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Efficiency Improvement Opportunities for Personal Computer Monitors: Implications for Market Transformation Programs

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Abbreviations and Acronyms

ABC	automatic brightness control
AC	alternating current
AM	active matrix
AIO-LCD	all-in-one computer with liquid crystal display
BAU	business as usual
CCE	cost of conserved electricity
CCFL	cold cathode fluorescent lamp
CES	Consumer Electronics Show
CRT	cathode ray tube
DBEF	Dual Brightness Enhancement Film
DC	direct current
DVI	digital video interface
EPA	Environmental Protection Agency
EU	European Union
HDMI	high definition multimedia interface
IC	incremental cost
ICT	information and communications technology
IPS	in-plane switching
LCD	liquid crystal display
LED	light emitting diode
MEPS	minimum energy performance standards
OEM	original equipment manufacturer
OLED	organic light emitting diode
PC	personal computer
PDP	plasma display panel
PM	passive matrix

SEAD	Super-efficient Equipment and Appliance Deployment
TFT	thin film transistor
TN	twisted nematic
TWh	terawatt-hours
UEC	unit energy consumption
US DOE	United States Department of Energy
USB	universal serial bus
VA	vertical alignment
VGA	video graphics array
W	watt

Abstract

Displays account for a significant portion of electricity consumed in personal computer (PC) use, and global PC monitor shipments are expected to continue to increase. We assess the market trends in the energy efficiency of PC monitors that are likely to occur without any additional policy intervention and estimate that display efficiency will likely improve by over 40% by 2015 compared to today's technology. We evaluate the cost effectiveness of a key technology which further improves efficiency beyond this level by at least 20% and find that its adoption is cost effective. We assess the potential for further improving efficiency taking into account the recent development of universal serial bus (USB) powered liquid crystal display (LCD) monitors and find that the current technology available and deployed in USB powered monitors has the potential to deeply reduce energy consumption by as much as 50%. We provide insights for policies and programs that can be used to accelerate the adoption of efficient technologies to capture global energy saving potential from PC monitors which we estimate to be 9.2 terawatt-hours [TWh] per year in 2015.

I. Introduction

The total global electricity consumption of personal computer (PC) and monitor stocks, including notebook computers, in the residential sector was estimated to be about 140 terrawatt hours [TWh] in 2008 (IEA 2009). Average unit energy consumption (UEC), of a PC varies highly with the specification and power management scheme applied to the system. Among key PC components, displays are responsible for the largest single portion of energy consumption in a PC system, accounting for 15-35% of the system's consumption (IVF 2007, IEA 2009, Delforge 2011, Horowits 2011).

An assessment of efficiency improvement opportunities in PC monitors is needed for two reasons. First, because the literature on the topic is limited and was published before the ongoing large scale transition from cold cathode fluorescent lamp (CCFL) backlit liquid crystal display (LCD) to light emitting diode (LED) backlit LCD monitors (likely at least 50% and 90% of the PC monitor shipments in 2012 and 2015 respectively). The applicability, the effect on energy consumption, and the cost effectiveness of some of the key efficiency improvement options is different for LED backlit LCD monitors compared to CCFL backlit LCD monitors and hence needs to be assessed. Second, no literature exists on the cost effectiveness of specific efficiency improvement options in LCD monitors. A recent study of this topic is the EuP Preparatory Study[1] *"Personal Computers and Computer Monitors"*(IVF 2007), which studies the following: market assessment, best available technologies, efficiency improvement potential, life cycle cost-effectiveness, and energy consumption scenarios. However, at the time the EuP study was prepared, LED backlighting was not yet mature enough to be thoroughly analyzed. Also, specific technology options within backlighting technologies were not discussed. Although other recent studies (IEA 2009, ACS 2010) addressed computer energy efficiency and consumption issues, those studies were primarily focused on computer sets, including displays, and also conducted before LED backlights began accelerated penetration into the market.

In this paper, we assess recent technology trends and their impact on the energy efficiency of PC monitors. We also assess technologies that can improve the efficiency of PC monitors beyond this trajectory in a cost-effective manner, and provide insights on policies that can accelerate their adoption. We focus on efficiency improvement options that are technically feasible, practical to manufacture, and therefore could be realized in the short term (over the next two or three years). We obtained the data for this paper primarily from the following sources: a review of the literature including technical reports, DisplaySearch reports[2], the ENERGY STAR data base, international conferences, and technical exhibitions

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[1] In 2005, the European Community adopted the Eco-design framework Directive which empowers the European Commission to set up Eco-design requirements for energy-using products (EuP). Implementing measures are preceded by preparatory studies conducted by external experts.

[2] DisplaySearch has been providing reliable information and analyses on the display market and related industries. This is one of key sources of market intelligence that the display industry itself relies on. For PC monitors, DisplaySearch provides quarterly-updated global/regional PC monitor shipment data; analysis of the display market and technology trends; and PC monitor manufacturing costs and average market prices.

along with interviews with manufacturers and experts in the field[3].

Information and communications technology (ICT) appliances such as desktop PCs, laptops and monitors are internationally traded, used in a similar manner globally and subject to internationally recognized energy efficiency specifications such as ENERGY STAR (Waide 2011). Hence the results of this analysis are likely to be useful for several countries (see Section II for details).

The remainder of this paper is organized as follows: In *Section II,* we present an overview of the PC monitor market, technology trends, and energy consumption. In *Section III,* we assess technologically feasible energy-efficiency improvement options, adoption trends of such options, and the impact of these options on energy consumption of PC monitors. We also review recent developments in highly efficient USB powered monitors. In *Section IV,* we present the cost-effectiveness analysis for a selected technology option, and in *Section V and VI,* we offer suggestions for accelerating the adoption of efficient technologies and estimate the corresponding global energy savings potential.

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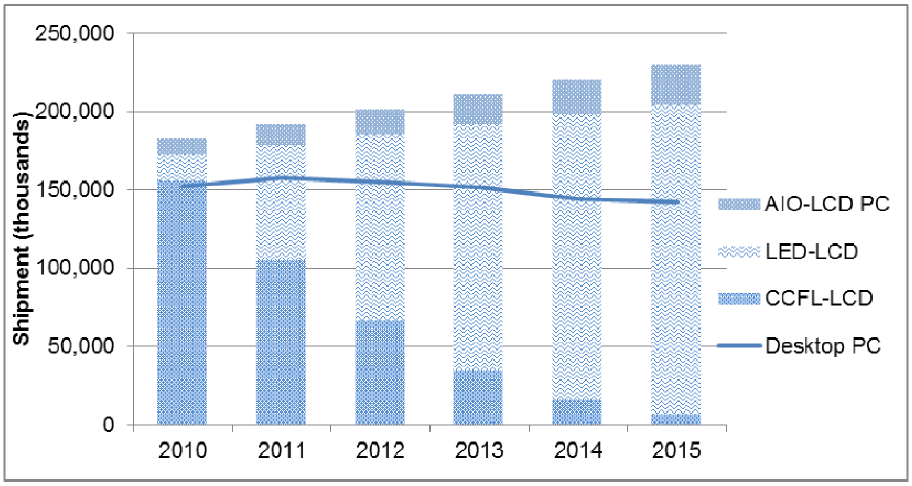
[3] The data used in this paper meet ENERGY STAR Displays Specification Version 5 which went into effect on October 30, 2009. Although ENERGY STAR-registered products typically represent energy-efficient models in the market, the consumption of ENERGY STAR products as of September 2011 can be regarded to represent majority of the market at that time. See the discussion under the subsection *PC Monitor Energy Consumption* in Section II for details.

II. Overview of PC Monitor Market and Energy Consumption

Since the early-2000s, the global PC monitor market has undergone a major transition from traditional CRTs to LCDs (IEA 2009, DisplaySearch 2011a). No CRT monitor shipments have been reported since 2010.[4]

As shown in Fig. 1, global PC monitor shipments are expected to experience a continual growth through 2015 and reach 230 million units, including all-in-one PCs, in 2015 (DisplaySearch 2011a). A large-scale transition is also ongoing and expected to continue from CCFL backlit LCDs (CCFL-LCDs) to LED backlit LCDs (LED-LCDs), resulting in further substantial improvements in efficiency. Fig. 1 also illustrates DisplaySearch's forecast that LED backlights will capture more than 80% of the global PC monitor shipment from 2013 onward.

