Energy Efficiency (2013) 6:545–569
DOI 10.1007/s12053-013-9191-0

ORIGINAL ARTICLE

Efficiency improvement opportunities for personal computer monitors: implications for market transformation programs

Won Young Park · Amol Phadke · Nihar Shah

Received: 29 June 2012 / Accepted: 10 December 2012 / Published online: 23 January 2013

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 PC monitor efficiency will likely improve by over 40 % by 2015 with saving potential of 4.5 TWh per year in 2015, compared to today's technology. We discuss various energy-efficiency improvement options and evaluate the cost-effectiveness of three of them, at least one of which improves efficiency by at least 20 % cost effectively beyond the ongoing market trends. We assess the potential for further improving efficiency taking into account the recent development of universal serial bus-powered liquid crystal display monitors and find that the current technology available and deployed in them has the potential to deeply and cost effectively 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 further capture global energy saving potential from PC monitors which we estimate to be 9.2 TWh per year in 2015.

W. Y. Park (✉) · A. Phadke · N. Shah
Environmental Energy Technologies Division,
Lawrence Berkeley National Laboratory,
Berkeley, CA, USA
e-mail: WYPark@lbl.gov

Keywords PC monitor energy efficiency · Cost-effectiveness · Market transformation

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 TWh in 2008, and of the electricity consumption, monitors are estimated to account for 30–40 TWh (IEA 2009).[1] Among the key components of a PC system, displays (i.e., monitors) are responsible for a significant portion of energy consumption in a PC system, accounting for 15–35 % of the system's consumption (IEA 2009; Delforge 2011; Horowitz 2011). The wide range of estimates for the share of PC energy consumption attributable to monitors is because average unit energy consumption (UEC) of a

---

[1] While the estimate from IEA (2009) is limited to the residential sector, the electricity consumption of PC monitors for all sectors in the USA was estimated to be 13–23 TWh/year for 2010 (Delforge 2011). The US PC monitor shipments accounted for about 17 % of the global shipments in 2010 (DisplaySearch 2011a). Assuming that PC monitor stock and PC monitor shipments have the same share for the USA versus the rest of the world, using the factor 17 % for a rough estimate, the global electricity consumption of PC monitors in 2010 is estimated to be 76–135 TWh across all sectors. This paper is based on annual global PC monitor shipments that include all sectors and focused on energy consumption contributed from the new shipments.

PC varies highly with the system specifications and power management scheme applied to the system.

An assessment of efficiency improvement opportunities in PC monitors is needed for three reasons. First, policies to facilitate the adoption of cost-effective efficiency improvements in PC monitors are necessary to correct market failures such as uncaptured economic and environmental benefits available from reduced PC monitor energy consumption. Although other recent studies (IEA 2009; Connection Research 2010) addressed computer energy efficiency and consumption issues, none of these studies assess the cost-effectiveness[2] of efficiency improvement options in detail for PC monitors. Such assessment is needed for designing appropriate policies and market transformation programs, e.g., energy efficiency standards and financial incentive programs, to facilitate the adoption of cost-effective efficiency improvements. Second, the literature focused on PC monitors is limited and was published before the ongoing large-scale transition from cold cathode fluorescent lamp (CCFL) backlit liquid crystal display (CCFL-LCD) monitors to light-emitting diode (LED) backlit LCD (LED-LCD) monitors. LED-LCD monitors are likely to be at least 50 % and 90 % of the PC monitor shipments in 2012 and 2015, respectively (DisplaySearch 2011a). Third, information and communications technology (ICT) appliances such as 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 applicable in several countries (see "Overview of PC monitor market and energy consumption trends" section for details).

This paper focuses on desktop PC monitors with a diagonal screen size between 15 and 30 in. and a pixel density greater than 5,000 pixels per square inch, which is designed to display information from a computer via one or more signal inputs. PC monitors with a tuner or receiver are included as long as they are sold to consumers as computer monitors, but notebook computer screens, digital picture frames whose primary function is to display digital images, signage displays, and televisions (TVs; i.e., products with a tuner or receiver and computer capability that are sold as TVs) are out of the scope of this paper.

This paper also focuses on LCD monitors which are expected to dominate worldwide sales, amounting to an expected 99 % of global PC monitor shipments by 2015 (DisplaySearch 2011a). In this paper, we assess recent technology trends and their impact on the energy efficiency of PC monitors, and related efficiency improvement programs. However, detailed program design questions are out of the scope of this paper. 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 consider efficiency improvement options that are technically feasible, practical to manufacture, and could be realized in the short term (over the next 3 years), as the rapid evolution of technology in the display market makes a forecast over a longer time scale highly uncertain and therefore not very useful from a policy perspective. We obtained the data for this paper primarily from the following sources: a review of the literature including technical reports, DisplaySearch reports,[3] the ENERGY STAR database,[4] international conferences, technical exhibitions, and interviews with manufacturers and experts in the field.

The remainder of this paper is organized as follows: In "Overview of PC monitor market and energy consumption trends" section, we present an overview of the PC monitor market, technology trends, and energy consumption trends. In "Efficiency improvement options and related trends for PC monitors" section, 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 universal serial bus (USB) direct current (DC)-powered

---

[2] In this analysis, cost-effectiveness is defined as cost of conserved energy (CCE), the annualized investment in more expensive equipment or component needed to provide a unit of energy saved (kilowatt-hour), less than electricity price.

[3] DisplaySearch has been providing reliable information and analyses on the display market and related industries which are widely used in the industry. 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.

[4] The displays modeled in data used here 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 the majority of the market at that time. See the discussion under the subsection "PC Monitor Energy Consumption" in "Overview of PC monitor market and energy consumption trends" section for details.

monitors that need to employ energy-efficient technologies due to the limitations on power inherent in USB-powered systems. In "Cost-effectiveness analysis" section, we present a cost of conserved energy (CCE) analysis to assess the cost-effectiveness of options identified in "Efficiency improvement options and related trends for PC monitors" section. "Policy insights to accelerate adoption of efficient PC monitors" section offers suggestions for accelerating the adoption of efficient technologies, and in "Global savings potential for efficiency improvement in PC monitors" section, we estimate the energy savings potential of such adoption. "Conclusions" section presents concluding remarks.

Overview of PC monitor market and energy consumption trends

Global PC monitor shipments

Since the early 2000s, the global PC monitor market has undergone a major transition from traditional CRTs to LCDs (IEA 2009; DisplaySearch 2011a).[5] As shown in Fig. 1, global PC monitor shipments are expected to experience continual growth through 2015 and reach 230 million units, including all-in-one PCs (i.e., integrated PCs) in 2015. A large-scale transition is also ongoing and expected to continue from CCFL-LCDs to LED-LCDs, resulting in further substantial improvements in efficiency. Fig. 1 illustrates DisplaySearch's forecast that LED backlights will capture more than 70 % of the global PC monitor shipment from 2013 onward.

While desktop PC shipment is expected to either stabilize just over 150 million units or decrease slightly from this level from 2011 onward (DisplaySearch 2011a), 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).

Screen resolution

The share of 1,920×1,080 resolution screens, i.e., approximately 2.07 megapixels (MP), in the PC monitor market is expected to increase (see Fig. 2), and screens with resolutions of 2.07 MP or less are likely to continue to dominate the market. The shipment-weighted average number of pixels per screen has been increasing since 2010, mainly due to the increase of LED backlight's market share (compare Fig. 2 with Fig. 1). Higher resolution monitors, e.g., enhanced performance display (EPD),[6] accounting for less than 3 % of the global market, are not expected to increase significantly in market share within the short term. While high resolution displays generally consume more electricity than low resolution ones, PC monitors with resolution higher than 1,920×1,080 consist of a niche market. Although we do not separately discuss the impact of high resolution monitors such as EPD on energy consumption in PC monitors, we account for the impact of resolution on energy consumption by selecting major product groups identified by screen size and resolution, which represent 93 % and 96 % of the market in 2012 and 2015, respectively (see "Global savings potential for efficiency improvement in PC monitors" section), in estimating PC energy consumption.

Screen size

Although 17- to 19-in. monitors were dominant in the market, manufacturers and DisplaySearch expect the share of 20- to 23-in. monitors to increase from 37 % in 2010 to over 60 % in 2015 (see Fig. 3). A further increase in monitor screen size beyond 26–30 in. is not likely to be significant.

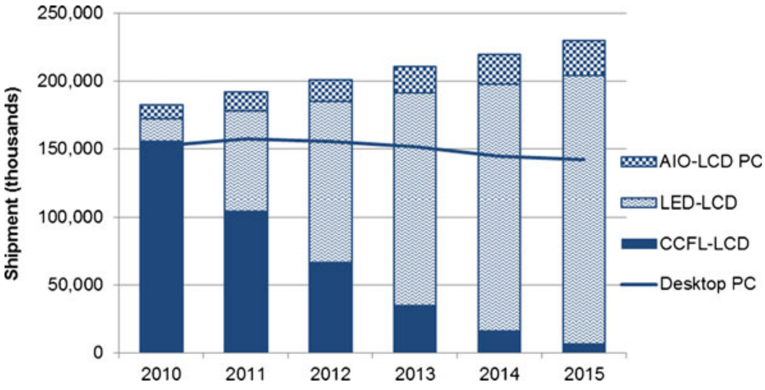
From 2010 to 2015, the average screen size (measured diagonally) and total annual shipments are projected to increase by 7 % and 19 %, respectively, leading to a 35 % increase in the aggregate screen area of annual PC monitor shipments. Figure 4 shows the average monitor screen area per unit and global shipments for 2010 and 2015, as well as the expected transition from CCFL backlight to LED backlights in terms of shipments and screen area. While the increase in both screen size and shipment is likely to increase energy consumption, the transition from CCFL-LCDs (inefficient) to LED-LCDs (efficient) is expected to reduce UEC. Figure 4 provides a picture illustrating the cumulative effect of both factors.

---

[5] 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). From 2010 onward, DisplaySearch has stopped tracking CRT monitor shipment arguably because of low and falling market share for CRT monitors.

