Energy Policy 59 (2013) 361–372

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Efficiency improvement opportunities in TVs: Implications for market transformation programs

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HIGHLIGHTS

- We analyze the impact of the recent TV market transition on TV energy consumption.
- We review TV technology options that could be realized in the near future.
- We assess the cost-effectiveness of selected energy-efficiency improvement options.
- We estimate global electricity savings potential in selected scenarios.
- We discuss possible directions of market transformation programs.

ARTICLE INFO

Article history:
Received 10 February 2012
Accepted 26 March 2013
Available online 15 May 2013

Keywords:
TV energy efficiency
Cost effectiveness
Market transformation

ABSTRACT

Televisions (TVs) account for a significant portion of residential electricity consumption and global TV shipments are expected to continue to increase. We assess the market trends in the energy efficiency of TVs that are likely to occur without any additional policy intervention and estimate that TV efficiency will likely improve by over 60% by 2015 with savings potential of 45 terawatt-hours [TW h] 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 these options improves efficiency by at least 20% cost effectively beyond ongoing market trends. We provide insights for policies and programs that can be used to accelerate the adoption of efficient technologies to further capture global energy savings potential from TVs which we estimate to be up to 23 TW h per year in 2015.

1. Introduction

The total global TV electricity consumption was estimated to be more than 250 terawatt hours [TW h] in 2008, i.e., more than 5% of total global residential electricity consumption (International Energy Agency (IEA) 2009). Since the mid-2000s, the global TV market has undergone a major transition from traditional cathode ray tube (CRT) TVs to other types, particularly flat panel display (FPD) TVs such as liquid crystal display (LCD) and plasma display panel (PDP).[1] While this market transition is expected to lead to efficiency improvement of TVs, other emerging technology trends such as larger average screen size, three-dimensional (3D) video capability, and network functions, e.g., ethernet and universal serial bus (USB), are likely to increase the energy consumption of new TVs.

A global assessment of efficiency[2] improvement opportunities in TVs is needed for three reasons. *First*, policies to facilitate the adoption of cost effective[3] efficiency improvements in appliances such as TVs are necessary to correct market failures such as uncaptured economic and environmental benefits available from reduced energy consumption. Even though the market is moving to increasing efficiency on its own under a business-as-usual (BAU) case, it is not capturing all available savings from adopting cost effective technologies such as backlight diming and efficient optical films. Section 3 and 4 provide such examples. Although several other studies develop potential scenarios of TV efficiency improvement (see for example, International Energy Agency (IEA), (2009), International Energy Agency - Efficient Electrical End-Use Equipment (IEA 4E) (2010), Market Transformation Programme (MTP) (2010b)), none of these studies assess the cost-effectiveness

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[1] LCD and PDP TV shipment in 2007 accounted for about 45% of the global TV shipments, and CRT TVs accounted for about 54% (DisplaySearch, 2010).

[2] In this paper, efficiency improvement in TVs is defined as reduction in on-mode power consumption [watts, W] for a given screen size, or equivalently better on-mode power performance in terms of watts per unit of screen area [W/m^2].

[3] 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 (kW h), less than electricity price.

0301-4215
http://dx.doi.org/10.1016/j.enpol.2013.03.048

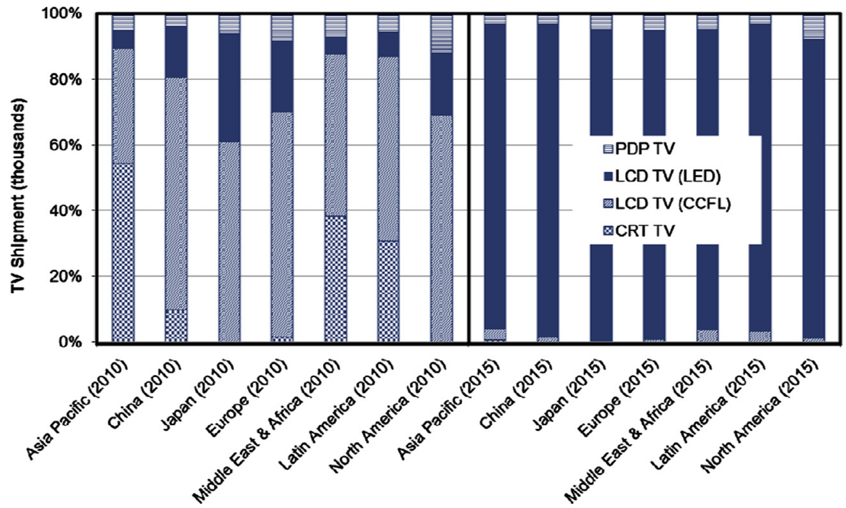


Fig. 1. Actual (2010) and Forecasted (2015) TV Market Transition by Region and Screen Technology
Source: DisplaySearch, 2011a

of efficiency improvement options in detail for TVs. Such assessment is needed for designing appropriate policies and market transformation programs[4], e.g., energy efficiency standards and financial incentive programs, to facilitate the adoption of cost effective efficiency improvements.