Desktop PC shipment is expected to either stabilize just over 150 million units or decrease slightly from this level from 2011 onward. However, stand-alone PC monitor purchase is expected to continue to increase through 2015 driven by upgrades, increased adoption of larger screen sizes, use with notebook computers, or dual monitor use. (DisplaySearch 2011a, Alexander 2010).



AIO-LCD PC (all-in-one computer with LCD monitor)
Organic light emitting diode (OLED) monitors are expected to reach 0.4 million units in 2015
Source: DisplaySearch 2011a

Fig. 1 Forecasts of Global PC Monitor Shipment

Although 17- to 19-inch monitors are currently dominant in the market, manufacturers and DisplaySearch expect the share of 20- to 23-inch monitors to increase from 37% in 2010 to over 60% in 2015 (see Fig. 2). The further increase in monitor screen size is not likely to be significant, because the limited space and viewing distances at desks act as a limiting factor

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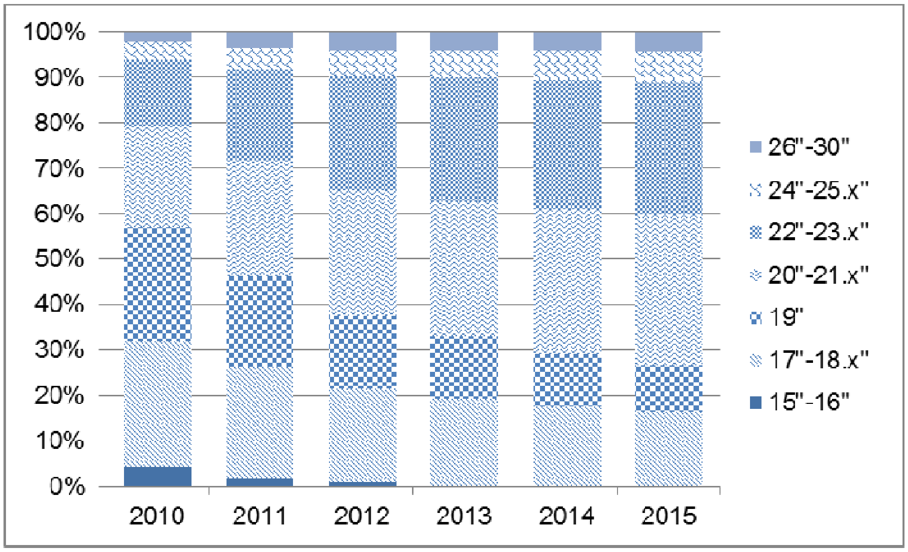
[4] Global CRT monitor shipment in 2009 was only 1.2 million units which accounted for 0.7% of total PC monitor shipments in 2009 (DisplaySearch 2011a).

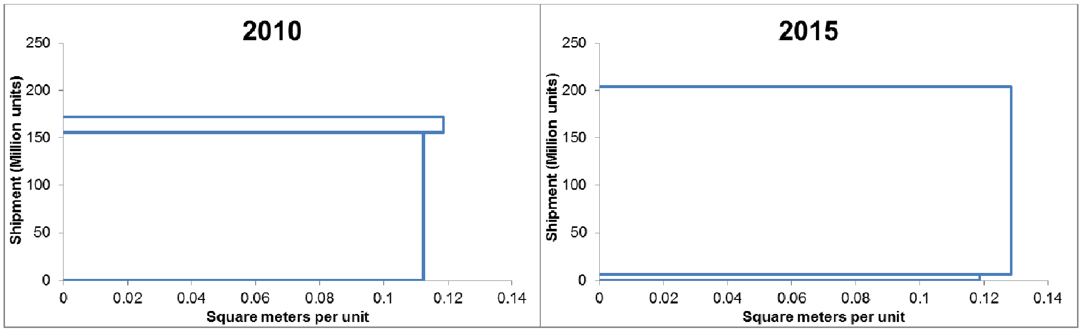
on screen size.



Source: DisplaySearch 2011a

Fig. 2 Global PC Monitor Shipment Distribution by Screen Size

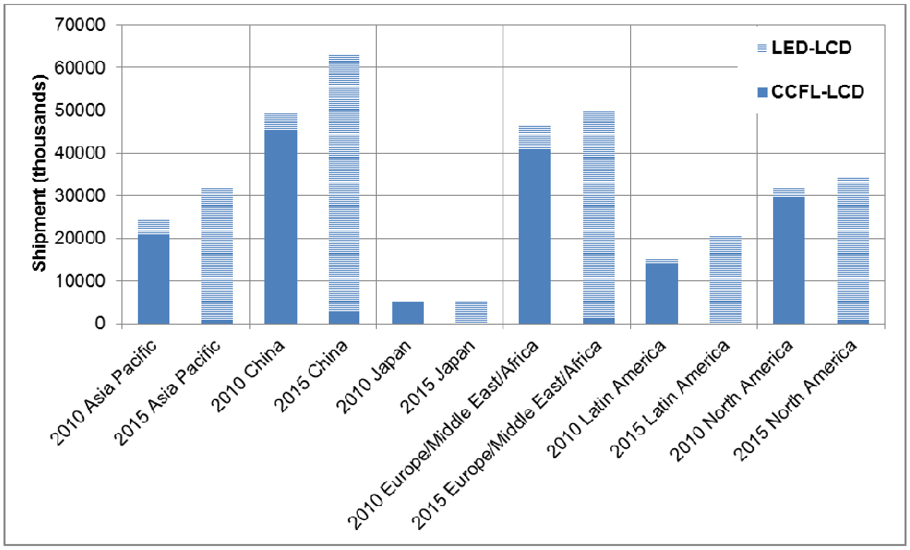
From 2010 to 2015, the average screen size (measured diagonally) and total annual shipments are projected to increase by 7% and 19% respectively, leading to a 35% increase in the aggregate screen area of annual PC monitor shipments. Fig. 3 shows the average monitor screen area per unit and global shipment for 2010 and 2015, as well as the expected transition from CCFL backlight to LED backlights in terms of shipments and screen area.



Authors' calculation from DisplaySearch 2011a

Fig. 3 Global Monitor Annual Shipments and Total Screen Area (2010 vs 2015)

There are only limited regional differences and significant global similarity in LCD and backlight technology (see Fig. 4). In addition, the top five global brands (Samsung, Dell, LG, HP, and Acer) and the top five original equipment manufacturers (OEMs) (Samsung, LG, TPV, Chimei, and Qisda) account for more than 50% and 80% respectively of the global PC monitor market (DisplaySearch 2011a). Hence, our analysis does not consider separate efficiency options and costs for different regions of the world, and the research presented in this paper is applicable to PC monitors in most countries.



Source: DisplaySearch 2011a

Fig. 4 Forecast of Market Transition by Region and Screen Technology

PC Monitor Energy Consumption

To estimate the energy consumption of PC monitors, we use the database of PC monitors registered in 2011 under ENERGY STAR Version 5. The rate of LCD monitor technology improvement is evident from the fact that even though the Version 5 specifications for displays went into effect in October 2009, the market penetration rate of ENERGY STAR-registered LCD monitors during 2009 was already 90%[5] (ENERGY STAR 2009). One year after the introduction of Version 5 specifications, the ENERGY STAR compliance of the whole market was 43% and is estimated to be about 80% in 2011 (ENERGY STAR 2010, ENERGY STAR 2012b). Further, non-registration of PC monitors with ENERGY STAR does not necessarily imply that such monitors do not meet ENERGY STAR specifications. A test performed by the U.S. Environmental Protection Agency (US EPA) during 2008-2009 on a sample of 10 monitors showed that 8 of the 10 of tested non-ENERGY STAR computer monitors met the then applicable ENERGY STAR version 4 criteria and performed similarly to tested ENERGY STAR registered models (US EPA 2009). The European Union (EU) region has also been experiencing similar trends of market compliance of ENERGY STAR PC monitors (IDC 2010, EC 2011). Table 1 summarizes the market compliance of ENERGY STAR PC monitors for the US and EU regions.

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[5] Since the new specification, i.e., Version 5, was updated during 2009, the shipment data used for calculating market compliance may have comprised a blend of products qualified under the old and new specifications (ENERGY STAR 2009).

