert estimates	Discussions with industry experts, based on DisplaySearch costs
Calibrate brightness to 200 nits	Measured power at 200 nits	No cost
Dimming to content	Measured best practices	Consultation with industry experts
Improved PSU	Measured best practice	Consultation with industry experts
Reflective polarizer	Component manufacturer estimates for BLU improvements (HDTVExpert.com 2012) (Green Tech World 2010)	Based on data supplied by DisplaySearch's BLU Cost Model (DisplaySearch 2013a)
Automatic brightness control[6]	Measured best practice, DOE test data (DOE 2012)	Conversations with sensor manufacturers

In addition to the measures shown above, we examined the incremental savings and costs for several emerging technologies including OLED, improved thin film transistors (TFTs) and quantum dots (Donnelly, Dayem, and Trimboli 2013). We did not include these in our cost effective strategies (next section) as there was less confidence in the cost and efficiency estimates. However, we analyzed these emerging technology options for each size and found at least one cost effective option for each. This is significant given likely future cost reductions would create even greater energy efficiency improvements in the coming years.

Using the 22" pair as an example, Figure 4 illustrates the relationship between incremental consumer cost (incremental BOM costs with retail markup) and efficiency for both test units, as well as several improved technology scenarios that increase display efficiency.

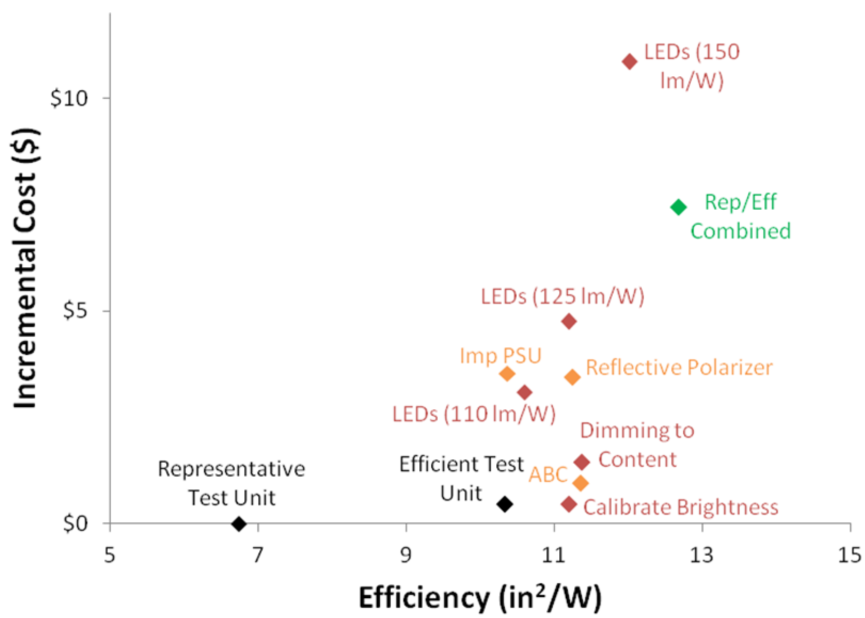

Figure 4. 22" computer display incremental consumer cost in 2013 shown as a function of efficiency for both test units (representative and efficient) as well as various improved technology scenarios.

[6] Automatic brightness control (ABC) is a feature that reduces the display's backlight in dark conditions and increases it in bright conditions. This reduces the contrast between the room and the screen for the viewer, reducing eye strain and often saving power in non-office settings where room illumination is typically lower.

The representative and efficient displays are shown in black. Improved technology scenarios involving improved LED efficacy and reduction of backlight output are shown in red. The addition of a more efficient power supply unit (PSU) and a reflective polarizer as well as the implementation of ABC are shown individually in orange. 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.

Cost Effective Approaches to Efficiency

We combined select individual efficiency measures (22” test units’ measures shown in Figure 4, other test units’ measures are not shown but are similar) to generate four cost effective measures for each size analyzed (Figure 5). 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 with 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.