Second, the literature focused on TVs is limited and was published before the ongoing large scale transition from cold cathode fluorescent lamp (CCFL) backlit LCD (CCFL–LCD) TVs to light emitting diode (LED) backlit LCD (LED–LCD) TVs. LED–LCD TVs are likely to be at least 50% and 90% of the TV shipments in 2012 and 2015, respectively, (DisplaySearch, 2011a).

Third, there are only limited regional differences and global similarity in TV screen (i.e., LCDs) and LCD backlight technology (see Fig. 1), although there are regional differences in screen size preferences and market share of TVs with additional 3D or network features. Major brands distribute similarly designed TVs with similar energy consumption characteristics across many regions. For example, 98% of Samsung's flat-panel TVs on the global market, which represent the largest single share (~18%) of the market, have met the ENERGY STAR Version 4 requirements (Samsung Electronics, 2011). In addition, TV manufacturing is highly globalized and concentrated. The top six TV brands[5] produce more than 60% of TVs sold worldwide (DisplaySearch, 2011a; Morrod, 2012). Accordingly, the research presented in this paper is applicable to TVs in most countries.

This paper focuses on LCD TVs since they are expected to dominate worldwide sales, amounting to an expected 95% of global TV shipments by 2015 (DisplaySearch, 2011a). Although large Organic Light Emitting Diode (OLED) TVs (larger than 40 in.) are expected to be on the market in 2013, they are not expected to be cost competitive against LCD TVs at least until 2015. PDP TVs are expected to remain viable but to decline steeply in market share as both LCD and OLED TV production costs decline. We consider efficiency improvement options for LCD TVs that are technically feasible, practical to manufacture, and could be realized in the short term (over the next three years), as the rapid evolution of technology in the display market makes a forecast over a longer time scale highly uncertain (see Section 2 for details) and therefore less useful from a policy perspective. Instead, a short-term policy action based on more reliable analysis can make a difference given the fact that the average economic life time of TVs is about 6–10 years (DisplaySearch, 2011c; Fraunhofer IZM, 2007 Task 2, Market Transformation Programme (MTP), 2010a). In spite of questions or concerns about the potential impacts of emerging technology trends such as new displays (e.g., OLEDs), 3D capability, and the increased network connectivity on energy consumption in TVs, we see that the dominant screen technology (i.e., LCDs) and screen size are more important in terms of energy consumption and savings potential than these emerging trends which are not significant now (in terms of market share) or whose energy consumption and savings impact are still uncertain within the time horizon relevant for such a rapidly evolving market and the global scale considered in this paper (see Section 2 for details).

We obtained the data for this paper primarily from the following sources: a review of the literature including technical reports, DisplaySearch reports and data sets[6], the ENERGY STAR database for TVs that meet the Version 4 or 5 specifications, international conferences and interviews with manufacturers and experts in the field.

The remainder of this paper is organized as follows. In Section 2, we present an overview of the TV market, technology trends and energy consumption trends. In Section 3, we assess technologically feasible energy-efficiency improvement options, adoption trends of such options, and the impact of these options on the energy consumption of TVs. In Section 4 we present a cost of conserved electricity (CCE) analysis to assess the cost-effectiveness of options identified in Section 3. Section 5 offers suggestions for accelerating the adoption of efficient technologies, and in Section 6 we estimate the energy savings potential of such adoption. Section 7 presents concluding remarks.

[4] We use the definition from American Council for an Energy-efficient Economy (ACEEE). "The term market transformation is the strategic process of intervening in a market to create lasting change in market behavior by removing identified barriers or exploiting opportunities to accelerate the adoption of all cost-effective energy efficiency as a matter of standard practice."

[5] Samsung, LG, Sony, Panasonic, Toshiba, and Sharp. TCL has been recently increasing its share and ranked in the Top 5 in Q1 2012.

[6] DisplaySearch has been providing reliable information based on manufacturer surveys and analyses on the display market and related industries. Because the data sets we used do not provide country-specific TV shipment data except for China and Japan, we assume country-specific contribution to the corresponding region in accordance with indicative recommendations from DisplaySearch and TV marketing experts in the field.