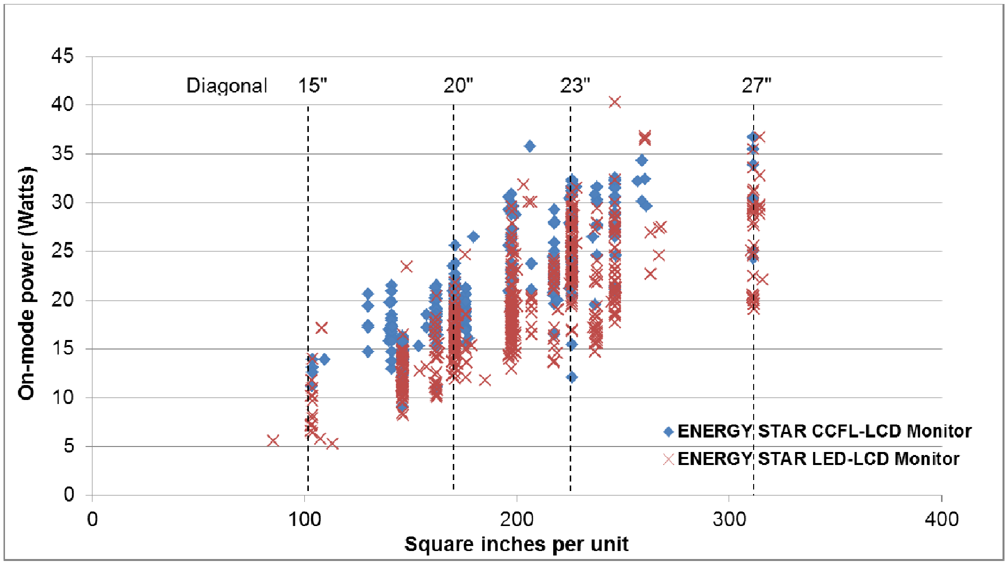
Table 1 Market Penetration of ENERGY STAR PC Monitors

	2009	2010	2011
Applicable Version of ENERGY STAR	Version 4 (Jan-Sep) Version 5 (Oct-Dec)	Version 5	Version 5
US	90%	43%	~80%[a]
EU	75% (1st half) 49% (2nd half)	60-70% [b]	70-80% [c]

[a, b, c] Authors' estimates based on the below sources
Source: Energy Star 2009, 2010, 2012b, EC 2011, IDC 2010

In addition, major brands distribute similarly designed PC monitors across many regions to capitalize on economies of scale. For example, as of August 2011, 89% of Samsung's LCD monitors on the global market, which represent the highest share (~15%) of the market, have met the ENERGY STAR Version 5 (Samsung Electronics 2011). Thus, given that the top five brands and the top five OEMs dominate the global PC monitor market, accounting for more than 50% and 80% respectively, the power consumption of ENERGY STAR PC monitors is likely to be representative of average models on the global market.

A 20-inch ENERGY STAR-registered LCD monitor consumes 10-25 W in on-mode (ENERGY STAR 2011a), while LED-LCD monitors are on-average more efficient than CCFL-LCD monitors by about 10-30% (see Fig. 5 and Table 2).



Source: ENERGY STAR 2011a

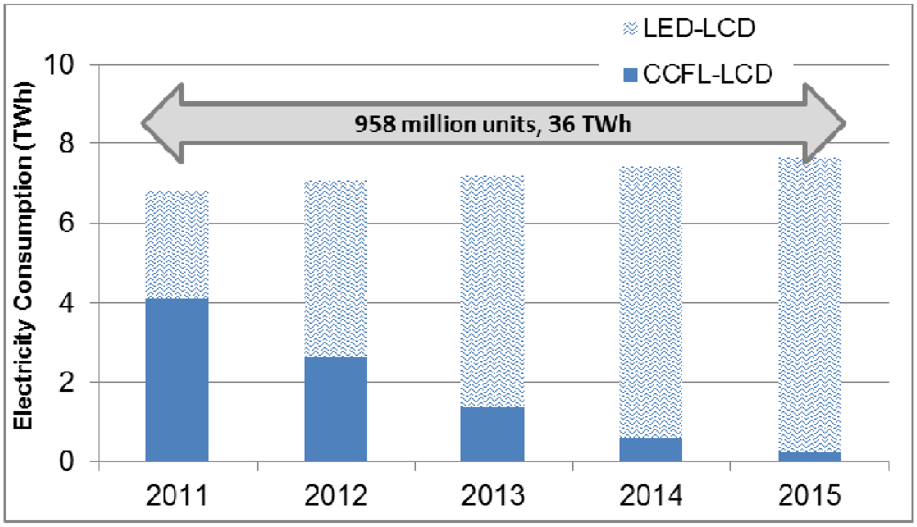
Fig. 5 LCD Monitor Power Consumption vs. Screen Size

Table 2 On-mode Power per Screen Area by Backlight

	Average	Min	Max
CCFL-LCD	0.111	0.053	0.174
LED-LCD	0.093	0.047	0.164

*unit: watts per square inch
Source: ENERGY STAR 2011a

CCFL- and LED-LCD monitors consume 0.111 watts [W] and 0.093 W per square inch respectively. Assuming all monitors consume about 0.5 W in sleep-mode[6], and assuming a daily usage of 5 hours at on-mode and 19 hours at sleep-mode (see Section IV-c), the annual electricity consumption contributed by monitors shipped globally in 2011 is about 6.8 TWh. If efficiency is frozen at 2011 levels, the annual electricity consumption contributed from 2015 global monitor shipment will increase to 7.6 TWh, even though the share of LED backlights is expected to significantly increase, because of increased sales and increased screen size. Fig. 6 shows PC monitor energy consumption contributed from annual global shipments.



Source: ENERGY STAR 2011a, DisplaySearch 2011a (no efficiency improvement assumed.)

Fig. 6 Estimated PC Monitor Energy Consumption from Annual Shipment

In the next section, we assess options to improve the energy efficiency of PC monitors, trends in their adoption, and their impact on energy consumption.

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[6] Most recent PC monitors consume less than 1 W in standby mode, since many major economies have been adopting "1-W Policy" since the International Energy Agency (IEA) proposed in 1999 that all countries harmonize energy policies to reduce standby power, setting the target of a maximum of 1 Watt per device. The mean value of ENERGY STAR qualified monitors used in the report is 0.4 W in sleep mode and 0.3 W in off mode. According to the results from Standby and Off-mode Energy Losses In New Appliances Measured in Shops (SELINA) project in EU, the mean values of off and standby modes power consumption in 2009-2010 are 0.50 and 0.60 W, respectively (Silva et al 2010).

III. Efficiency Improvement Options and Related Trends for PC Monitors

This paper focuses on efficiency improvement options for LCD monitors because LCD monitors are expected to continue to dominate worldwide sales, amounting to an expected 99% of global PC monitor shipments by 2017 (DisplaySearch 2011a).

An LCD, unlike other self-emissive flat-panel[7] displays such as plasma display panel (PDP) and OLED, is a non-emissive display that uses a backlight, e.g., CCFL or LED, as a light source. An LCD is made up of millions of pixels consisting of liquid crystals (LCs) that can alter their crystalline orientation when voltage is applied, resulting in different transparency levels. The light from the light source first passes through a polarization film, gets modulated by the LCs, and appears as a red, blue, or green pixel after passing through a color filter (IZM 2007 Task 4). Thin Film Transistor (TFT) technology[8] on glass is used to drive or control the orientation of the LCs, i.e., pixels. Fig. 7 shows a typical LCD structure.