[6] According to ENERGY STAR's definition, an enhanced-performance display must have a native resolution greater than 2.3 megapixels (ENERGY STAR 2012a).

Fig. 1 Actual (Q1 2010–Q2 2011) and forecasted (Q3 2011–Q4 2015) global PC monitor shipments



There are only limited regional differences and significant global similarity in PC monitor screen (i.e., LCDs) and LCD backlight technology (see Fig. 5), although there are regional differences in screen size/resolution preferences and the market share of LCD backlights. Major brands distribute similarly designed PC monitors with similar energy consumption characteristics across many regions. 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 from one manufacturer, have qualified for ENERGY STAR Version 5 (Samsung Electronics 2011). 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, as these are globally applicable, but does take into account regional differences in screen size, resolution, and market share of backlight technologies. Accordingly, the research presented in this paper is applicable to PC monitors in most countries.

Emerging trends

Organic light-emitting diodes (OLEDs) are expected to begin penetrating into the PC monitor market from 2013 onward, but reach only 0.4 million units (less than 0.5 % of the global market) in 2015. It does not appear that new screen technology such as OLEDs will become popular in the PC monitor market within the short term.[7] Hence, we have not focused on OLED technology here.

Another technology trend in the digital display market is 3D-capable displays. However, the share of 3D-capable monitors in the desktop PC monitor market was less than 0.5 % (less than one million units) in 2011 (DisplaySearch 2012b) and is not likely to increase significantly in the short term at least until 3D technologies become more convenient to use (e.g., glass-free 3D) and 3D-ready monitors become more affordable to consumers.[8] An existing 3D display in 3D mode requires additional 3D image processing and results in a relatively lower brightness level due to additional films or 3D glasses in comparison to 2D mode. Therefore, manufacturers may increase brightness level and correspondingly increasing power consumption in 3D mode in comparison to 2D mode (Park et al. 2011). Manufacturers are overcoming this increase in energy consumption by improving screen technologies, including 3D technologies. While we do not focus on 3D-capable PC monitors here, all the efficiency improvement options studied here for 2D monitors are also applicable to 3D-capable monitors.

---

[7] In the TV industry, Samsung and LG announced in January 2012 that they would provide 55″ OLED TVs first to the market, even though they had demonstrated 30-in. class OLED TVs since a few years ago. Medium-size (20–30 in.) OLEDs are not expected to be cost competitive against LCDs in the short term.

[8] For example, LG has launched glass-free 3D monitors (LG D2500N-PN, 25-in.) in early 2012, with a market price of approximately $1,900, while the price of typical 25-in. LED-LCD monitors is less than $300.

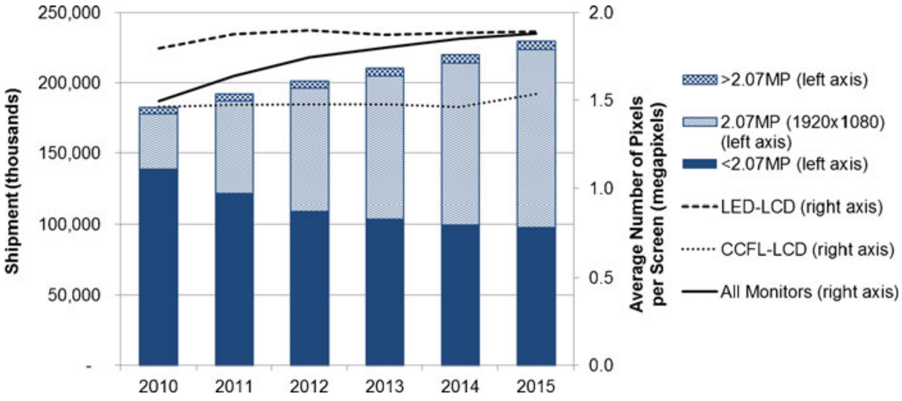


Fig. 2 Global PC monitor shipment distribution by resolution and average number of pixels per screen (actual shipment: Q1 2010–Q2 2011, forecast: Q3 2011–Q4 2015)

In spite of concerns about the potential impacts of emerging technology trends such as new displays (e.g., OLEDs), higher resolution, and 3D capability on energy consumption in PC monitors, we see that the dominant screen technology (i.e., LCDs) and screen size (combined with resolution) are more important than these emerging trends which are not significant now (in terms of market share) or expected to grow significantly in the PC monitor market and whose energy consumption and savings impact are still low and uncertain within the time horizon and the global scale considered in this paper.

PC monitor energy consumption

Average on-mode power of PC monitors

To estimate the energy consumption of PC monitors, we use the database of PC monitors registered in 2011 under ENERGY STAR Version 5. The rapid rate of LCD monitor technology improvement is evident. The market penetration rate of ENERGY STAR-registered LCD monitors during 2009 was 90 %.[9] In 2010, a year after the introduction of the new Version 5 specifications, the market share of ENERGY STAR qualified products was 43 % and is estimated to have increased to about 70–80 % in 2011 (ENERGY STAR 2011a, b). Further, non-registration of certain PC monitor models with ENERGY STAR does not necessarily imply that such monitors do not meet ENERGY STAR specifications. A test performed by the US Environmental Protection Agency (US EPA) during 2008–2009 on a sample of ten monitors showed that eight of the ten 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 market share trends for 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.

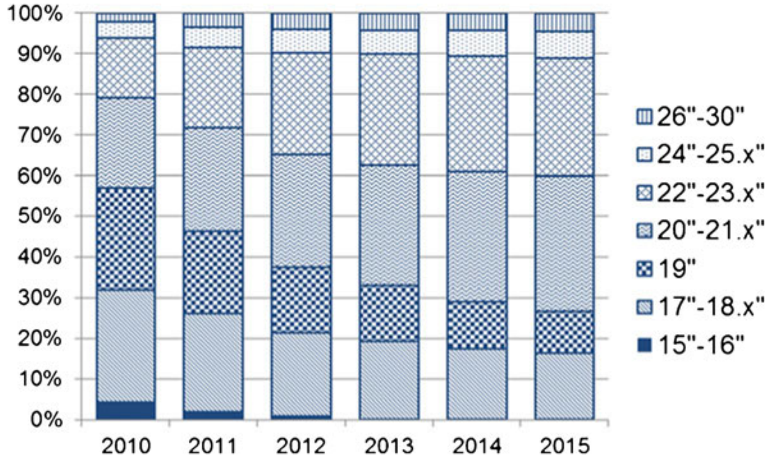
In addition, as discussed above, major brands distribute similarly designed PC monitors across many regions to capitalize on economies of scale. Thus, given that the top five brands and the top five OEMs dominate the global PC monitor market and the 2011 rate of compliance with ENERGY STAR is estimated to be over 70 %, the power consumption of ENERGY STAR PC monitors is likely to be representative of average models on the global market.

A 20-in. ENERGY STAR-registered LCD monitor consumes 10–25 W in on-mode (ENERGY STAR 2011b), while LED-LCD monitors are on average more efficient than CCFL-LCD monitors by about 10–30 %. We calculated simple mean on-mode power per unit screen area for ENERGY STAR-qualified products. As seen in Table 2, CCFL- and LED-LCD monitors consume 0.018 and 0.015 W/cm^2, respectively, on average and

---

[9] Since the new specification, i.e., Version 5, was updated during 2009 and officially went into effect in October 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 2010). The majority of the 90 % is estimated to be Version 4-qualified monitors.

Fig. 3 Global PC monitor shipment distribution by screen size (actual shipment: Q1 2010–Q2 2011, forecast: Q3 2011–Q4 2015)



about 0.5 W in sleep mode[10] (see Table 2 and Fig. 6).

PC monitor energy consumption from annual shipment

To estimate PC monitor energy consumption from annual shipment, we calculated average watts per square centimeter for each product group categorized by backlight type, resolution, and screen size[11] from ENERGY STAR-registered monitors. Multiplying each average watts per square centimeter by annual shipment of each product group, the total annual electricity consumption contributed by PC monitors shipped globally in 2011 is estimated to be 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. Figure 7 shows PC monitor energy consumption contributed from annual global shipments.

Efficiency improvement options and related trends for PC monitors

As discussed in "Introduction" section, this paper focuses on efficiency improvement options for LCD PC monitors which are expected to continue to dominate worldwide sales, i.e., 99 % by 2015.

An LCD, unlike other self-emissive flat-panel[12] 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 (Fraunhofer IZM 2007). Thin film transistor (TFT) technology[13] on glass is used to drive or control the orientation of the LCs, i.e., pixels. Figure 8 shows a typical LCD structure.

When viewed in terms of change in luminance (candela per square meter) as light travels through the LCD screen, LCDs' overall efficiency appears to have significant further potential for improvement, since the final

---

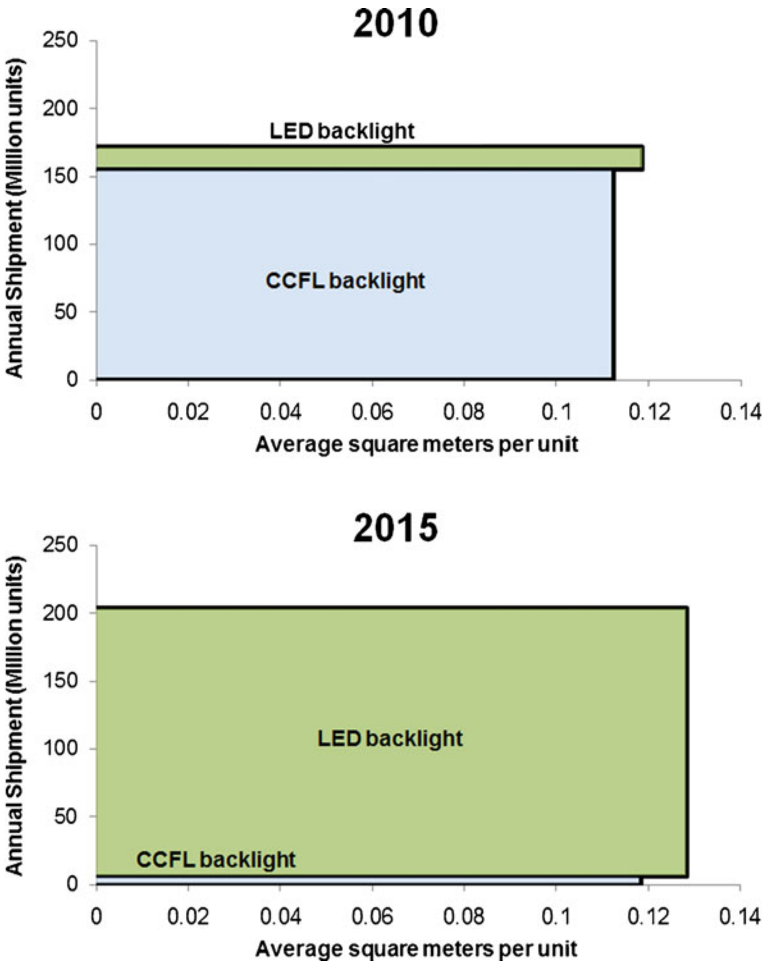
[10] Most recent PC monitors consume less than 1 W in standby mode, since many major economies have been adopting "1 W Policy" since the International Energy Agency (IEA) proposed in 1999 that all countries harmonize energy policies to reduce standby power, setting the target of a maximum of 1 W per 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 0.5 and 0.6 W, respectively (Da Silva et al. 2010).