2. Overview of TV market and technology trends

2.1. Global TV shipments and screen size

LCD TVs are expected to account for more than 85% of the global TV market through 2012, including all screen sizes (DisplaySearch, 2011a; Morrod, 2012). Further, within the LCD TV market, a large-scale transition is expected from conventional CCFL–LCD TVs to LED–LCD TVs for all screen sizes, resulting in substantial improvements in the average efficiency of TVs on the market. Fig. 2 illustrates these predicted market transitions from CRT to LCD, and CCFL–LCD to LED–LCD TVs.

From 2010 to 2015, the average screen size (measured diagonally) and total annual TV shipments are projected to increase by about 9% and 15%, respectively, leading to a 31% increase in the aggregate screen area of annual TV shipments (DisplaySearch, 2011a). This increase in both screen size and shipment is likely to increase energy consumption in new TVs. However, the transition from CCFL–LCDs (inefficient) to LED–LCDs (efficient) and efficiency improvement within each technology in a BAU scenario, likely to be adopted regardless of policy intervention, are expected to reduce total energy consumption in the new TVs (see Section 6 for details). Fig. 3 provides a picture illustrating the cumulative effect of both factors.

2.2. Emerging trends

OLEDs are expected to begin penetrating into the TV market through 2013, but only reach sales of 2.7 million units (less than 1% of the global market) in 2015 (DisplaySearch, 2011a; McKinsey and Company, 2011). OLEDs have an inherent advantage over LCDs in terms of power management because each pixel in an OLED is individually controlled to generate light according to input signal images. Moreover, phosphorescent light-emitting materials enable greater power efficiency (Kim et al., 2009; Park et al., 2011). However, it does not seem that OLEDs will be cost competitive in the short term against LCD TVs (DisplaySearch, 2011a). This is likely even accounting for the fact that economies of scale and technological learning will reduce costs as the number of products being produced increases. This uncertainty implies that designing market transformation programs to encourage penetration of energy-efficient OLED TVs are still premature. Hence we have not focused on OLED technology here.

Another technology trend in the digital display market is 3D-capable displays. Current 3D-capable displays in 3D mode require

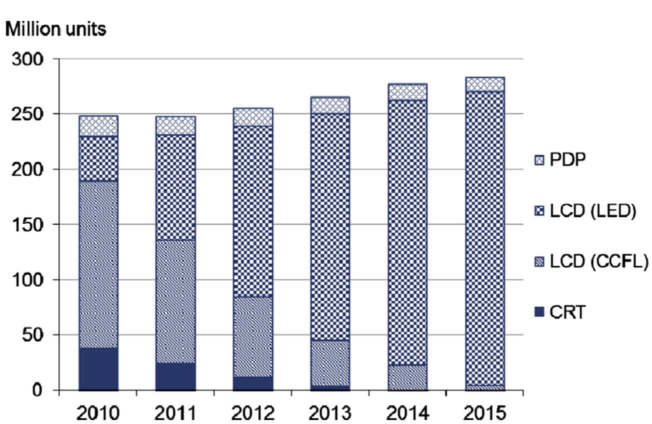


Fig. 2. Actual (Q1 2010-Q3 2011) and Forecasted (Q4 2011-Q4 2015) Global TV Shipments.
Note: Global shipments of projection TVs were 0.17 million units in 2010 and are expected to decrease. OLED TVs are not included in this graph as expected to reach only 2.7 million units in 2015.
Source: DisplaySearch, 2011a

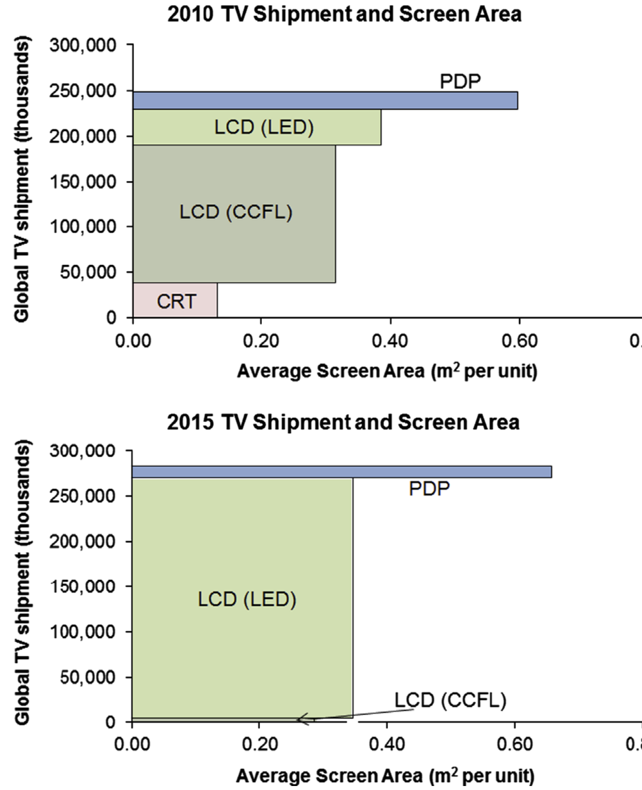


Fig. 3. Global TV Annual Shipments and Screen Area for 2010 (actual) and 2015 (forecast)
Note: Each shaded area represents the total screen area by screen or backlight technology. OLED TVs are not included in this graph as they are expected to reach only 2.7 million units in 2015.
Source: Author's calculation from DisplaySearch (2011a)