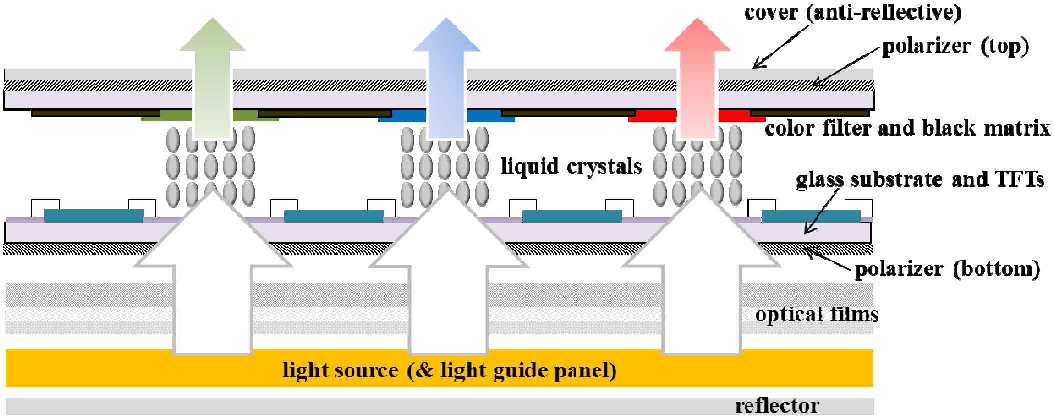

Fig. 7 Typical Structure of a Liquid Crystal Display (LCD)

When viewed in terms of change in luminance (cd/m^2) as light travels through the LCD screen, LCDs' overall efficiency appears to have significant further potential for improvement. The final luminance delivered out of the LCD is generally less than 10% of the initial luminance coming out of the backlight unit, because two crossed polarizers, a color filter, and TFT arrays in the LCD panel absorb a significant amount of light from the backlight unit (Shieh et al. 2009, Park et al. 2011). The required backlight luminance is therefore highly sensitive to the panel transmittance and optical film efficiency, making even small improvements in these yielding large payoffs in terms of required luminance and therefore

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[7] The term "panel" generally refers to the entire assembly of layers, excluding electronics such as the drive circuit, the image circuit and the power supply unit.

[8] TFT is a transistor whose electrical current-carrying layer is a thin film, usually made of silicon. In general, as active matrix (AM) displays can independently control each pixel by TFTs, AM displays show higher-quality performance than passive matrix (PM) displays which use an X and Y grid to operate a pixel.

overall efficiency. For example when panel transmittance improves from 7% to 8% required backlight luminance drops by about 13%.

Efficiency Improvement Options and Trends

Efficiency improvement options which also lead to concurrent improvement in other desirable product characteristics (e.g. LED backlighting leads to thinner/lighter monitors and better picture quality such as color reproduction capability and contrast ratio) or lead to reduction in overall costs (e.g. high transmittance LCD panels require fewer optical films or backlight lamps) - are more likely to be adopted on their own without additional policy intervention compared with options which predominantly improve efficiency. This is also aided by the fact that electricity costs for PC monitors and corresponding savings from efficiency improvement are a relatively minor component of the total costs over the lifecycle of the monitor. Thus efficiency is unlikely to be a major consideration in price-sensitive consumer's selection of PC monitors.[9] Although we assess several efficiency improvement options and analyze their impact on PC monitor electricity consumption, we limit our analysis of cost-effectiveness to those options which are unlikely to be adopted on their own since they do not directly lead to improvement in other desirable characteristics of PC monitors. Table 3 summarizes LCD monitor efficiency-improvement options which are also discussed in further detail below:

Table 3 LCD Monitor Efficiency Improvement Options

Components		Improvement options	Notes
Backlight Unit	Backlight source	· CCFL to LED transition	· Cost increase · Adopted by manufacturers due to improved product quality
		· High LED efficacy	· Cost reduction in the long term · Technical barrier in thermal management and short term cost increase from adoption of higher efficiency LEDs (i.e., high power LEDs)
	Optical films	· Optimized combination of films	· Trade-offs in material cost, ease of manufacture, and efficiency
		· Reflective polarizer	· Cost increase, proprietary technology
LCD Panel		· Improvement in panel transmittance by optimizing pixel design, functional layers, e.g., polarizer, color filter, and data line	· Proprietary technology · R&D investment required but driven by cost reduction
Power management		· Brightness control based on computer usage patterns · Auto brightness control by ambient light condition	· Efficiency improvement varies with settings and usage patterns. · Efficiency improvement varies with settings and ambient light condition.
Other		· USB-powered monitor: video and power over one single USB 3.0 cable	· High-efficiency LCD panel required · Cost increase for the LCD panel but likely cost neutral for the monitor set

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[9] A 23 inch LCD monitor consuming 30 Watts used for 8 hours a day for 365 days at an electricity price of 10 cents/kWh has an electricity cost of $ 8.8 per year. Thus a 20% efficiency improvement for such a 23-inch LCD monitor will lead to saving of $ 1.8 per year. Market prices of 23 inch LCD monitors are typically above $150.

a. Backlight Sources

Major manufacturers have reduced the number of lamps used in CCFL-LCD monitors smaller than 20 inches from 4 lamps to 2, thereby reducing power consumption by about 30% (DisplaySearch 2011b, Lee 2010). Also, LED-LCD monitors are more efficient than CCFL-LCD monitors by about 10-30%, and expected to dominate the market in the short to medium term as discussed earlier in Section II. The efficiency of LED backlight units is itself also expected to improve as a result of developments in advanced LED structure, phosphors, thermal management, and beam angles. Material cost reduction is an intrinsic motivation for manufacturers to achieve high efficiency in their LED backlights. The efficacy of LEDs available for use in LCD monitors is 70-90 lumens per watt in 2011-2012, and expected to go beyond 100 lm/W in 2013 (DisplaySearch 2012b, Park et al. 2011, US DOE 2011).

b. Optical Films: Cost-effective Combinations

Improving the amount of light that can pass through optical films without compromising on their function (e.g., light uniformity) and productivity reduces the amount of backlight needed, resulting in a corresponding reduction of the electricity consumption of LCD monitors. Optical films have been combined in many ways to reduce material costs (i.e., total cost of the backlight unit) as well as to increase efficiency. For example, if a reflective polarizer[10] is applied, LCD monitor efficiency could be further improved by 20-30% (DisplaySearch 2011b, 3M 2011a). However, most LCD monitors meet the current energy efficiency standards even without a reflective polarizer. A reflective polarizer, such as 3M Vikuiti™ Dual Brightness Enhancement Film (DBEF), is being used only for a few LCD monitors with vertical alignment (VA) or in-plane switching (IPS) structure whose panel transmittance is low. Even though the DBEF contributes significantly to power savings, it is a proprietary technology that is sometimes viewed as unnecessary from a perspective focused solely on cost reduction in a cost-competitive market.

c. High Panel Transmittance

Improvement in LCD panel transmittance decreases the luminance that the backlight must achieve and therefore allows manufacturers to reduce the number of lamps in the backlight unit. Twisted nematic (TN) structure being applied to most LCD monitors is more efficient than other LCD panel structures such as VA and IPS. However, manufacturers are likely to gradually increase the share of these (i.e. VA and IPS) LCD panel structures in LCD monitors, from 6.5% in 2011 to about 15% in 2013 (DisplaySearch 2011c). This is because the demand for LCD monitors larger than 20 inches is increasing due to an increased preference for better viewing angles and higher contrast driven by users watching visual content through the Internet, DVDs, or TV tuners. Although manufacturers have been improving the viewing angle of current TN-based LCDs with the help of optical films, the TN panel's inherently narrow viewing angle, low contrast ratio, and imperfect gray scale are still limiting factors in

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[10] A reflective polarizer recovers a certain type of polarized light, which cannot be transmitted through the rear polarizer of the LCD panel, by reflecting this portion of light back to the backlight unit and depolarizing it so that the light can be newly polarized to transmit back to the panel (Park et al. 2011).

manufacturing large monitors. Instead, manufacturers are improving the panel transmittance of IPS- and VA-based LCD monitors in larger monitors. For example, low-voltage driven liquid crystal (LC) materials would allow manufacturers to use narrower low-resistance data lines, resulting in high cell aperture ratio, and therefore higher LC panel transmittance than can currently be used. It is expected that LCD panel transmittance for IPS and VA structures will improve by 20-50% to levels of 6-10% in 2015, compared to levels of 5-6.5% in 2010 (DisplaySearch 2011b, Park et al. 2011).

d. Power Management - Brightness Control

Since an LCD is a non-emissive display, dark parts of the picture are shown by blocking the polarized light with LC orientation adjusted in each pixel according to voltage applied. In this case the LCD backlight is still on and consuming the same amount of power. Employing technology to dim the backlight lamps behind the required part of the screen can lead to reducing the backlight electricity consumption. The simplest dimming option is to dim the whole backlight by a universal amount varying by frame, which is called *zero-dimensional (0D), complete, or global* dimming. This option can be applied to all types of backlights. Backlight dimming in relation to the ambient light conditions or user inactivity, i.e., auto-brightness control (ABC), can also be generally regarded as part of this method. Another option is to dim part of the backlight area depending on input image, which has two variations; 1) *one-dimensional (1D), partial, or line* dimming, and 2) *two-dimensional (2D), or local* dimming. Local dimming of LED-direct backlights is more effective in reducing power consumption than partial dimming of LED-edge backlights.[11] However, only partial or complete dimming methods are applicable to all PC monitors as almost all PC monitors, excluding high performance professional monitors, have been employing LED-edge backlights. This is because of the LED-edge backlight's fewer LEDs and simpler configuration, compared to LED-direct backlights.