[11] 15.6″ (1,366×768), 17″ (1,280×1,024), 18.5″ (1,366×768), 19″ (1,440×900, 1,280×1,024), 20″ (1,600×900), 21.1″ (1,680×1,050, 1,600×1,200), 21.3″ (1,600×1,200), 21.5″ (1,920×1,080), 22″ (1,680×1,050), 23″ (1,920×1,080), 23.6″ (1,920×1,080), 24″ (1,920×1,080), 25″ (1,920×1,080), 26″ (1,920×1,080), and 27″ (1,920×1,080, 2,560×1,440).

[12] 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.

[13] A TFT is a transistor whose electrical current-carrying layer is a thin film, typically made of silicon.

Fig. 4 Global monitor annual shipments and total screen area (actual shipment 2010 vs. forecast 2015)



luminance delivered out of the LCD is generally less than 10 % of the initial luminance coming out of the backlight unit. This is 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 overall efficiency. For example, when panel transmittance improves from 7 % to 8 %, required backlight luminance drops by about 10–15 %.

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 in 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 only efficiency. Furthermore, 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 in many countries, presenting an additional rationale for policy intervention to improve efficiency.[14] Thus, efficiency is unlikely to

---

[14] A 23-in. LCD monitor consuming 30 W used for 8 h a day for 365 days at an electricity price of 10 cents/kWh has an electricity cost of $8.8/year. Thus, a 20 % efficiency improvement for such a 23-in. LCD monitor will lead to saving of $1.8/year. However, this is less so in places such as the EU, e.g., at 30–40 cents/kWh, the energy savings benefit could be a significant fraction of the market price.

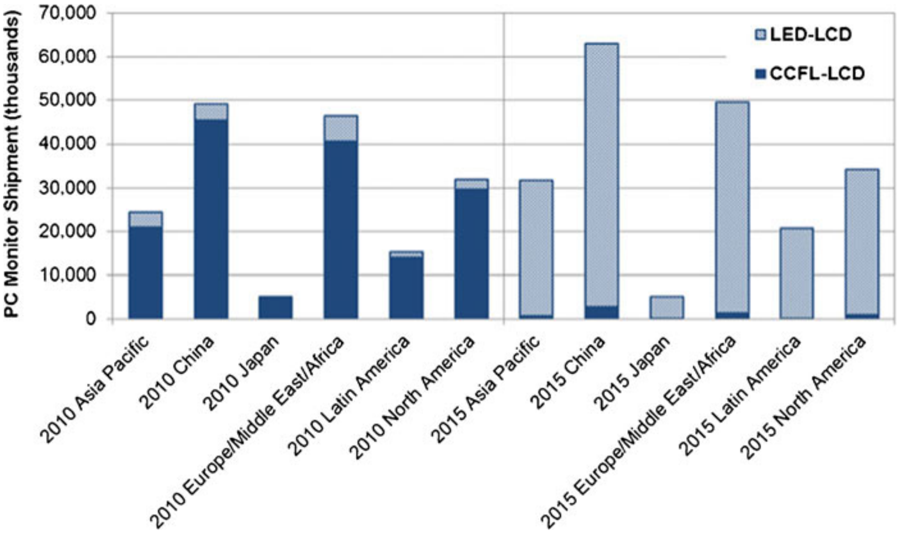


Fig. 5 Actual (2010) and forecasted (2015) shipments showing market transition by region and screen technology

be a major consideration in price-sensitive consumer's selection of PC monitors in many countries. 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.

Backlight sources

Major manufacturers have reduced the number of lamps used in CCFL-LCD monitors smaller than 20 in. from four lamps to two, 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 "Overview of PC monitor market and energy consumption trends" section. 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 luminous efficacy of LEDs available for use in LCD monitors is 70–90 lm/W in 2011–2012, and expected to go beyond 100 lm/W in 2013 (DisplaySearch 2011b; Park et al. 2011; US DOE 2011). Driven by this efficiency improvement, the average number of LED lamps used for a 23-in. LCD monitor is expected to decrease by about 43 % in 2015, compared to 2011 (DisplaySearch 2011b).

Optical films

Improving the amount of light that can pass through optical films without compromising on their function (e.g., light uniformity) reduces the amount of backlight

Table 1 Market penetration of ENERGY STAR PC monitors

	2009	2010	2011
Applicable version of ENERGY STAR	Version 4 (January–September) Version 5 (October–December)	Version 5	Version 5
US	90%	43%	70–80%[a]
EU	75% (first half) 49% (second half)	60–70%[b]	70–80%[c]

[a, b, c] Authors' estimates based on the below sources

Source: ENERGY STAR 2010, 2011a, 2012b; EC 2011; IDC 2010

Table 2 On-mode power per unit screen area by backlight

	N	Mean	Min	Max	Std.
CCFL-LCD	396	0.018	0.008	0.027	0.003
LED-LCD	731	0.015	0.007	0.025	0.003

Unit: watts per square centimeter (W/cm^2)

Source: ENERGY STAR (2011b)

Std. standard deviation

needed to achieve an equivalent screen luminance, 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[15] 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 such as ENERGY STAR specifications even without a reflective polarizer. A reflective polarizer, such as 3M Vikuiti™ Dual Brightness Enhancement Film (DBEF), is being used only for a few high-end models of LCD monitors with vertical alignment (VA) or in-plane switching (IPS) structure whose panel transmittance is low but picture quality is good. Twisted Nematic (TN) structure that has been employed in most LCD monitors is more efficient than VA and IPS structures. 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. (For the purposes of this paper, we use DBEF not as an endorsement of any particular technology, but as an illustration of the energy savings potential available from optical films.)

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. As discussed earlier, the 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 in. is increasing due to an increased preference for better viewing angles driven by users watching visual content through the Internet, DVDs, or TV tuners, and the fact that TN LCD panels do not deliver a wide viewing angle, high contrast ratio, and good gray scale in comparison to the other panel structures. 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 marketing large TN monitors. Instead, manufacturers are improving the panel transmittance of IPS- and VA-based LCD monitors in larger monitors. For example, low-voltage-driven 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 from 4–6 % to levels of 6–10 % in 2015, compared to levels of 5–6.5 % in 2010 (DisplaySearch 2011b; Park et al. 2011).

Power management—brightness control

In general, PC monitors incorporate backlight dimming in relation to usage pattern. For example, PCs dim and subsequently turn off the screen after a certain time period of user inactivity,[16] and users can also customize sleep settings for their preferences. In addition to this default power management scheme used in PC monitors, there are three other types of brightness control methods.

Backlight dimming in relation to image signals Since an LCD is a non-emissive display, dark parts of a picture are created by blocking the polarized light with LC orientation adjusted in each pixel. In this case, the

---

[15] 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 (DisplaySearch 2011b; Park et al. 2011).

[16] 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.”

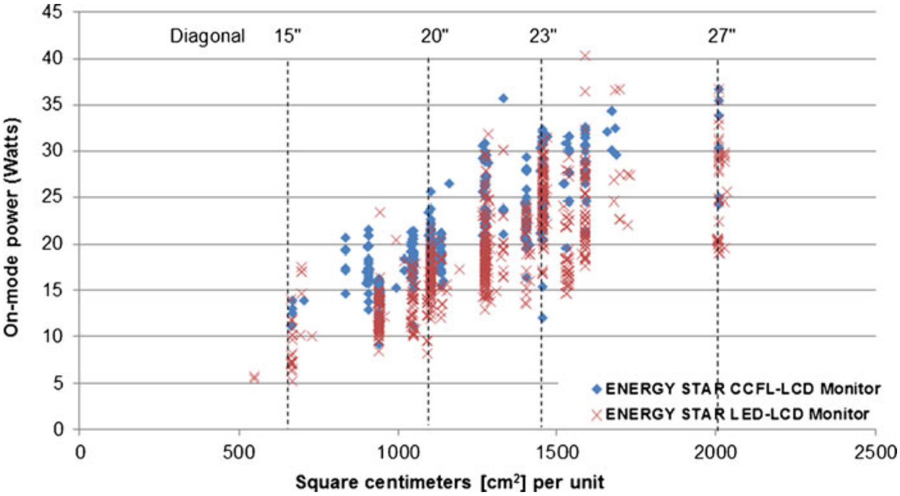


Fig. 6 LCD monitor power consumption vs. screen size

LCD backlight is still on and consuming the same amount of power. Employing technology to locally dim the backlight lamps behind the dark parts of an image can lead to reduction in 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 user inactivity or ambient light conditions, generally called automatic 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 at reducing power consumption than partial dimming of LED-edge backlights.[17] However, only partial or complete dimming methods are applicable to PC monitors since most PC monitor products, excluding high performance professional monitors, employ LED-edge backlights to reduce costs and make displays thinner.