additional image processing and yield a relatively lower brightness level due to additional films or 3D-glasses in comparison to 2D mode. Therefore, manufacturers may increase the brightness level thus correspondingly increasing power consumption in 3D mode in comparison to 2D mode (Park et al., 2011). However, some manufacturers are overcoming the need for higher backlight brightness by improving screen technologies, including 3D technologies. In addition, as 3D content available to consumers is still limited, it is uncertain how many hours per day viewers will spend on 3D content.

Internet connected TVs, also known as "Smart TVs", are another recent trend. Smart TVs are expected to consume more energy relative to conventional (non-smart) TVs because of the following factors: advanced signal processing for additional network connectivity, the potential larger (or wider) screens and increased daily usage, quick start options, and network standby mode (Park et al., 2011). However, consumer behavioral patterns and integrated network features are beyond the scope of this paper, although the potential increase in TV screen size and corresponding energy consumption increase is included in the analysis. While we do not focus here on 3D technologies and Smart TV efficiency improvement here, all the efficiency improvement options and corresponding analysis presented here are also applicable to 3D TVs and Smart TVs.

3. Efficiency improvement options

An LCD, unlike other self-emissive flat-panel[7] displays such as PDP and OLED, is a non-emissive display that uses a backlight, e.g.,

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

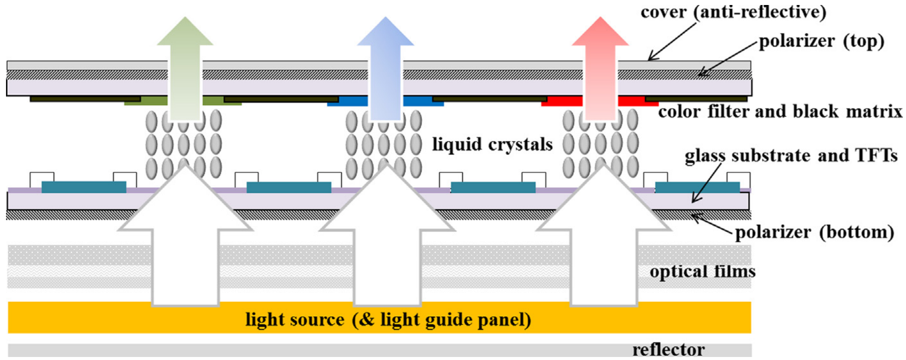


Fig. 4. Typical structure of a liquid crystal display (LCD).
Author's artwork.

CCFL or LED, as a light source. Millions of pixels of an LCD consists of liquid crystals (LCs) that can alter their crystalline structure or 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 Task 4). Thin film transistor (TFT)[8] technology on glass is used to drive or control the orientation of the LCs, i.e., pixels. Fig. 4 shows a typical LCD structure.

LCD TVs' overall efficiency, if viewed in terms of change in luminance[9] as light travels through the LCD TV set, has significant room for improvement. The final luminance leaving the screen is less than 10% of the initial luminance available from the backlight source because two crossed polarizers, a color filter, and TFT arrays in the LCD panel collectively absorb or reflect a significant amount of light from the backlight unit (Shieh et al., 2009). The required backlight luminance is thus highly sensitive to the panel transmittance and optical film efficiency. Therefore even small efficiency improvements in these components yield large payoffs in terms of required luminance and therefore overall efficiency.

3.1. *Efficiency improvement options and trends*

Efficiency improvement options—which also lead to concurrent improvements in other desirable product characteristics (e.g., LED backlighting leads to thinner/lighter TVs and better picture quality in color reproduction capability) or lead to reduction in overall costs (e.g., high efficiency LCD panels require fewer optical films or backlight lamps)—are more likely to be adopted on their own without additional policy intervention in comparison with options which predominantly improve only efficiency, or which increase manufacturing cost. Furthermore, electricity costs for TVs and corresponding savings are relatively a minor component of the total costs over the lifecycle of the TV in many countries.[10] Thus efficiency is unlikely to be a primary consideration in price-sensitive consumer's selection of TVs in many countries, presenting an additional rationale for policy intervention to improve efficiency. Table 1 summarizes LCD TV efficiency-improvement options which are also discussed in further detail below.