While dimming backlights according to dynamically changing pictures (e.g., TVs) can be an effective way to reduce power consumption and enhance dynamic contrast ratio, its use is much more limited in displaying static images such as high-resolution photos and characters on a monitor screen. *First,* it is because dimming the backlight results in degradation of legibility and colors (Chang et al. 2004). *Second,* existing 1D dimming techniques may let users perceive side effects such as blurred images and partially-dimmed block segment on the backlight behind the LCD screen due to limited space and viewing distances at personal desks. *Third,* white backgrounds on the Internet and popular software programs such as Microsoft Word and Excel reduce the energy savings available from dimming technology in LCD monitors. Even if the screen is assumed to be operated in black background, white characters may be blurred on the black background. As high-resolution and sharpness are important factors for consumers to choose PC monitors, these are limiting factors for manufacturers in using dimming.

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[11] "LED-direct" or "LED full-array" configuration means that the LEDs are uniformly arranged behind the entire LCD panel. Unlike LED-direct models, "LED-edge" or "Edge-lit backlight" configuration means that all of the LEDs are mounted on sides of the display. Majority of PC monitors has an edge-lit configuration on only one side.

In general, PC monitors go into sleep mode after a certain time period of user inactivity.[12] Users can fit the setting for their preferences, and the savings from this option depends on computer usage patterns. Brightness control in relation to ambient light condition, i.e., ABC may be useful as well. Windows 7 provides *Adaptive brightness*, a feature that enables a computer with a light sensor on the display to automatically adjust the brightness to match the lighting conditions in user computer's surroundings (Microsoft Corporation 2012). In case the ambient light level decreases from 300 lux to 10 lux, it is reasonable to expect a power reduction of about 20%. However, it is still difficult to determine the average effect of ABC on total energy consumption of a PC monitor because enough data on the varied lighting conditions where PC monitors are typically used is not available (ENERGY STAR 2012a).

e. Direct Current (DC) USB Powered Monitors - Efficiency Related Trend

Manufacturers are developing monitors which can be powered with just one or two universal serial bus (USB) cables. This is because DC USB powered monitors have several advantages in terms of energy efficiency, portability, and easy applicability to off-grid areas. As the limited ability of the USB cable in transmitting power itself limits the total amount of power consumed by the device, such monitors need to employ very efficient technologies to use the USB cable for both power and video signal sources. For example, USB 3.0 is available up to 4.5 Watts (W) of power output (USB 2011). Hence a USB-powered monitor requires an extremely efficient display. In 2010, 3M demonstrated that a 18.5-inch LED-LCD monitor could consume 40% less power (i.e. reducing power from 14.0 W to 8.3 W), by using a high transmittance LCD panel, and a reflective polarizer (i.e., DBEF) and drawing power through two USB 3.0 ports (Siefken et al. 2011). In 2011, 3M expanded the technology to a 23-inch USB-powered monitor, claiming 9W power consumption (3M 2011b). At the Consumer Electronics Show (CES) in January 2012, AOC demonstrated a new 22-inch USB powered monitor (e2251Fwu) which is available in the market, in addition to AOC's other USB powered monitors. At the CES 2012, DisplayLink, which supplies core technologies that drive USB powered monitors, also demonstrated their USB 3.0 chips which can drive monitors up to 2560×1600 pixels (Ken Werner 2012).

There are significant advantages to DC-powered monitors. *First*, DC-powered monitors have lower costs and increased efficiency due to the elimination of electronic components required for conventional alternating current (AC) powered systems, e.g., power cord, AC/DC converter, and video cables. *Second*, DC-powered monitors do not need to adapt to different AC input voltages across regions. *Third*, DC-powered monitors allow expansion to new power sources such as Ethernet, inductive/wireless power transfer, solar or even fuel cells, in addition to USB (Siefken et al. 2011, Lee 2010).

The future of USB-powered DC monitors as a mainstream technology is still uncertain. At present there is no market report that predicts the future of USB-power monitors. While USB 2.0 is currently dominant in the market, it will take time for USB 3.0 to penetrate

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[12] According to ENERGY STAR computer requirement (ENERGY STAR 2011b), *"Display Sleep Mode shall be set to activate after no more than 15 minutes of user inactivity."*

further in the market. Also, there are a few USB-powered monitors that work with USB 2.0. The technical capacity to make and deploy these low powered monitors exists currently, illustrating the efficiency potential available for PC monitors.

In summary, significant further improvement in power consumption is not expected for CCFL-LCD monitors due to decreasing market share. LED-LCD monitors are expected to have a reduced (30-42% lower) number of LEDs across screen sizes by 2015, compared to 2011 levels, due to improvements in LED efficacy, LED packaging technology, and LCD panel transmittance (DisplaySearch 2011b, Park et al. 2011). In addition to these technological options which are expected to be implemented even without policy action, PC monitor efficiency can be further improved by 20-30% by addition of a reflective polarizer. Reflective polarizers are a mature technology, although currently restricted in use only to a few models with low transmittance LCD monitors. Finally, USB-powered monitors with efficient LCD panels are currently feasible that use currently feasible technologies that can reduce power consumption by 40-50%, compared to typical monitors. In the next section, we analyze the cost effectiveness of efficiency improvement options in LCD monitors.

IV. Cost Effectiveness Analysis

Cost of Conserved Electricity (CCE) is a metric widely used to assess the desirability of energy efficiency policies. Estimating CCE for a policy option involves calculating the cost of saving electricity which can then be compared to the cost of providing electricity, to the utility or consumer. We calculate CCE from two perspectives: 1) considering the incremental cost to the manufacturer, which we label $\mathrm{CCE_m}$ (upstream CCE) and 2) the incremental cost to the consumer which includes retailer markups[13] on the incremental manufacturing cost, which we label $\mathrm{CCE_p}$ (downstream CCE). The former estimate can be used for assessing the cost effectiveness of upstream incentive programs, whereas the latter can be used to assess that of downstream incentive or minimum energy performance standards (MEPS) programs.

CCE is estimated by dividing the annualized incremental cost (IC) that is required to add the efficiency improvement option by annual energy savings. Product categories are defined by screen size and backlight type (e.g., 23-inch LED-LCD monitor). The CCE for the i^{th} product category is calculated using annualized IC for the i^{th} product category (IC_i) and energy savings for the i^{th} product category ($Energy\ Savings_i$), as follows:

$$CCE_i = \frac{annualized\ IC_i}{energy\ savings_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ldots\ldots\ldots\ldots.(1)$$

where

$$annualized\ IC_i = IC_i\left[\frac{discount\ rate}{1-(1+discount\ rate)^{-lifetime_i}}\right]\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots(2)$$

$$Energy\ Savings_i\left(\frac{kWh}{year}\right)$$

$$= Power\ reduced\left(\frac{watts}{unit}\right)\times daily\ usage\left(\frac{hours}{day}\right)\times\frac{365\ days}{year}$$

$$\times\frac{1\ kilowatts}{1000\ watts}\ldots.\ldots(3)$$

where *lifetime*$_i$ is the PC monitor economic lifetime.

All PC monitors in the i^{th} product category are assumed homogeneous. Thus, total annual

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[13] For the purposes of this paper, retailor markups are based on the U.S. market.

energy savings from the i^{th} product category will be calculated by $Energy\ Savings_i$ times the annual sales of the i^{th} product category.

a. Energy Savings

We estimate energy savings of an efficiency improvement option based on the incremental reduction from the baseline PC monitor power consumption. The baseline is calculated from the ENERGY STAR Version 5-registered PC monitors listed on September 2011. As discussed in Section II, this data set can be treated as representative of average PC monitors sold in that year.

b. Economic Lifetime

The economic lifetime, or replacement cycle, of PC monitors can vary with region, income, sector of use, and consumer lifestyle. US EPA uses 5 years as a default value for the average lifetime of PC monitors in the ENERGY STAR office equipment savings calculator (ENERGY STAR 2011c). For the European region, estimates of lifetime range from 3.5 to 7 years, with an average of 6 years (IVF 2007). In this analysis, we assume an average lifetime of 6 years.

c. Average Usage

Computer usage patterns vary with region, sector of use, consumer lifestyle, and power management scheme applied to the system. For the US, the average daily usage of PC monitors ranges from 2.2 to 6.4 hours per day. US EPA uses 5.2 hours per day as a default value for the average usage of PC monitors in the ENERGY STAR office equipment savings calculator (ENERGY STAR 2011c). For the European region, estimates of average daily usage of monitors range from 3.5 to 7.1 hours (IVF 2007). For the purposes of this analysis we assume that average daily usage at on-mode is 5 hours for all monitors.