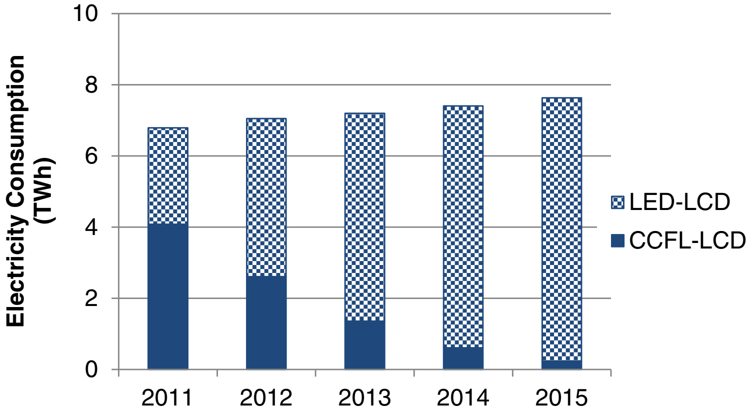
While dimming backlights according to dynamically changing pictures (i.e., 1D or 2D dimming) can be an effective way to reduce power consumption and enhance dynamic contrast ratio, its use is much more limited in displaying static images such as high-resolution photos and characters on a desktop PC monitor screen. First, dimming the backlight may result in degradation of legibility and colors (Chang et al. 2004). Second, existing 1D dimming techniques may cause users to perceive side effects such as blurred images and partially dimmed block segments on the backlight behind the LCD screen. Third, white backgrounds on websites and popular software programs such as Microsoft Word and Excel reduce the total energy savings available from dimming technology in LCD monitors. Even if the screen is assumed to be operated in black background, white characters or a moving mouse cursor 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 more advanced dimming than 0D dimming. Although manufacturers are motivated to use such advanced dimming for battery-operated displays such as laptop screens, they are not likely to use advanced dimming methods for typical desktop PC monitors.

Backlight dimming in relation to ambient light condition Windows 7 provides adaptive brightness, a feature that enables a computer with a light sensor on

---

[17] "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.

Fig. 7 Estimated PC monitor energy consumption from annual shipment



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 to 10 lux, it is reasonable to expect a power reduction of about 20 % (ENERGY STAR 2012a), although the effect varies with manufacturers' setting. However, it is still difficult to determine the average effect of ambient light sensors on total energy consumption of a PC monitor because sufficient data on the varied lighting conditions where PC monitors are typically used across regions and sectors is not available (see “Option 3: Ambient Light Sensor” section for details).

Backlight dimming in relation to user presence Occupancy sensors or motion sensors might also help save energy by preventing PC monitors from being left on when people leave the room. However, the way how occupancy sensors work is similar to existing PC's power management scheme related to user inactivity. It is also difficult to determine the average effect of occupancy sensors or isolate their individual effect from other power management methods on PC monitor's on-mode power consumption.

Low voltage direct current (DC)-powered monitors—efficiency-related trend

DC-powered monitors are expected to have several advantages in terms of energy efficiency, portability, and easy applicability to off-grid areas where DC power sources are available. For example,

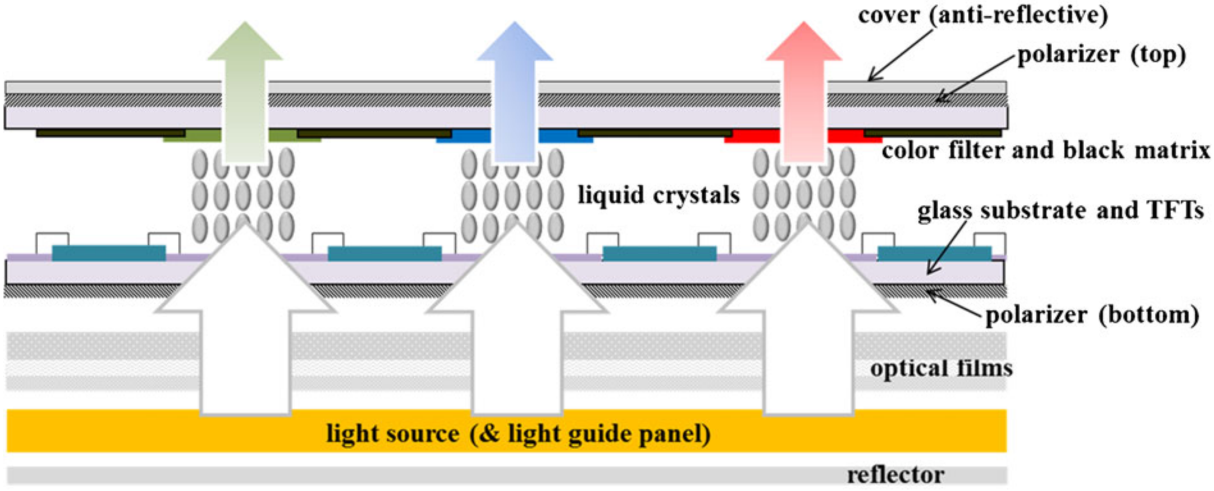


Fig. 8 Typical structure of a liquid crystal display (LCD)

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
			Expected to be accelerated by economies of scale and technological learning (BAU[b])
		High LED efficacy	Cost reduction in the long term (BAU)
			Technical barrier in thermal management and short term cost increase from adoption of much higher efficiency LEDs (i.e., high power LEDs) than BAU
	Optical films	Optimized combination of films	Trade-offs in material cost, ease of manufacture, and efficiency (BAU)
		Reflective polarizer (DBEF[a])	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 (BAU)
Power management		Brightness control based on computer usage patterns	Efficiency improvement varies with settings and usage patterns (BAU)
		Brightness control based on ambient light condition	Efficiency improvement varies with settings and ambient light condition
		Brightness control (local dimming) based on image signals	Efficiency improvement varies with manufactures' design scheme. The use of local dimming in PC monitors is more limited than in TVs
Other		Low voltage DC powered monitors (e.g., USB-powered monitors)	High-efficiency LCD panel required
			Cost increase for the LCD panel but likely cost neutral for the monitor set

[a] DBEF (dual brightness enhancement film) produced by 3M

[b] BAU options are likely to be adopted regardless of policy intervention

manufacturers are developing monitors which can be powered with just one or two USB cables. The limited power transmitting ability of a USB cable limits the total amount of power that may be consumed by an end use, so USB-powered monitors need to employ very efficient technologies. Specifically, the USB 3.0 protocol permits up to 4.5 W of power output (USB 2011). In 2010, 3M demonstrated that a 18.5-in. LED-LCD monitor could consume 40 % less power (i.e., reducing power from 14.0 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-in. USB-powered monitor, claiming 9 W power consumption (3M 2011b). At the International Consumer Electronics Show (CES) in January 2012, AOC[18] demonstrated a

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

Sources: ENERGY STAR (2011c) and IVF (2007)

---

[18] AOC (Admiral Overseas Corporation), an electronics company headquartered in Taiwan, produces LCD monitors and LCD TVs which are sold worldwide.

Table 5 Cost of conserved electricity (CCE) for reflective polarizers

Screen size/resolution	Backlight	$\Delta P_{\text{on-mode}}$[a] (W/unit)	ΔC_{m}[b] ($/unit)	CCE_{m}[c] ($/kWh)	ΔC_{p}[d] ($/unit)	CCE_{p}[e] ($/kWh)
21.5″ (1,920×1,080)	CCFL	4.7	3.4	0.079	4.7	0.109
	LED	3.6	3.2	0.097	4.4	0.134
23.0″ (1,920×1,080)	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

Assumptions: discount rate=5 %, economic lifetime=6 years, daily usage=5 h

[a] 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)

[b] Incremental manufacturing cost=(manufacturing cost for 2012 standard models predicted by DisplaySearch)−(manufacturing cost for 2012 standard models with reflective polarizers estimated by authors)

[c] Cost to the manufacturer of conserved energy which is calculated by Eqs. 1 through 3 at IC=ΔC_{m}

[d] Incremental price=(average market price for 2012 standard models predicted by DisplaySearch)−(price for 2012 standard models with reflective polarizer estimated by authors)

[e] Cost to the final user of conserved energy which is calculated by Eqs. 1 through 3 at IC=ΔC_{p}

new 22-in. USB-powered monitor which is available in the market, in addition to AOC's other USB-powered monitors.

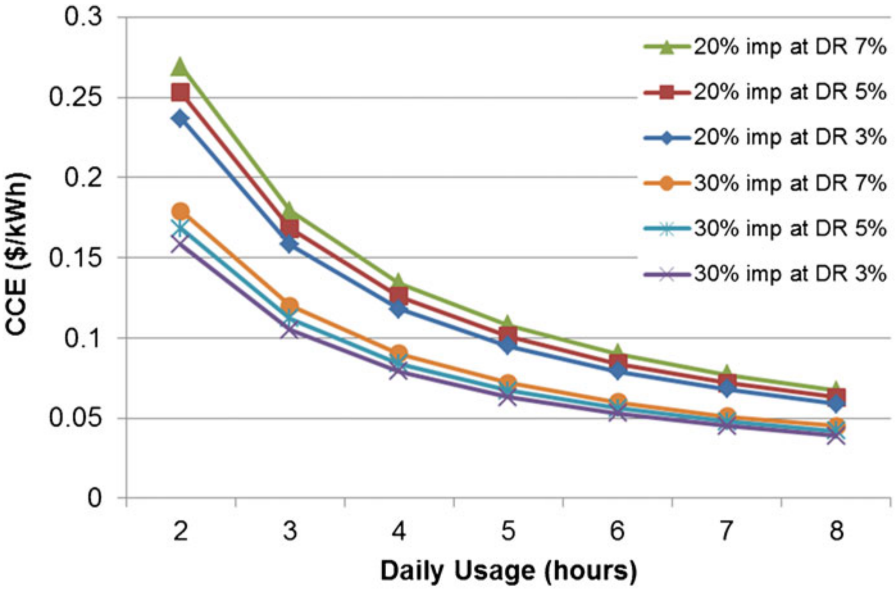
The future of DC-powered monitors as a mainstream technology is still uncertain. At present, sufficient market data does not exist to estimate the future market share of DC-powered monitors. However, the technical capacity to make and deploy these low-powered monitors exists currently, illustrating the efficiency potential available for PC monitors. There are significant additional 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 and AC/DC converter. 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 (Siefken et al. 2011; Lee 2010).