3.1.1. *Backlight sources*

CCFLs and LEDs dominate the current LCD TV backlight market. Based on 2010–2011 data for ENERGY STAR-qualified TVs, LED–LCD TVs are 20% to 30% more efficient on average than CCFL–LCD TVs (see Fig. 5). This is because LED efficacy (e.g., 50–70 lm/W in 2010) is higher than CCFL efficacy (e.g., 30–50 lm/W), and LEDs have a wide range of dimming methods, compared to CCFLs (Bousquet, 2010; DisplaySearch, 2011b). As TV manufacturers receive additional benefits from LED backlighting, such as high color reproduction capability and thinner/lighter form factors resulting in reduced logistics costs, a large scale transition from CCFL to LED backlight is expected to take place even under a BAU scenario.

LED backlight unit efficiency will improve even under a BAU scenario as a result of developments toward higher LED efficacy, optimized LED backlight structure, and better thermal management. Higher LED efficacy enables an LCD TV to employ fewer quantities of LEDs, whereby manufacturers can reduce material costs. The average LED efficacy for TVs in 2010 was 50–70 lm/W, which is expected to increase up to 100–125 lm/W in 2012 (DisplaySearch, 2011b; Park et al., 2011). Driven by this efficiency improvement, the average number of LED lamps used for a 32-in. LCD TV is expected to decrease by about 57% in 2015, compared to 2011 (DisplaySearch, 2011b).

3.1.2. *Optical films*

Improving the amount of light that can pass through optical films used in a TV without compromising on their function (e.g., light uniformity) reduces the amount of backlight needed to achieve an equivalent screen luminance, resulting in a corresponding reduction of the electricity consumption of LCD TVs. Optical films have been combined in many ways to reduce material costs as well as to increase efficiency.

Among many types of films, a reflective polarizer[11] such as 3M's Vikuiti™ Dual Brightness Enhancement Film (DBEF), is recognized by manufacturers as one of the best options for efficiency improvement in optical films. Such a reflective polarizer typically improves the LCD backlight unit by 30–50%, resulting in 20–30% efficiency improvement in the LCD TV (Fraunhofer, IZM. 2007 Task 6). Recent tests by 3M with CCFL–LCD and LED-LCD TVs found that DBEFs reduced power by 20% in CCFL–LCD and 24% in

[8] A Thin Film Transistor (TFT) is a transistor whose electrical current-carrying layer is a thin film, typically made of silicon.

[9] Luminance is a quantitative measure of the luminous intensity per unit area of a light source or an illuminated surface in a given direction. It is a value measured by a photo-detector and usually expressed in the form of candela per square meter [cd/m^2]. In general, brightness is the subjective visual perception for the luminance of an object, in which viewers experience a degree on the spectrum of intensity between "dim" and "bright".

[10] A 40 in. TV consuming 100 W used for 5 h a day for 365 days at an electricity price of 10 cents/kW h has an electricity cost of $18 per year. Thus, a 20% efficiency improvement will lead to saving of $ 3.6 per year. The retail prices of 40 in. LCD TVs are typically above $ 300.

[11] 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).

Table 1
LCD TV 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 (BAU)
		• High LED efficacy	• Cost reduction in the longer term (BAU) • Technical barrier in thermal management and short term cost increase from adoption of much higher efficacy LEDs than BAU trajectory
	Optical films	• Optimized combination of films • Multi-function film	• Trade-offs in material cost, ease of manufacture, and efficiency (BAU)
		• Reflective polarizer (e.g., 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 potential for total cost reduction.
Power management		• Brightness control (local dimming) by image signals	• Cost increase • The effect varies with backlight structure, input images, and algorithm.
		• Brightness control based on ambient light condition	• Cost increase • The effect varies with settings and ambient light condition
Other		• Power Supply Unit (PSU) Efficiency • Color gamut (by color filter or light source)	• Trade-off between cost and efficiency • Trade off with efficiency

Author's summary based on the following details.
[a] Dual brightness enhancement film produced by 3 M.

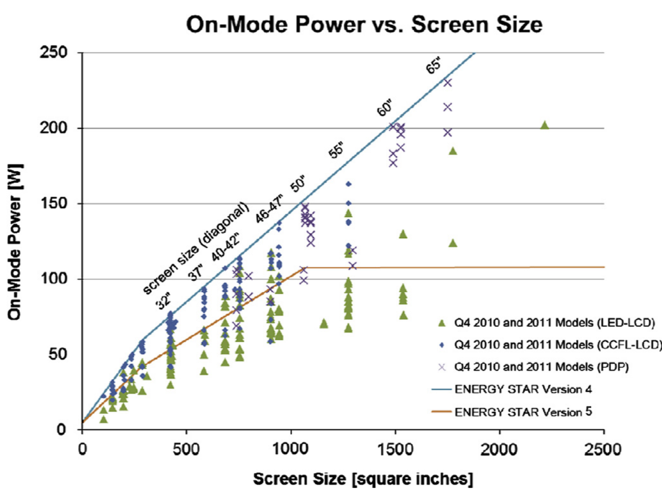


Fig. 5. On-mode Power of ENERGY STAR-qualified TVs.
Source: Author's calculation based on ENERGY STAR, 2011b