Table 4 Average Usage (hours per day) of PCs and Monitors at On-Mode

Category	Sector	US	EU
Desktop	Office	2.2-5.2	6.2
	Home	2.9-6.3	4.3
Laptop	Office	2.2-5.2	7.2
	Home	2.9-6.3	3.8
Monitor	Office	2.2-5.2	7.1
	Home	3.4-6.4	3.5

Source: ENERGY STAR 2011c, IVF 2007

d. Discount Rate

Residential and commercial sectors may use various methods to finance the purchase of appliances. A technical support document, prepared by US Department of Energy (DOE), of energy efficiency programs for consumer products analyzed that the average discount rates are 4.8% for residential consumers and 6.2% for commercial consumers (US DOE 2009). We assumed an average discount rate of 5% for all cases, and perform a sensitivity analysis in the range of 3% to 7% to account for country-specific variations.

e. Product Categories Analyzed

For the cost effectiveness analysis, we selected two product categories (21.5 and 23 inches). While the selected product groups represented about 15% of the global PC monitor shipments in 2010, they are expected to account for about 31% and 41% of the market in 2012 and 2015, respectively (DisplaySearch 2011a).

f. Option Analyzed: Reflective Polarizers

We focus on assessing the cost effectiveness of adopting reflective polarizer films which reduce energy consumption by 20%-30% and are unlikely to be widely adopted in the market (see Section III). The results of our analysis for product categories for selected screen sizes are likely to scale linearly for other screen size categories since the costs and benefits of adopting reflective polarizer films are proportional to screen area.

We assumed that reflective polarizers improve PC monitor efficiency by at least 20% regardless of backlight source (see Section III for details). A 20% reduction in required backlight luminance can lead to a corresponding 20% savings in backlight lamp cost. Hence the incremental cost of using a reflective polarizer is obtained by subtracting the cost saved in backlights from the cost of a reflective polarizer. Using the net incremental manufacturing cost, we estimate CCE for using a reflective polarizer in each product class of monitors. Table 5 shows annualized CCE by product class for reflective polarizers. The selected product groups have an upstream CCE_m with a range of \$0.08 per kWh and \$0.10 per kWh and a downstream CCE_p with a range of \$0.11 per kWh and \$0.15 per kWh.

Table 5 Cost of Conserved Electricity (CCE)[a] for Reflective Polarizers

Screen Size / Resolution	Backlight	$\Delta P_{on\text{-}mode}$[b] (W/unit)	ΔC_m[c] (\$/unit)	CCE_m[d] (\$/kWh)	ΔC_p[e] (\$/unit)	CCE_p[f] (\$/kWh)
21.5" (1920×1080)	CCFL	4.7	3.4	0.079	4.7	0.109
	LED	3.6	3.2	0.097	4.4	0.134
23.0" (1920×1080)	CCFL	5.0	3.8	0.081	5.2	0.111
	LED	3.8	3.7	0.104	5.4	0.152
Weighted average	CCFL	4.8	3.5	0.080	4.9	0.110
	LED	3.7	3.5	0.101	4.9	0.144

[a] assumptions: discount rate=5%, economic lifetime=6 years, daily usage=5 hours

[b] average power saving per unit = (average on-mode power of 2012 standard models estimated by authors) – (estimated average on-mode power of 2012 models with reflective polarizer)

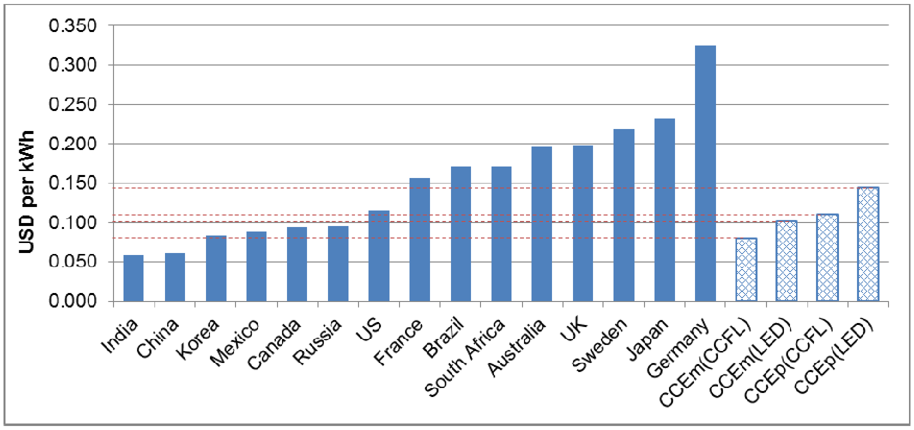
[c] incremental manufacturing cost = (manufacturing cost for 2012 standard models predicted by DisplaySearch) – (manufacturing cost for 2012 standard models with reflective polarizers estimated by authors)

[d] cost to the manufacturer of conserved energy which is calculated by Eq. (1) through (3) at $IC=\Delta C_m$

[e] incremental price = (average market price for 2012 standard models predicted by DisplaySearch) – (price for 2012 standard models with reflective polarizer estimated by authors)

[f] cost to the final user of conserved energy which is calculated by Eq. (1) through (3) at $IC=\Delta C_p$

The deployment of reflective polarizers can be encouraged in a cost effective manner to improve PC monitor efficiency because the CCEs are less than average residential electricity prices of many countries (see Fig. 8). Typically, *average* residential prices (tariffs) are lower than the *marginal* residential tariffs (tariff for the last unit consumed which is equivalent to the reduction in consumer bill if one unit of electricity is saved) and the marginal cost of electricity supply which indicates that the benefits of adopting such options are likely to be higher than those estimated based on average residential tariffs.



Source for energy prices: IEA 2011, US EIA 2010, McNeil 2008, Rosen and Houser 2007

Fig. 8. Energy Prices and Cost per unit of Conserved Electricity (CCE)

CCE is inversely proportional to hours of use, i.e. if hours of use are halved (2.5 hours a day from our assumption of 5 hours/day), CCE will double. For example, if the economic lifetime is half (3 years) of what we have assumed, CCE will be increased by 81%. However, as shown in Fig. 8, CCEs calculated based on the average hours of use and lifetime indicate that the adoption of reflective polarizers is cost effective. Further, reflective polarizers increase efficiency by 20%-30% (versus our assumption of 20%), hence our analysis is conservative. Fig. 9 shows CCE for LED-LCDs according to daily usage at various combinations of discount rates and efficiency improvement potential.

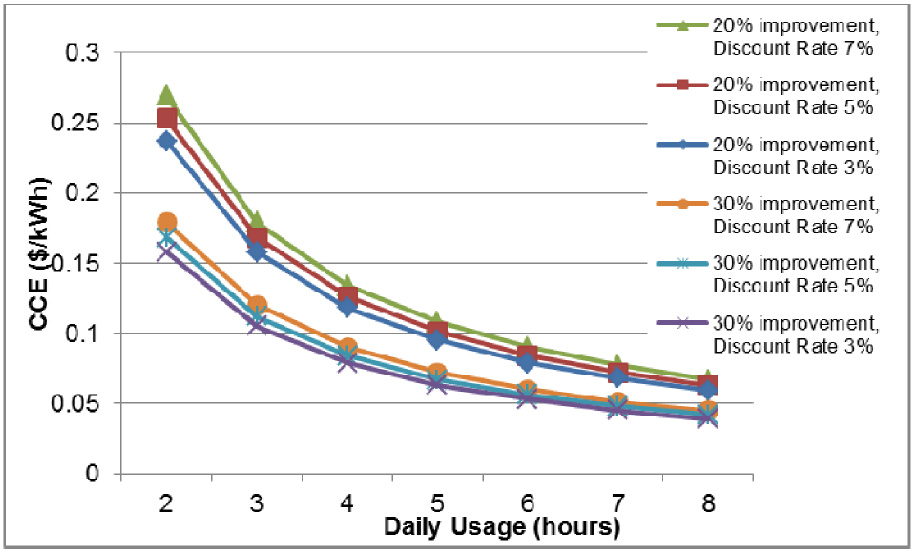


Fig. 9. Sensitivity of Cost per unit of Conserved Electricity (CCE) to Daily Usage and Discount Rates

USB-powered monitors

Although efficient LCD monitor *panels* required for USB powered DC monitors would cost more than the average LCD panels available today, the final LCD monitor *set* can be manufactured without many electronic components typically required in AC powered PC monitors such as power cord, AC/DC converter, and VGA cable. As a result, the total manufacturing cost for DC monitors is not likely to increase compared to conventional AC-powered PC monitors (Lee 2010). For example, both the cost savings and the incremental costs for 23-inch monitors are estimated to be similar and in the range of at least $5 to $6, effectively cancelling each other out (Display Search 2011b, 2011d). Hence, energy savings due to USB-powered monitors are likely to be cost-neutral.