In summary, significant further improvement in power consumption is not expected for CCFL-LCD monitors, as manufacturers are not likely to invest further in making CCFL-LCD monitors more efficient due to their 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 the addition of an optical film such as a reflective polarizer. Reflective polarizers are a mature technology, although currently restricted in use only to a few high-end models. DC-power monitors such as USB-powered monitors with efficient LCD panels are currently feasible that can reduce power consumption by 40–50 %, compared to typical monitors currently on the market. Ambient light sensor is also a commercially available option for manufacturers to choose to improve efficiency of PC monitors. In the next section, we discuss the cost-effectiveness of these three efficiency improvement options for LCD monitors.

Cost-effectiveness analysis

Cost of conserved energy (CCE) is a metric 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

Fig. 9 Sensitivity of cost per unit of conserved electricity (CCE_m) to daily usage and discount rates



Assumption: economic lifetime=6 years (imp=improvement potential, DR=discount rate)

compared to the cost of providing electricity, to the utility or consumer.[19] We calculate CCE from two perspectives: First, considering the incremental cost to the manufacturer, which we label CCE_m, and second, the incremental cost to the consumer which includes retailer markups[20] on the incremental manufacturing cost, which we label CCE_p. The former estimate can be used for assessing the cost-effectiveness of upstream incentive programs (e.g., manufacturer incentives), whereas the latter can be used to assess that of downstream incentive (e.g., consumer incentives) 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 the annual energy savings due to the efficiency improvement. Product categories are defined by screen size and backlight type (e.g., 23-in. 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:

$$CCE_i = \frac{\text{annualized } IC_i}{\text{energy savings}_i} \tag{1}$$

where

$$\text{annualized } IC_i = IC_i\left[\frac{\text{discount rate}}{1-(1+\text{discount rate})^{-\text{lifetime}_i}}\right] \tag{2}$$

$$\text{Energy Savings}_i\left(\frac{\text{kWh}}{\text{year}}\right) = \text{Power reduced (watts)} \times \text{daily usage}\left(\frac{\text{hours}}{\text{day}}\right) \times \frac{365\text{ days}}{\text{year}} \times \frac{1\text{ kW}}{1,000\text{ W}} \tag{3}$$

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

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

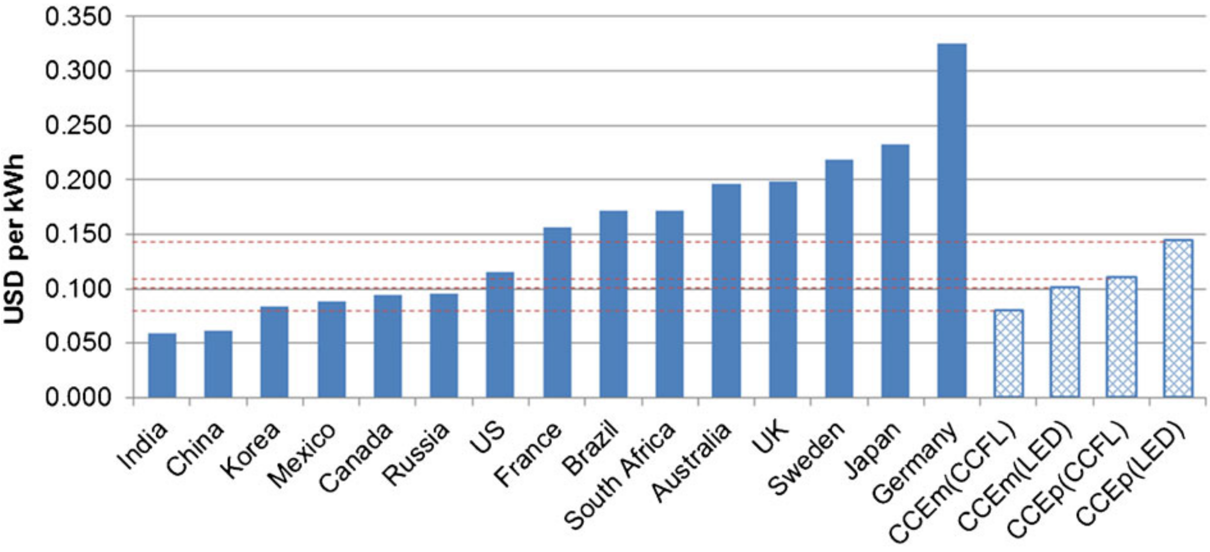
Energy savings

We estimate energy savings of an efficiency improvement option based on the incremental reduction from the baseline PC monitor power consumption.

---

[19] We do not include program administration and implementation costs in this cost-effectiveness analysis, as we are assessing cost-effectiveness to the consumer of standards and labeling programs, as well as incentive programs. Typical customer incentive program administration costs in the USA are in a range of 8–38 % of the total program costs (Friedrich et al. 2009).

[20] For the purposes of this paper, retailer markups are based on the US market.



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

Fig. 10 Energy prices and cost per unit of conserved electricity (CCE)

The baseline is calculated from the ENERGY STAR Version 5-registered PC monitors listed on the ENERGY STAR website as of September 2011. As discussed in "Overview of PC monitor market and energy consumption trends" section, this dataset can be treated as representative of average PC monitors sold in that year.

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 2011d). 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.

Average usage

Computer usage patterns also vary with region, sector of use, consumer lifestyle, and power management scheme applied to the system. For the USA, the average daily usage of PC monitors ranges from 2.2 to 6.4 h per day.[21] ENERGY STAR uses 5.2 h per day as a default value for the average usage of PC monitors in its office equipment savings calculator (ENERGY STAR 2011d). For the European region, estimates of average daily usage of monitors range from 3.5 to 7.1 h (IVF 2007), or 2 to 8 h by sector of use (EU-ENERGY STAR 2011). For the purposes of this analysis, we assume that average daily usage at on-mode is 5 h for all monitors, and perform a sensitivity analysis in the range of 2 to 8 h to account for country-specific variations (Table 4).

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,

---

[21] Estimated average operating hours for PC monitors are categorized into user behavior patterns for both residential and commercial uses: "power managed and turned off," "not power managed and turned off," "power managed and left on," and "not power managed and left on".

Table 6 Estimate of incremental costs for a 23-in. USB-powered monitor

Base model	LED backlit LCD monitor, 23″, 1,920×1,080		
Components	Sub-components	Change in efficiency	Change in cost
Backlight unit	Optimized optical film stack (a)	+20–30 %	↑ \$4.8–5.0
	Backlight lamps/LED driver (b)		↓ \$0.7–1.0
LCD panel	Optimization for efficient LCD panel (c)	+10–20 %	↑ (unknown)
Other electronics	Power supply and AC power cable (d)	+5–10 %	↓ \$4.5–5.5

Authors' estimates as of Q3 2011 products based on DisplaySearch (2011b, d, e)

and perform a sensitivity analysis in the range of 3 % to 7 % to account for country-specific variations.

Product categories analyzed

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 in the absence of policy intervention. For the cost-effectiveness analysis, we selected two product categories (21.5 and 23 in.) which become the most common screen sizes through 2012. While the selected product groups together 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). The results of our analysis for selected screen sizes also hold for other screen size categories since the costs and benefits of adopting the selected options are generally proportional to screen area or independent of screen size. Thus, any size variation does not largely affect cost-effectiveness.

Option 1: 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 in the absence of any market transformation policy action.

We assumed that reflective polarizers improve PC monitor efficiency by at least 20 % regardless of backlight source (see “Efficiency improvement options and related trends for PC monitors” section 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

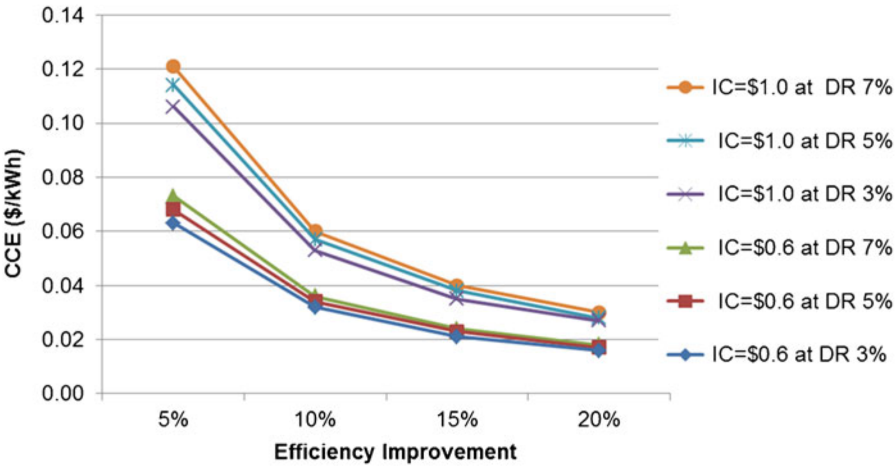


Fig. 11 Sensitivity of cost per unit of conserved electricity (CCE_m) for ambient light sensors

Assumption: economic lifetime = 6 years, daily usage = 5 hours (IC=incremental cost, DR=discount rate)

Table 7 Cost of conserved electricity (CCE_m) for 23-in. LED-LCD monitors

Option	Savings potential	CCE_m (\$/kWh)
Reflective polarizer	20–30%	0.070–0.104
Efficient LCD panel	10–20%	0.077–0.256[a] (indicative)
USB-powered monitor with efficient LCD panel and reflective polarizer	50%	<0.100
Ambient light sensor	5–20%	0.017–0.114

Assumptions: discount rate=5%, economic lifetime=6years, daily usage=5h

[a] Based on the estimated incremental costs for efficient LCD panels (i.e., \$1.7–9) where the USB-powered monitor is cost effective

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 a CCE_m with a range of \$0.08/kWh and \$0.10/kWh and a CCE_p with a range of \$0.11/kWh and \$0.15/kWh.