LED–LCD TVs (Fraunhofer IZM, 2007; DisplaySearch, 2011b; 3M, 2011). Even though DBEF contributes significantly to power savings, it is a proprietary technology that is viewed as unnecessary from a perspective focused solely on manufacturing cost reduction. For example, in 2010, a DBEF accounted for about 12% and 33% of total backlight unit costs for a 40-in. LED–LCD TV and a 40-in. CCFL–LCD TV, respectively (DisplaySearch, 2011b). As LCD panel transmittance and LED efficacy are improved, it is anticipated that manufacturers will be able to use more combinations of films in place of a reflective polarizer in the near future.

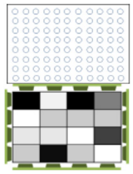
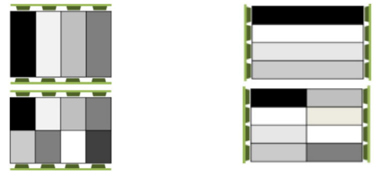
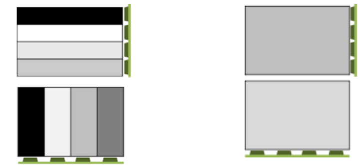
3.1.3. *High panel transmittance*

Improvement in LCD panel transmittance decreases the luminance that the backlight must achieve and thereby allows manufacturers to reduce the number of manufacturing steps as well as the amount of lamps in the backlight unit. Thus, manufacturers have an incentive to improve panel transmittance. An example of a recent technology trend in panel efficiency improvement is the development of low-voltage driven LCD panels. Low-voltage driven LC materials would allow manufacturers to use narrower low-resistance data lines, leading to high cell aperture ratio, than can currently be used, increasing the area available for light transmission, i.e., panel transmissivity. Aluminum (Al) has been used for data lines and can be replaced with copper (Cu) (DisplaySearch, 2011b). Even though manufacturers can achieve higher transmittance by adjusting cell structure, such new cell structures are not expected to cause panel performance and productivity to diminish. Because cell structure is the most technically complex element in LCD manufacture, changing cell structures requires further R&D investment associated with changes in cell-structure dependent components. In addition, LCD panel design and manufacturing technologies are proprietary. Depending on each type of LC cell structure, the average panel transmittance is expected to increase from 5–7% in 2011 to 7–10% in 2015 (Shieh et al., 2009; Baker, 2011; DisplaySearch, 2011b).

3.1.4. *Power management 1—Backlight dimming in relation to image signals*

Since an LCD is a non-emissive display, typically dark parts of a picture are created by blocking the polarized light in each pixel by adjusting LC orientation without dimming the LCD backlight and corresponding power reduction. Employing technology to locally dim the backlight lamps behind the dark parts of an image can thus 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 ambient light conditions, i.e., auto-brightness control (ABC), can 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. While

Table 2
Structures of LED backlight and dimming methods. *Source* for product category: DisplaySearch, 2011b.

Structure[a]	Direct/4 sides	2 sides	1 side
			
Applicable dimming	2D	1D/2D	1D/0D
Product category	Flagship (> 46″)	Main-stream to high-end (40″–55″)	Entry to mainstream (32″–47″)

[a] The above figures are for illustration purposes only. The number of block segments varies by TV model.

local dimming of LED-direct[12] backlights will be more effective in reducing power consumption than partial dimming of LED-edge backlights, LED-edge backlights are usually more efficient than LED-direct backlights because of the simple structure and fewer LEDs. In addition, LED-edge backlights are expected to dominate the LED–LCD TV market, accounting for over 95% of total LED–LCD TVs through 2011 (DisplaySearch, 2011a). Because the savings associated with various dimming methods varies with input images, dimming algorithm (including block segmentation), and backlight structure, the average effect needs to be determined using the IEC 62087 standard video clip. While a detailed investigation to estimate average savings from various dimming methods is beyond the scope of this study, according to Shiga et al., 2008, with 0D, 1D, and 2D dimming techniques, a sample movie consumed 83%, 71%, and 50% of the original backlight power, respectively. Manufacturers currently employ either a 0D dimming or no dimming option for low-end products, and advanced dimming methods are mostly limited to mid-range and/or high-end products (DisplaySearch, 2011b). Table 2 illustrates the sizes of TVs which these options are currently employed in.