V. Policy Insights Accelerated Adoption of Efficient PC Monitors

In order to design policies to effectively encourage the efficiency improvement of PC monitors, it is important to first estimate the effect of efficiency improvements that will take place without additional policy intervention and then assess how further efficiency improvements can be facilitated.

Based on the discussion in Section III, we assume that the energy consumption of CCFL-LCD and LED-LCD monitors will reduce by about 20% and 30% from 2011 levels by 2015, respectively, without additional policy intervention. In addition to these business-as-usual (BAU) improvements, manufacturers can further reduce power consumption by about 20% by using cost effective options such as reflective polarizers. While the technical direction and eventual market share of DC-powered monitors is uncertain, adoption of such monitors, or monitors with equivalent energy efficient technology in the mainstream has the potential to deeply reduce energy consumption by as much as 50% compared to LED-LCD's BAU consumption. Table 6 summarizes LCD monitor efficiency improvements possible by adopting the efficiency improvement options discussed above. Numbers (except for market share) in Table 6 are based on 23-inch LCD monitors and the reference value (100% in gray color) is the average on-mode power consumption of CCFL-LCD monitors in 2011. As seen in Table 6, although ENERGY STAR Version 6 draft specification is expected to be 23% more efficient than the 2011 baseline, the market compliance rate of the new ENERGY STAR criteria in 2013 is expected to remain over 70% as highly efficient LED-LCD monitors become dominant in the BAU case. In 2013, even CCFL-LCD monitors can achieve an energy consumption level 5% less than the draft Version 6 by employing a cost-effective option such as reflective polarizer, while LED-LCD monitors will likely meet the level without any further efficiency improvement technology. Since almost all PC monitor technologies currently on the market can cost effectively meet the draft Version 6 efficiency specification, this level can be a possible level for standards programs.

LED-LCD monitors which use reflective polarizers and USB powered LED-LCD monitors currently available use technologies that can further achieve energy consumption 23% and 43% less than the Version 6 respectively. These can be possible target efficiency specifications for labeling and incentive programs. In 2015, share of LED-LCDs is expected to be 97% in the market. Thus, potential levels for standards and incentives will have to be more aggressive than the draft Version 6 levels in order to impact efficiency further beyond these levels.

Table 6 LCD Monitor Power Consumption Improvement Trajectory

			2011	2013	2015
Market Share[a]	CCFL-LCD		59%	18%	3%
	LED-LCD		41%	82%	97%
Average On-Mode Power Consump-tion[b]	CCFL	BAU	100%	90%	81%
		BAU+(A)	80%	72%	65%
	LED	BAU	80%	68%	58%
		BAU+(A)	64%	54%	46%
		BAU+(A)+(B)[c]	40%	34%	29%
Voluntary Label (ENERGY STAR)	Ver. 5		124% (~80%)[d]	-	-
	Ver. 6 (draft)[e]		-	77%(>70%)[f]	77% (>85%)
Potential Level for Standards			-	72%	65%
Potential Level of Incentives/Labels			-	34%	29%

[a] DisplaySearch 2011a
[b] Authors' estimates based on ENERGY STAR-qualified monitors and the discussion in Section V
[c] (A): reflective polarizer, (B): USB-powered system with high-efficiency LCD panel, including reflective polarizer
[d] is market penetration rate of PC monitors that are estimated to meet ENERGY STAR Version 5.
[e] ENERGY STAR 2012a
[f] is predicted market penetration rate of monitors that meet the corresponding efficiency level. Majority of LED-LCD monitors are expected to meet the efficiency level.

We estimate that incentive programs designed at the level that can be achieved by reflective polarizers would need to provide an average of $3-$6 per monitor to manufacturers for 2012 LCD monitors depending on screen size (i.e. 3%-4% of the total manufacturing cost of the monitor) to allow them to employ these or equivalent cost-effective energy efficiency improvement options, in a cost-neutral fashion. Fig. 10 shows an example of possible power consumption levels for standards, labeling and incentive programs.

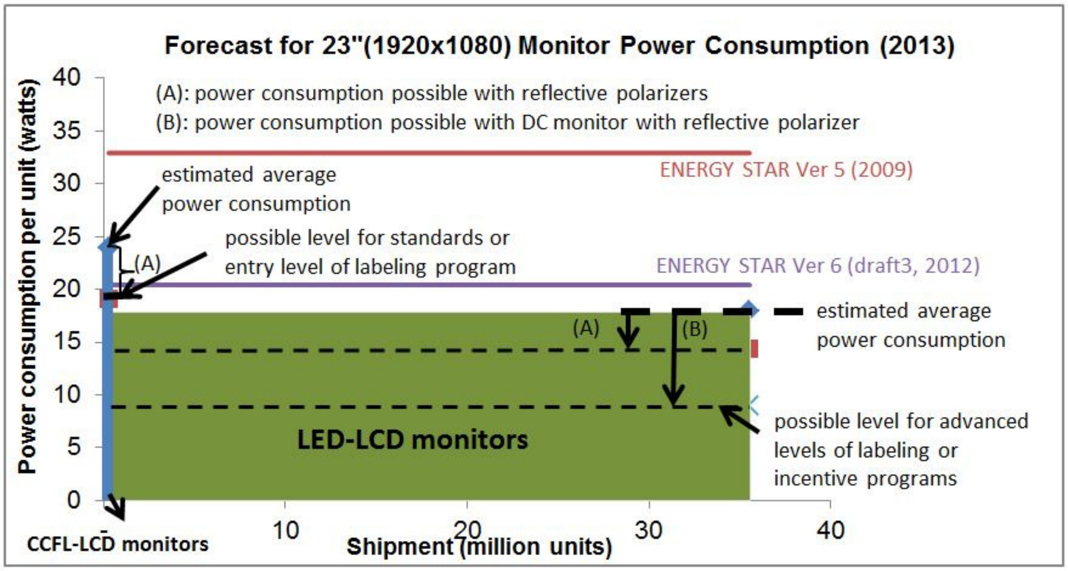


Fig. 10 Possible Levels for Standards, Labeling and Incentive Programs

VI. Global Savings Potential for Efficiency Improvement in PC Monitors

To estimate global savings potential, we selected ten product categories[14] identified by screen size and resolution. The selected product groups represented 84% of the global PC monitor shipments in 2010 and are expected to account for about 93% of the market in 2012 (DisplaySearch 2011a). First, we estimated the baseline on-mode power consumption for each of the product categories based on the ENERGY STAR data. We assumed that average daily usage at on-mode is 5 hours for all monitors (see Section IV for details on usage) and estimated the UEC per year for all the selected products by multiplying the power consumption for a product with the annual usage.[15] Based on the shipment data (projected by DisplaySearch 2011a) for each product type, we estimate total consumption for year by multiplying the UEC for a product with the projected sales of that product. We assessed the following scenarios in estimating the global saving potential:

> <u>*Frozen Efficiency Scenario*</u>– In this scenario, we take into account the projected large scale market transition in LCD technology, from less efficient backlight units (CCFLs) to efficient backlights (LEDs) *with no further efficiency improvement* within the technologies (frozen efficiency) from 2011 onward. Global PC monitor electricity consumption contributed from the annual shipments of the selected classes is estimated to increase by 18%, from 6.1 TWh per year in 2011 to 7.2 TWh per year in 2015 because of the predicted increase in sales and average screen size (DisplaySearch 2011a), despite of the large scale transition towards more efficient LED backlight technology (see Fig. 3).
>
> <u>*Base Case (BAU) Scenario*</u> – Based on the discussion in Section IV, the power consumption of LCD monitors is likely to be improved by 20-30% until 2015, compared to 2011, given the projected technology improvement trends in CCFL and LED backlit LCD monitors. As a result, global PC monitor electricity consumption contributed from the annual shipments of the selected classes is estimated to decrease by about 12%, from 6.1 TWh per year in 2011 to 5.4 TWh per year in 2015.
>
> <u>*Efficiency Scenario (standards)*</u> – In this scenario we assume that, in addition to the base case improvement, CCFL-LCD monitors employ a cost effective option such as a reflective polarizer, to meet the proposed power consumption requirement, i.e., 5% below ENERGY STAR Version 6 (see Table 6 and Section IV for more details). The majority of LED-LCD monitors are expected to meet the proposed standard without needing to employ further options. Under such a scenario, global PC monitor electricity consumption contributed from the annual shipments of the selected classes is estimated to be decreased by about 18%, from 6.1 TWh per year in 2011 to 5.4 TWh per year in 2015. The effect of

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[14] 17.0"(1280×1024), 18.5"(1366×768), 19.0"(1440×900), 20.0"(1600×900), 21.5"(1920×1080), 22.0"(1680×1050), 23.0"(1920×1080), 23.6"(1920×1080), 24.0"(1920×1080), and 24.0"(1920×1080)

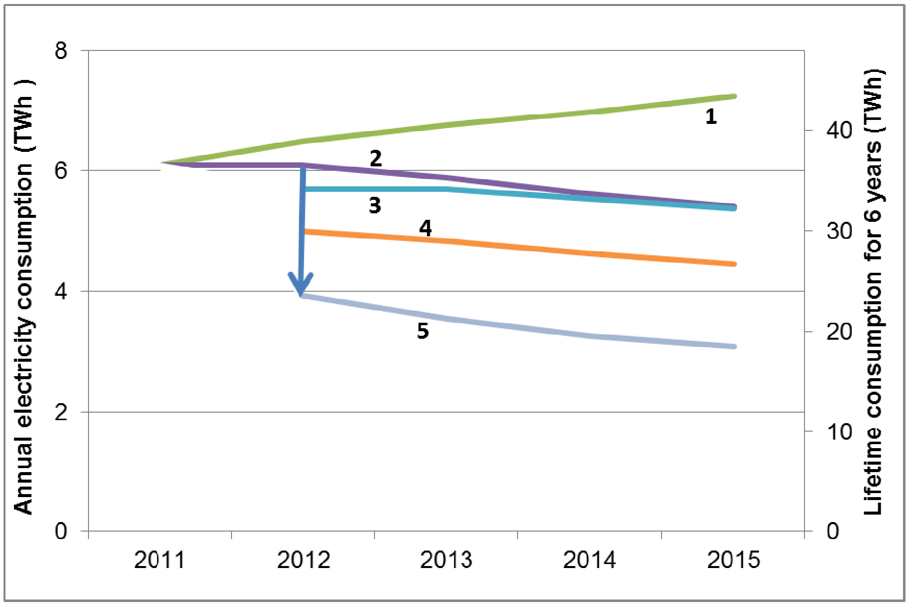
[15] We assumed that all monitors consume 0.5 W in sleep mode for 19 hours a day for 365 days.

this case will significantly decrease through 2014 because CCFL backlights are expected to be phased out of the market. In 2015, the savings potential contributed from 2012-2015 monitor shipments, compared to scenario 2, is estimated to be about 0.7 TWh per year.

<u>*Super-efficiency Scenario I*</u> – In this scenario we assume all LCD monitors, i.e., both CCFL- and LED-LCD monitors, adopt a cost-effective option such as a reflective polarizer. In this case, global PC monitor electricity consumption contributed from the annual shipments of the selected classes is estimated to be decreased by about 26%, from 6.1 TWh per year in 2011 to 4.5 TWh per year in 2015. In 2015, the savings potential contributed from 2012-2015 monitor shipments, compared to scenario 2, is estimated to be about 4.1 TWh per year.

<u>*Super-efficiency Scenario II*</u> – In this scenario, we assume all *LED-LCD* monitors employ technology as energy efficient as USB-powered monitors with reflective polarizers, while CCFL-LCD monitors also adopt reflective polarizers. In this case, global PC monitor electricity consumption contributed from the annual shipments of the selected classes is estimated to be decreased by about 43%, from 6.1 TWh per year in 2011 to 3.1 TWh per year in 2015. In 2015, the savings potential contributed from 2012-2015 monitor shipments, compared to scenario 2, is estimated to be about 9.2 TWh per year. The cumulative savings from 2012 through 2015 is estimated at about 22.7 TWh and lifetime savings for 6 years will be 55.1 TWh. As discussed above, the technical and market evolution of DC-powered monitors is uncertain. However, the current technology available and deployed in DC powered monitors indicates that the market has the potential to deeply reduce energy consumption by as much as 50%.

Fig. 11 shows the results by scenario and Fig. 12 shows the projected annual savings by scenario.



1 Frozen Efficiency Scenario / 2 BAU Scenario / 3 Efficiency Scenario / 4 Super-efficiency Scenario I / 5 Super-efficiency Scenario II

Fig. 11 Global PC Monitor Electricity Consumption for Annual Shipment

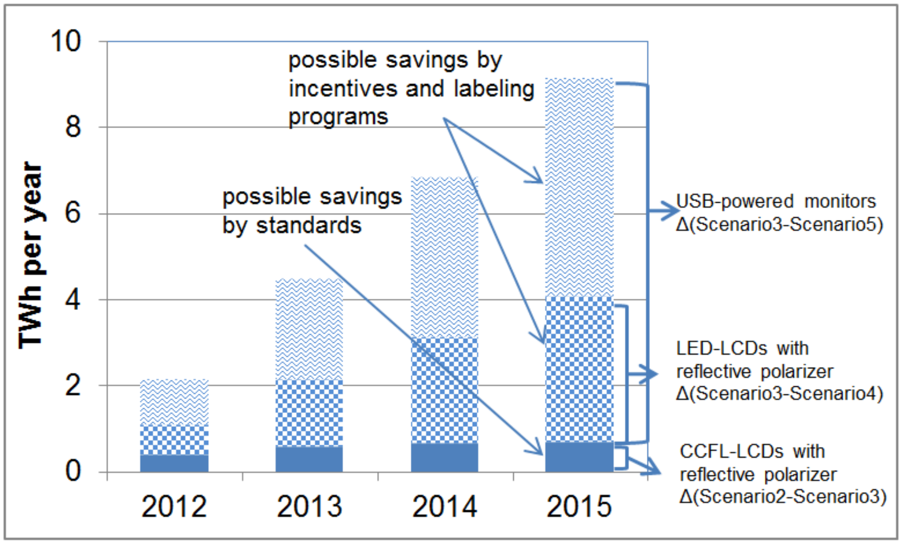


Fig. 12 Global PC Monitor Annual Savings Potential

VII. Conclusions

Our analysis finds that a significant decrease, about 25% from 2011 to 2015, in on-mode energy consumption for newly sold PC monitors globally is likely because of the large-scale transition toward LED-LCD monitors and rapid efficiency improvement in monitors, in spite of the projected growth in screen size and monitor sales which leads to a 35% increase in the total screen area of PC monitors.

We also find that PC monitor consumption can be cost effectively reduced further beyond these improvements. If in every year the efficient designs discussed in this paper reach 100% of the product groups analyzed, i.e., about 90% of the whole market, the total energy savings potential would be about 4.1 to 9.2 TWh per year in 2015, and up to 55.1 TWh during their lifetime. About 45% of this savings is achievable by adoption of reflective polarizers or equivalent technology resulting in global savings of 4.1 TWh per year in 2015 and 24.6 TWh during their lifetime, whereas adoption of technology as efficient as that used in USB powered monitors accounts for the remainder of the savings potential.

These findings have two implications for energy efficiency market transformation programs. First, as a result of the transition and technology improvement, more than 70% of PC monitors, will be able to meet ENERGY STAR Version 6 draft requirements in 2013. Second, in order to facilitate further improvement in efficiency by the adoption of cost-effective options, market transformation programs need to take into account these rapid developments and determine more stringent efficiency targets than are currently in place, as well as re-evaluate these levels often, as technology evolves.

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