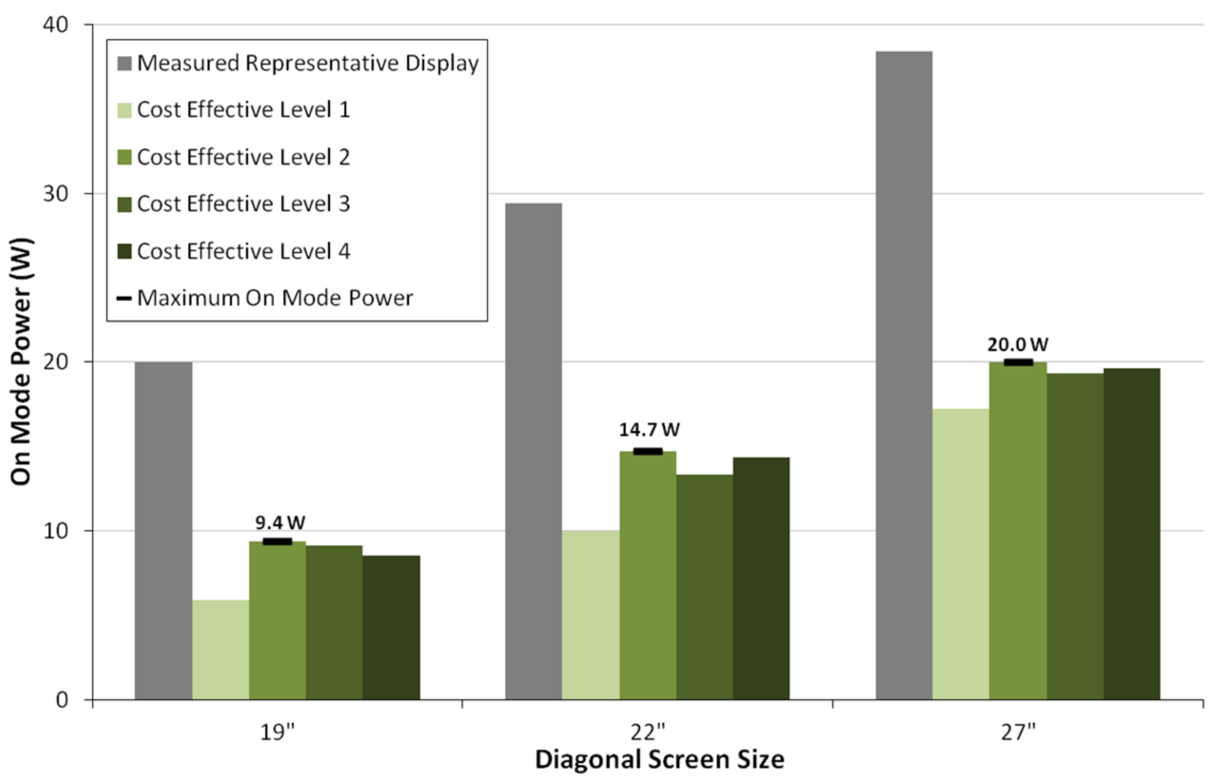

Figure 5. Cost effective strategies for computer monitors – representative display power was measured in display’s default luminance settings.

Details regarding which efficiency measures we utilized for each scenario and the impact to on mode power draw are described in Table 4.

Table 4. Description of cost effective strategies

Diagonal Screen Size	Baseline Model Attributes	Cost effective strategy 1	Cost effective strategy 2	Cost effective strategy 3	Cost effective strategy 4
19"	On mode: 20.0 W PSU: 80% Reflective polarizer: none Lamp efficacy (CCFL): 47 lm/W Screen brightness: 255 cd/m^2 Global dimming: none ABC: none	On mode: 5.9 W PSU: 88% Reflective polarizer: yes Lamp efficacy (LED): 110 lm/W Screen brightness: 200 cd/m^2 Global dimming: yes ABC: yes	On mode: 9.4 W PSU: 88% Reflective polarizer: none Lamp efficacy (LED): 110 lm/W Screen brightness: 255 cd/m^2 Global dimming: yes ABC: none	On mode: 9.2 W PSU: 88% Reflective polarizer: none Lamp efficacy (LED): 110 lm/W Screen brightness: 200 cd/m^2 Global dimming: none ABC: none	On mode: 8.6 W PSU: 83% Reflective polarizer: yes Lamp efficacy (LED): 125 lm/W Screen brightness: 255 cd/m^2 Global dimming: none ABC: none
22"	On mode: 29.4 W PSU: 87% Reflective polarizer: none Lamp efficacy (LED): 105 lm/W Screen brightness: 275 cd/m^2 Global dimming: not enabled by default ABC: none	On mode: 13.8 W PSU: 88% Reflective polarizer: yes Lamp efficacy (LED): 110 lm/W Screen brightness: 200 cd/m^2 Global dimming: enabled by default ABC: yes	On mode: 14.7 W PSU: 87% Reflective polarizer: none Lamp efficacy (LED): 125 lm/W Screen brightness: 241 cd/m^2 Global dimming: not enabled by default ABC: none	On mode: 13.3 W PSU: 87% Reflective polarizer: yes Lamp efficacy (LED): 105 lm/W Screen brightness: 241 cd/m^2 Global dimming: enabled by default ABC: none	On mode: 14.3 W PSU: 87% Reflective polarizer: none Lamp efficacy (LED): 110 lm/W Screen brightness: 241 cd/m^2 Global dimming: enabled by default ABC: none
27"	On mode: 38.4 W PSU: 88% Reflective polarizer: yes Lamp efficacy (LED): 87 lm/W Screen brightness: 400 cd/m^2 Global dimming: none ABC: none	On mode: 17.3 W PSU: 88% Reflective polarizer: yes Lamp efficacy (LED): 110 lm/W Screen brightness: 170 cd/m^2 Global dimming: yes ABC: none Improved TFT	On mode: 20.0 W PSU: 88% Reflective polarizer: yes Lamp efficacy (LED): 107 lm/W Screen brightness: 170 cd/m^2 Global dimming: none ABC: yes	On mode: 19.4 W PSU: 88% Reflective polarizer: yes Lamp efficacy (LED): 110 lm/W Screen brightness: 170 cd/m^2 Global dimming: yes ABC: none	On mode: 19.6 W PSU: 88% Reflective polarizer: yes Lamp efficacy (LED): 107 lm/W Screen brightness: 170 cd/m^2 Global dimming: yes ABC: none

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 thin film transistor technology and quantum dots to be cost effective. However, lower 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.

Simply measuring overall plug loads of monitors does not allow for this level of detail and insight into what efficiency improvements are possible. By examining consumer electronics at the component level, we can understand what subsystems significantly contribute to the overall power draw of a device. In the example of computer monitors, we show that by simply implementing existing industry best practices for power supply efficiency, LED efficacy, scaling the backlight to screen content (dimming), and optimizing the film stack, overall power draw can be reduced by 50%.

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