3.1.5. Power management 2—Ambient light sensors and occupancy sensors

As a thumb rule, display power consumption is proportional to luminance. Ambient light sensors (i.e., auto brightness control or ABC) enables a TV to adjust its brightness level in response to ambient light levels, although the effect varies from model to model based on the manufacturers' design scheme. In case the ambient light level decreases from 300 lx to 10 lx, it is reasonable to expect a power reduction of about 20% on average (ENERGY STAR, 2012a). In fact, the majority of TV viewing in the U.S. is reported to occur between 0 lx and 100 lx (Wold, 2011)[13] where ambient light sensors work effectively. However, it is difficult to accurately estimate the average effect of ambient light sensors on energy consumption of a TV because sufficient data on the varied lighting conditions where TVs are typically used across regions and sectors is not available. In case a TV unit is featured with backlight dimming in relation to both image signals and ambient light levels, there will be an overlap both in energy savings and the incremental cost. For example, the net incremental cost for adding ABC to a TV unit with backlight dimming scheme would depend solely on the cost of ambient light sensors, and the net incremental savings of ABC will be lower in a TV with such dimming.

Occupancy sensors can also help save energy by preventing TVs from being left on when people leave the room or fall asleep. Occupancy sensors are expected to become more important as it becomes easier to have TV displays in multiple rooms keyed to a primary source to enable users not to lose visual contact (or good audio) as they move from room to room. However, more research is needed to estimate the effect of this option on household TV energy consumption.

4. Cost-effectiveness analysis

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 compared to the cost, to the utility or consumer, of providing electricity.[14] 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 on the incremental manufacturing cost, which we label CCE_p.[15] 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 option by annual energy savings due to the efficiency option. Product categories are defined by screen size and backlight type (e.g., 32-in. LED–LCD TV). 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:

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

where

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

[12] "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" configuration means that all of the LEDs are mounted on sides (or edges) of the display.

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

[14] 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 US are in a range of 8–38% of the total program costs (Friedrich et al., 2009).

[15] DisplaySearch models standard LCD fabrication assumptions when generating the LCD module costs which is a major component of total LCD TV cost. The estimated markups are based on DisplaySearch (2011d) which is designed for the US market price, and the numbers for 2012 vary from 20% to 38% varying by specification such as screen size, frame rate and resolution.

$$\text{Energy savings}_i\left(\frac{\text{kW h}}{\text{year}}\right) = \text{Power reduced}\left(\frac{\text{watts}}{\text{unit}}\right) \times \text{daily usage}\left(\frac{\text{h}}{\text{day}}\right) \times \frac{365\ \text{days}}{\text{year}} \times \frac{1\ \text{kwatt}}{1000\ \text{watts}} \quad (3)$$

lifetime_i is the TV economic lifetime, i.e., replacement cycle, and discount rate discount rate of the end user.

All TVs 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, e.g., annual *sales* represented by annual shipment of a product category, such as 32-in. LED–LCD TVs.

4.1. Energy savings

We estimate energy savings based on the percentage reduction due to efficiency improvements to the baseline TV consumption which is based on ENERGY STAR registered TVs listed on March 2011 (ENERGY STAR, 2011a; ICF, 2011). The market penetration of these TVs was estimated to be 80–96% (ENERGY STAR 2011d, 2012b). The on-mode power test method[16] is based on the international standard IEC[17] 62087. As discussed above, for a given size and display technology, TVs sold in different regions of the world are very similar. As a result, the information presented here is globally relevant.

4.2. Economic lifetime

In the U.S., the average age of recently replaced TVs was about 8 years (DisplaySearch, 2011c). In the European region, the deviation in reported economic lifetime of TVs ranges from 7 to 15 years, varying by screen technology and source of the data (Fraunhofer IZM, 2007 Task 2; Market Transformation Programme (MTP) 2010a). Falling prices and the demand for new TV models may lead to shorter periods of primary TV use, while secondary TVs are likely to be used as long as they function. A telephone survey conducted in 2004 from the United Kingdom showed that primary TV's were replaced after 4.9 years on average (Fraunhofer IZM, 2007 Task 2). In this analysis, we assume the average TV lifetime is 8 years, and perform a sensitivity analysis in the range of 4 to10 years to include a range of scenarios.

4.3. Discount rate

Residential and commercial consumers may use various methods to finance the purchase of TVs. US Department of Energy (DOE) in a technical support document of energy efficiency programs for consumer products analyzed that the average discount rates in the U.S. are 4.8% for residential consumers and 6.2% for commercial consumers (US DOE, 2009). However, discount rate varies with country. In this analysis, we assumed an average discount rate of 5% for all cases, and perform a sensitivity analysis in the range of 3% to 10%, to indicate the range encountered in country-specific circumstances.