CCE is inversely proportional to hours of use, i.e., if hours of use are halved (2.5 h a day from our assumption of 5 h/day), CCE will double (see Eq. 1 and 3). Further, reflective polarizers increase efficiency by 20–30 % (versus our assumption of 20 %); hence, our analysis is conservative. Figure 9 shows CCE_m for LED-LCDs versus daily usage at various combinations of discount rates and efficiency improvement potential.

The deployment of reflective polarizers can be encouraged in a cost-effective manner to improve PC monitor efficiency because the CCEs are less than the average residential electricity prices of many countries (see Fig. 10). The results of our sensitivity analyses indicate that this result would also hold under cases where 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), or vice versa.

Table 8 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 consumption[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 % (70–80 %)[d]	–	–
		Ver. 6[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 "Efficiency improvement options and related trends for PC monitors" section

[c] (A): reflective polarizer, (B): USB-powered system with high-efficiency LCD panel, including reflective polarizer

[d] Market penetration rate of monitors that are estimated to meet ENERGY STAR Version 5

[e] ENERGY STAR 2012a

[f] Predicted market penetration rate of monitors that meet the corresponding efficiency level. Majority of LED-LCD monitors are expected to meet the efficiency level

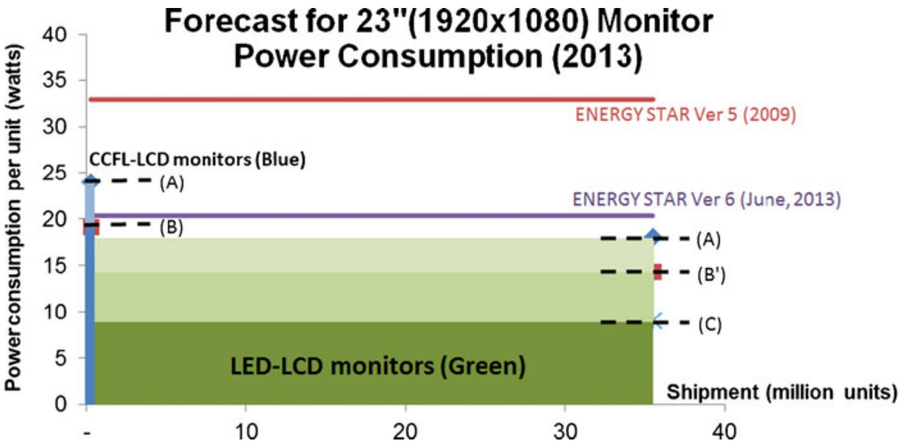


Fig. 12 Possible levels for standards, labeling, and incentive programs

Option 2: efficient LCD panels and DC-powered monitors

Although efficient LCD panels[22] required for DC-powered 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 and AC/DC converter, leading to further cost reduction in packaging and shipping.

In fact, the total manufacturing cost for USB-powered DC monitors is not likely to increase compared to conventional AC-powered PC monitors (Lee 2010). For example, the on-line market price of AOC 22-in. (actual screen size, 21.5″) E2251FWU (1,920×1,080, USB-powered) is available from about $150 upward (as of September 2012),[23] while the average market price of 21.5-in. 1,920×1,080 LED-LCD monitors in the US market is recently estimated at about $148 as of third quarter of 2012 (DisplaySearch 2012a).

To be specific, we estimated the incremental costs of a 23-in. USB-powered monitor (see Table 6). First of all, manufacturers may need to optimize the currently employed film stack when adding a reflective polarizer to the film stack ((a) in Table 6). Here, we consider only the material cost of a reflective polarizer. Second, higher brightness achieved by the optimized film stack allows manufacturers to reduce the number of LEDs or enables the LEDs driven at a lower power level ((b) in Table 6). Here, we assume that a 20–30 % reduction in backlight luminance can lead to a corresponding 20–30 % savings in backlight lamp cost. Then, manufacturers need to use a low power-driven LCD panel to optimize the LCD for the USB-powered system ((c) in Table 6). However, the incremental cost of this particular element (i.e., efficient LCD panel) is difficult to estimate. Lastly, as the efficiency of power supply units is generally between 85 % and 95 % (Park et al. 2011), a DC-powered system is expected to become more efficient than conventional AC-powered system by at least 5 %. Additional cost reduction in the packaging and shipping process seems possible, but is not included in this estimate.

If the incremental manufacturing cost to optimize the LCD panel for the USB-powered system is in a range of $0.2 and $1.7 (see Table 6), both the cost savings and the incremental costs for 23-in. USB-powered monitors could be similar in the range of at least $5 to $7, effectively cancelling each other out. This is borne out by the example cited above.

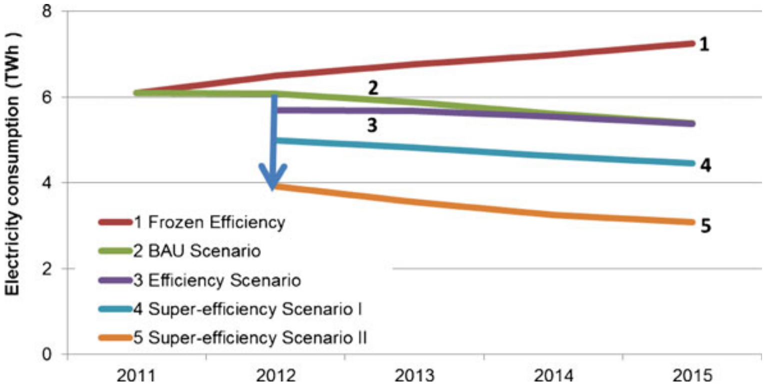
The incremental cost for efficient LCD panel (optimized for the USB-powered system) may vary as it

---

[22] Efficiency improvement of most commercially used LCD panel technologies (e.g., high panel transmittance discussed in "Efficiency improvement options and related trends for PC monitors" section) usually requires R&D investment because it involves a non-linear process of re-engineering the whole panel, and would involve changes in other components as well as the manufacturing process. Here, we consider efficiency of LCD panels currently achievable without additional R&D investment within the specific context of DC-powered monitors.

[23] Based on the search "AOC E2251FWW" at www.google.com/shopping.

Fig. 13 Global PC monitor electricity consumption for annual shipment



involves a non-linear process of re-engineering the whole panel, and would involve changes in other components as well. Assuming that the incremental cost for the efficient 23-in. LED-LCD panel with a saving potential of 20 % is \$1.7, where the USB-powered monitor is likely to be cost neutral, the $\mathrm{CCE_m}$ (at 5 % of discount rate, 6 years of economic lifetime, and 5 h of daily usage) for the efficient LCD panel only is \$0.077/kWh. Assuming that the incremental cost for the efficient 23-in. LED-LCD panel with a saving potential of 20 % is \$9, the $\mathrm{CCE_m}$ for the USB-powered monitor[24] with the efficient LCD panel is \$0.100/kWh, which is less than an average electricity price of many countries (see Fig. 9), while the $\mathrm{CCE_m}$ for the efficient LCD panel is \$0.256/kWh. The \$9 accounts for about 4.4 % of a normal 23-in. LED-LCD monitor set (as of second quarter of 2011, DisplaySearch 2011d). Thus, DC monitors are likely to be cost effective and provide savings on the order of approximately 50 % from current levels as long as the incremental cost for efficient LCD panels is less than about 4–5 % of the LCD monitor price.

Option 3: ambient light sensor

Ambient light sensors are commercially available, and their material cost does not vary with screen size or resolution. As discussed in "Efficiency improvement options and related trends for PC monitors" section, in case the ambient light level decreases from 300 to 10 lux, it is expected to bring a power reduction of about 20 % (ENERGY STAR 2012a). According to the PC monitor industry,[25] the material cost of an ambient light sensor for PC monitors is in a range of \$0.6 and \$1.0 per unit as of the first quarter of 2012. If we assume that a 5–20 % (i.e., Δ0.95–3.8 W) energy saving is possible for 23-in. LED-LCD PC monitors, the $\mathrm{CCE_m}$ (at 5 % of discount rate, 6 years of economic lifetime, and 5 h of daily usage) for the ambient light sensor is in a range of \$0.017/kWh and \$0.114/kWh, which could be regarded as cost effective. Figure 11 shows CCE for LED-LCDs versus efficiency improvement at various combinations of discount rates and incremental material costs.

Ambient light sensors might enable TVs and PC monitors being used at home to reduce energy consumption. For example, the majority of TV viewing in the USA occurs between 0 and 100 lux (Wold 2011)[26] where ambient light sensors work effectively. However, as already discussed in "Efficiency improvement options and related trends for PC monitors" section, it is difficult to more accurately determine the average effect of ambient light sensors on energy consumption of a PC monitor because sufficient data on the varied lighting conditions where PC monitors

---

[24] Total savings potential=50 %, total net incremental cost= \$8.8.

[25] We got the cost information from a top-tier manufacturer, but the identities of the expert we interviewed and the manufacturer source are kept confidential at the interviewees' request.

[26] Wold (2011) is based on data collected from 60 residences over a 7-day time period in October 2011 in both the Washington, DC, USA and Sacramento, CA, USA metro areas.

Table 9 Summary of global savings potential in LCD monitors by scenario

	Scenario compared	Annual savings in 2015	Cumulative savings from 2012 through 2015	Lifetime savings (4–6years)
Base case (BAU)	Frozen efficiency	4.5	8.9	18.0–27.0
Efficiency case	Base case	0.7	2.3	2.8–4.2
Super-efficiency case I	Base case	4.1	8.1	16.3–24.5
Super-efficiency case II	Base case	9.2	22.7	36.7–55.1

Unit: terawatt-hours (TWh)

are used across regions and sectors is not available. Also, ambient light sensors are not expected to provide a significant contribution to energy savings of PC monitors being used at the commercial sector (i.e., office) because typically recommended light level for office work with computers is between 300 and 500 lux[27] (US GSA 2003) as excessive contrast levels between a visual target and the background may cause eye fatigue to computer users (US GSA 2003).

Table 7 summarizes the $\mathrm{CCE_m}$ ranges and savings estimates of the technical options discussed above.

Policy insights to accelerate adoption of efficient PC monitors

Although we analyzed currently available and dominant technologies in order to identify feasible and cost-effective efficiency improvement options, there is uncertainty regarding precisely which efficiency improvement options will be adopted. We do not claim that the selected options are the best or only efficiency improvement options available. This analysis does not endorse any specific technology nor advocate prescription of proprietary technology for a standards-setting process or design of incentive programs, but merely discusses certain technologies with to illustrate the magnitude of cost-effective savings available.

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 (i.e., BAU options in Table 3) and then assess how further efficiency improvements can be facilitated.

Based on the discussion in “Efficiency improvement options and related trends for PC monitors” section, 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 BAU improvements, manufacturers can further reduce power consumption by using cost-effective options such as optical films, efficient LCD panels, ambient light sensors, a combination of these, or other equivalent technologies. 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 and cost effectively reduce energy consumption by as much as 50 % compared to LED-LCD's BAU consumption. Table 8 summarizes LCD monitor efficiency improvements possible by adopting the efficiency improvement options discussed above. Numbers (except for market share) in Table 8 are based on 23-in. LCD monitors, and the reference value (100 %, highlighted in gray) is the average on-mode power consumption of CCFL-LCD monitors in 2011. As seen in Table 8, although ENERGY STAR Version 6 specifications are 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

---

[27] The Illuminating Engineering Society (IES)'s Lighting Handbook is widely used as a general guide.

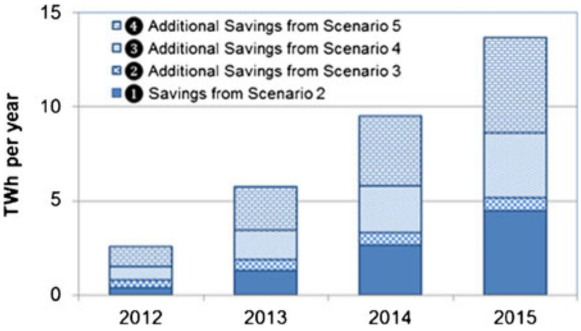


Fig. 14 Global PC monitor savings potential

consumption level 5 % less than the 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 Version 6 efficiency specification, this level can be considered for minimum standards.

LED-LCD monitors which use efficient optical films such as reflective polarizers, efficient LCD panels, or other equivalent efficiency improvement options and USB-powered LED-LCD monitors using similar efficient technologies can further achieve energy consumption 23 % and 43 % less than the ENERGY STAR Version 6, respectively.[28] These can be possible target efficiency specifications for advanced labeling or incentive programs. In 2015, the share of LED-LCDs is expected to be 97 % in the market. Thus, potential levels for future standards and incentives will have to be more aggressive than the Version 6 levels in order to impact efficiency further beyond these levels.

We estimate that a power consumption level 20 % below ENERGY STAR 6.0 can be achieved by deploying cost-effective, energy-efficient technologies at relatively small incremental costs (for example, applying reflective polarizers has an incremental costs of \$3–6). A part of these incremental costs can be covered by incentives to facilitate adoption of models which reach this level. Incentive programs may incur program design, and implementation costs which need to be considered while evaluating the cost-effectiveness of such programs.[29]

Figure 12 shows an example of possible power consumption levels for standards, labeling, and incentive programs.

Insights from the above example are not limited to ENERGY STAR and provide policy makers with a sense of what levels of efficiency are possible for PC monitors currently and in the next 2–3 years.

Global savings potential for efficiency improvement in PC monitors

To estimate global savings potential, we selected ten product categories[30] 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 h for all monitors (see "Cost-effectiveness analysis" section 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.[31] 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 shipments of that product. We assessed the following scenarios in estimating the global saving potential, and Fig. 13 shows the results by scenario.

Frozen efficiency scenario

In this scenario, we take into account the projected large-scale market transition in LCD technology,

---

[28] Ambient light sensors have not been included in this section due uncertainty of savings potential and limitation of the impacts on commercial sector.

[29] In fact, for ENERGY STAR-qualified PC monitors, many US utilities have been providing incentives to manufacturers or retailers in a range of \$5–30 between 2010 and 2012 (ENERGY STAR 2011e).

[30] 17″ (1,280×1,024), 18.5″ (1,366×768), 19″ (1,440×900), 20″ (1,600×900), 21.5″ (1,920×1,080), 22″ (1,680×1,050), 23″ (1,920×1,080), 23.6″ (1,920×1,080), 24″ (1,920×1,080), and 27″ (1,920×1,080).

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

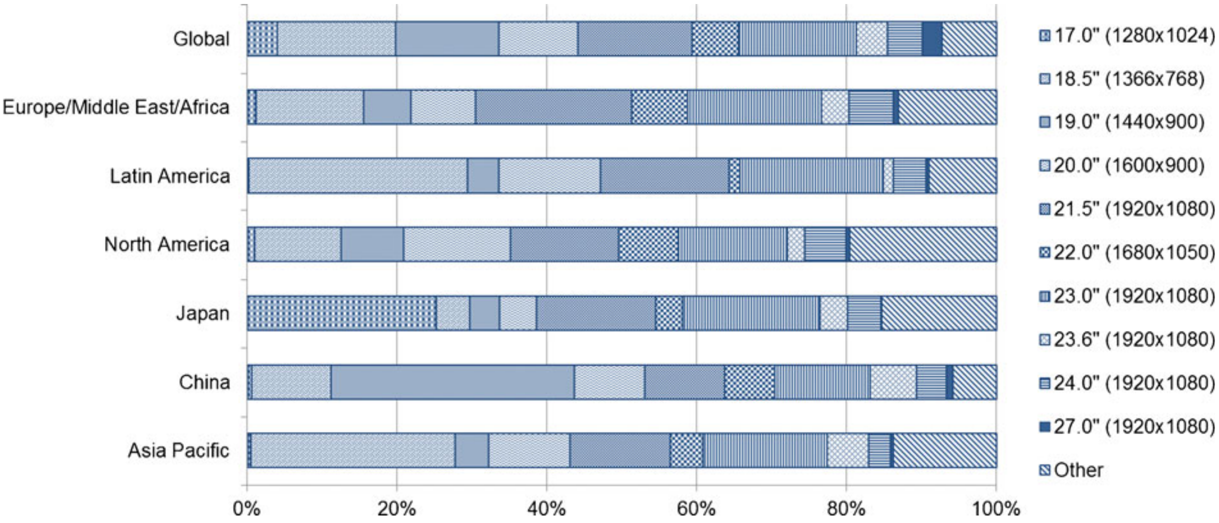


Fig. 15 Forecast for PC monitor market distribution in 2012 by selected product group

from less efficient backlights (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/year in 2011 to 7.2 TWh/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 Figs. 1 and 4).

Base Case (BAU) scenario

Based on the discussion in "Efficiency improvement options and related trends for PC monitors" section, 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-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/year in 2011 to 5.4 TWh/year in 2015.

Efficiency scenario

In this scenario, we assume that, in addition to the base case improvement, CCFL-LCD monitors employ a cost-effective option, to meet the proposed power consumption requirement, i.e., 5 % below ENERGY STAR Version 6 specification (see Table 7). 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/year in 2011 to 5.4 TWh/year in 2015. The effect of this case will significantly decrease through 2014 because CCFL backlights are expected to be phased out of the market.

Super-efficiency scenario I

In this scenario, we assume all LCD monitors with efficiency levels equivalent to those achievable by employing a cost-effective option such as an efficient optical film. 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/year in 2011 to 4.5 TWh/year in 2015.

Super-efficiency scenario II

In this scenario, we assume all LED-LCD monitors employ technology as energy efficient as

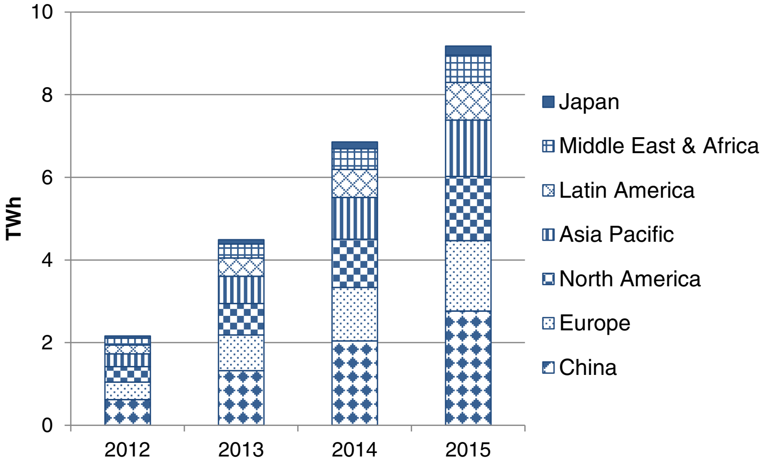


Fig. 16 PC monitor cost-effective savings potential by region

USB-powered monitors[32] with efficient optical films such as reflective polarizers, while CCFL-LCD monitors also adopt technology as efficient as 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/year in 2011 to 3.1 TWh/year in 2015.

The energy savings potential contributed from 2012 to 2015 PC monitor shipments by each scenario and corresponding policy programs, compared to scenario 1 or 2, are summarized in Table 9 and Fig. 14.

While we selected the ten major product groups which represent 93 % of the 2012 global PC monitor market, the main stream product group varies with region. For example, 17-in. 1,280× 1,024 monitors represented about 32 % of the Japanese market and are expected to account for 25 % of the market in 2012, while 18.5-in. 1,366×768 monitors are dominant in Asia Pacific and Latin America (DisplaySearch 2011a). Figure 15 shows a predicted PC monitor market distribution in 2012 by selected group and region.

Based on these regional differences, Fig. 16 shows the energy savings potential by region with scenario 5, compared to scenario 2, i.e., cost-effective savings potential by scenarios 3 through 5.

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/year in 2015, and up to 55.1 TWh during their lifetime. About 44 % of this savings is achievable by adoption of efficient optical films such as reflective polarizers or equivalent technology resulting in global savings of about 4.1 TWh/year in 2015 and 24.5 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.

---

[32] When a monitor is in sleep mode, USB ports powering it might be still consuming electricity to charge a device, e.g., iPod or iPhone. While we conservatively assume that USB-powered monitors consume the same amount of power (0.5 W) as other scenarios in sleep mode in “Super-efficiency Scenario II,” it is possible that true savings potential with USB-powered systems may be greater than that described here.

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 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. Even though the savings potential estimated in this study may be difficult to capture fully, given the long time, it can sometimes develop and adopt energy efficiency programs. However, a short-term policy action based on the reliable results presented here can make a difference given the average economic lifetime of PC monitors is about 4–6 years. Furthermore, our results also highlight the open question of the appropriate policy tool to capture these savings fully in a rapidly evolving market. Further research is necessary to address this question fully.

Acknowledgements We wish to thank the reviewers of this article as well as the report, “Efficiency Improvement Opportunities for Personal Computer Monitors: Implications for Market Transformation Programs” (LBNL5533-E), on which this paper is based. This work was funded by the Bureau of Oceans and International Environmental and Scientific Affairs, US Department of State, and administered by the US Department of Energy in support of the Super-efficient Equipment and Appliance Deployment (SEAD) initiative through the US Department of Energy under Contract No. DE-AC02-05CH11231. Any errors or omissions are the authors' own.

References

Alexander, R. (2010). LCD monitor shipments defy downturn in 2009. March. IHS iSuppli. http://www.isuppli.com/display-materials-and-systems/news/pages/lcd-monitor-shipments-defy-downturn-in-2009.aspx.

Connection Research (2010). Carbon and computers in Australia—the energy consumption and carbon footprint of ICT usage in Australia. May. Prepared for the Australian Computer Society. http://www.computersite.com.au/assets/files/ACS_Computers_and_Carbon_Report.pdf.

Chang, N., et al. (2004). DLS: dynamic backlight luminance scaling of liquid crystal display. *IEEE transactions on very large scale integration systems (VLSI)*, vol. 12, No. 8, August 2004.

Da Silva, D., et al. (2010). Standby and Off-mode Energy Losses in New Appliances Measured in Shops (SELINA): consumption monitoring campaign of standby and off-mode energy losses in new equipment. http://www.selina-project.eu/files/Measurements%20of%20standby%20energy%20losses%20in%20new%20equipment.pdf.

Delforge, P. (2011). NRDC comments on energy star computers version 6 kickoff meeting (March 10, 2011). Natural Resources Defense Council. April.

DisplaySearch (2012a). Quarterly LCD monitor cost and price forecast report, second quarter 2012.

DisplaySearch (2012b). DisplaySearch's comment on 3D desktop PC monitor shipments. 10 Aug 2012.

DisplaySearch (2011a). Quarterly advanced desktop monitor shipment and forecast report, second quarter 2011.

DisplaySearch (2011b). LED&CCFL backlight cost report, second quarter 2011.

DisplaySearch (2011c). Quarterly advanced desktop monitor shipment and forecast report, fourth quarter 2011.

DisplaySearch (2011d). Quarterly LCD monitor cost and price forecast report, third quarter 2011.

DisplaySearch (2011e). Quarterly large-area TFT LCD cost model, second quarter 2011.

ENERGY STAR (2010). ENERGY STAR unit shipment and market penetration report calendar year 2009 summary. http://www.energystar.gov/ia/partners/downloads/2009_USD_Summary.pdf.

ENERGY STAR (2011a). ENERGY STAR unit shipment and market penetration report calendar year 2010 summary. http://www.energystar.gov/ia/partners/downloads/unit_shipment_data/2010_USD_Summary_Report.pdf.

ENERGY STAR (2011b). ENERGY STAR-qualified displays product list 2011. September.

ENERGY STAR (2011c). ENERGY STAR program requirement for displays version 5.

ENERGY STAR (2011d). ENERGY STAR office equipment savings calculator. http://www.energystar.gov/ia/products/fap//Calc_office_eq.xls. Accessed 16 Nov 2011.

ENERGY STAR (2011e). ENERGY STAR summary of consumer electronics programs by energy efficiency program sponsors (EEPS). October. http://www.energystar.gov/ia/partners/downloads/2011_ENERGY_STAR_Summary_of_Consumer_Electronics_Programs.pdf.

ENERGY STAR (2012a). ENERGY STAR program requirements product specification for displays—version 6.0.

ENERGY STAR (2012b). ENERGY STAR display dataset (as of August 23, 2011) to inform the development of the version 6 specification. 22 Feb 2012.

EU-ENERGY STAR (2011). Energy calculator PC and imaging equipment. http://www.eu-energystar.org/en/calculator.shtml.

European Commission (EC) (2011). Communication from the commission on the implementation of the ENERGY STAR programme in the European Union in the period 2006–2010. http://www.eu-energystar.org/downloads/EC%

20-%20ENERGY%20STAR%20programme%20in%20the%20European%20Union%202006-2010.pdf.

Fraunhofer, I. Z. M. (2007). EuP preparatory studies "televisions" (lot 5)—task 4 technical analysis. August. http://www.ecotelevision.org/finalised_documents.php.

Friedrich, K., et al. (2009). Saving energy cost-effectively: a national review of the cost of energy saved through utility-sector energy efficiency programs. American Council for an Energy-Efficient Economy. September.

International Data Corporation (IDC) (2010). EU ENERGY STAR penetration of efficient of office equipment. June 2010. Presentation. http://www.eu-energystar.org/downloads/specifications/20100610/EUESB%20Meeting%20market%20survey.pdf.

IVF Industrial Research and Development Corporation (2007). EuP preparatory studies lot 3—personal computers (desk tops and laptops) and computer monitors. August. http://extra.ivf.se/ecocomputer/downloads/Eup%20Lot%203%20Final%20Report%20070913%20published.pdf.

Horowitz, N. (2011). NRDC Title 20 recommendations for electronics products. California Efficiency Committee Scoping Workshop for Appliances. August.

International Energy Agency (IEA) (2009). Gadgets and gigawatts—policies for energy efficient electronics. http://www.iea.org/textbase/nppdf/free/2009/gigawatts2009.pdf.

International Energy Agency (IEA) (2011). 2011 key world energy statistics. http://www.iea.org/textbase/nppdf/free/2011/key_world_energy_stats.pdf.

Lee, D. (2010). USB-power monitor—promising eco-friendly, low power technology (Korean). DisplayBank Co. Ltd. July. https://www.displaybank.com/_kor/research/markettrack_view.html?id=4754&&startPage=10.

Microsoft Corporation (2012). Adjust your monitor's brightness and contrast. http://windows.microsoft.com/en-US/windows7/Adjust-your-monitors-brightness-and-contrast.

McNeil, M. A., et al. (2008). Potential benefits from improved energy efficiency of key electrical products: the case of India. *Energy Policy, 36*, 3467–3476.

Park, W. Y., et al. (2011). TV energy consumption trends and energy-efficiency improvement options. Lawrence Berkeley National Laboratory. LBNL5024-E. http://superefficient.org/Activities/Technical%20Analysis/SEAD%20TV%20Analysis.aspx.

Rosen, D. H., & Houser, T. (2007). China energy—a guide for the perplexed. Peterson Institute for International Economics. May.

Samsung Electronics (2011). Energy star compliance by product categories. August. http://www.samsung.com/us/aboutsamsung/sustainability/environment/eco_products/download/EnergyStar_compliance_by_product_category.pdf.

Shieh, H. D., et al. (2009). *Eco-display—an LCD TV powered by a battery?* Taiwan: Society for Information Display (SID), National Chiao Tung University.

Siefken, S., et al. (2011). 20.3: All-in-one monitor capable of power-over-ethernet or USB. *SID Symposium Digest of Technical Papers, 42*(1), 259–260.

3M (2011a). Demonstration of "DBEF energy saving solution". International Meeting on Information Display (IMID) 2011. Korea. October.

3M (2011b). Demonstration of "23-inch USB-powered monitor solution". International Meeting on Information Display (IMID) 2011. Korea. October.

United States Department of Energy (US DOE) (2009). Preliminary technical support document: energy efficiency program for consumer products: refrigerators, refrigerator-freezers, and freezers. November.

United States Department of Energy (US DOE) (2011). Solid-state lighting research and development: multi year program plan. March 2011 (Updated May 2011).

United States Energy Information Administration (US EIA) 2010. Electricity prices for households (updated on June 10, 2010). http://www.eia.gov/emeu/international/elecprih.html.

United States Environmental Protection Agency (US EPA) (2009). ENERGY STAR program integrity can be enhanced through expanded product testing. Report No. 10-p-0040. 30 Nov 2009. http://www.epa.gov/oig/reports/2010/20091130-10-P-0040.pdf.

United States General Services Administration (US GSA) 2003. 2003 Facilities standards—6.15 lighting. Last Reviewed 3 July 2012. http://www.gsa.gov/portal/content/101308.

Hewlett-Packard Company, Intel Corporation, Microsoft Corporation, NEC Corporation, ST-Ericsson, and Texas Instruments (2011). Universal Serial Bus 3.0 specification revision 1.0. http://www.usb.org/developers/docs/usb_30_spec_022412.zip.

Waide, P. (2011). Opportunities for success and CO_2 savings from appliance energy efficiency harmonisation. Navigant Consulting. March. http://www.clasponline.org/en/ResourcesTools/Resources/StandardsLabelingResourceLibrary/2011/Opportunities-for-appliance-EE-harmonization.

Wold, C. (2011). Analysis of background illuminance levels during television viewing. December. The Collaborative Labeling and Appliance Standards Program (CLASP). http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/analysis_of_background_illuminance_levels_during_television_viewing.pdf.