4.4. Average usage

TV usage patterns vary by region, sector of use, consumer lifestyle, and power management scheme applied to the system. The ENERGY STAR Program uses 5 h per day as a default value for the average usage of TVs based on Roth et al., 2008. For other countries, estimates of average daily usage of TVs range from 3.5 to 6.5 h (Park et al., 2011). For the purposes of this analysis we assume that average daily usage at on-mode is 5 h for all TVs.

[16] This analysis is based on on-mode power data of ENERGY STAR qualified TVs with ABC disabled or without ABC.

[17] International Electrotechnical Commission.

Table 3
Share of selected product groups in the LCD TV market. *Source*: DisplaySearch, 2011a.

	CCFL		LED	
	2012 (%)	2015 (%)	2012 (%)	2015 (%)
32″	18.9	1.5	20.8	38.6
40″–42″	4.4	0.2	17.6	22.0
Total	23.3	1.7	38.4	60.6

4.5. Product categories analyzed

Although we assess several efficiency improvement options and analyze their impact on TV electricity consumption, we limit our analysis of cost-effectiveness to those options which are unlikely to be adopted in the absence of policy intervention. We selected two product groups, representing about 60% of the global LCD TV market (see Table 3), the majority of which are expected to be manufactured without reflective polarizers or advanced backlight dimming in the absence of policy intervention. These options have been used primarily for some high-end models with screens larger than 40 in. 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 efficiency improvement options are generally proportional to screen area, and thus any size variation does not largely affect cost effectiveness.

4.6. Option 1: Reflective polarizers

Based on the estimated demand for reflective polarizers (DisplaySearch, 2011e) and comments from the industry, it is expected that more than 90% of LCD TVs with screen size less than 40 in. and more than 30% of LCD TVs with screen size larger than 40 in., collectively more than 70% of all new LCD TVs in terms of shipments, have not employed reflective polarizers in 2012.

We assumed that a reflective polarizer improves TV efficiency by at least 20% regardless of backlight source (see Section 3 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 LED backlighting 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 TVs. Table 4 shows annualized incremental CCE by product class for reflective polarizers. The selected product groups have a CCE_m with a range of \$0.04 per kW h to \$0.06 per kW h, and a CCE_p with a range of \$0.05 per kW h to \$0.12 per kW h (see Table 4 for descriptions of CCE_m and CCE_p). As the supply of current reflective polarizers is mostly dominated by 3M the material cost is not likely to vary by TV manufacturer. Fig. 6 shows CCE_m for LED–LCDs versus lifetime at various combinations of discount rates and efficiency improvement potential.

4.7. Option 2: Backlight dimming

Over 50%[18] (not sales-weighted) of the product groups selected in the reflective polarizer calculation are expected to be manufactured without the capacity for dimming. As discussed in Section 3, both 0D and 1D dimming methods are applicable to CCFL and LED backlights, while 2D dimming is only possible for LED-direct or a few types of LED-edge backlights. As LED-edge backlights are

[18] In 2010 and 2011 50% to 97% of ENERGY STAR qualified TV models did not employ any backlight dimming in the range of 32 and 42 in., depending on backlight source. While 31% to 50% of LED-LCD TVs employed dimming, only 3% to 36% of CCFL-LCD TVs employed dimming, depending on screen size (ICF, 2011).

Table 4
Cost of conserved electricity (CCE)[a] for reflective polarizer.

Screen size	Backlight	$\Delta P_{on\text{-}mode}$[b] per unit (W)	ΔC_m[c] per unit ($)	CCE_m[d] ($/kW h)	ΔC_p[e] per unit ($)	CCE_p[f] ($/kW h)
32"	CCFL	12.3	6.0	0.041	17.0	$0.117
	LED	8.2	5.5	0.058	7.0	$0.072
42"	CCFL	17.9	9.9	0.047	16.0	$0.052
	LED	12.6	7.4	0.050	10.0	$0.067
Weighted	CCFL	12.9	6.4	0.042	16.4	$0.110
average	LED	9.4	6.1	0.056	7.8	$0.071

[a] Assumptions: discount rate=5%, economic lifetime=8 years, daily usage=5 h.
[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 with reflective polarizers estimated by authors)—(manufacturing cost for 2012 standard models predicted by DisplaySearch).
[d] Cost to the manufacturer of conserved energy which is calculated by Eqs. (1)–(3) at IC=ΔC_m.
[e] Incremental price=(price for 2012 standard models with reflective polarizer estimated by authors)—(average market price for 2012 standard models predicted by DisplaySearch).
[f] Cost to the final user of conserved energy which is calculated by Eqs. (1)–(3) at IC=ΔC_p.

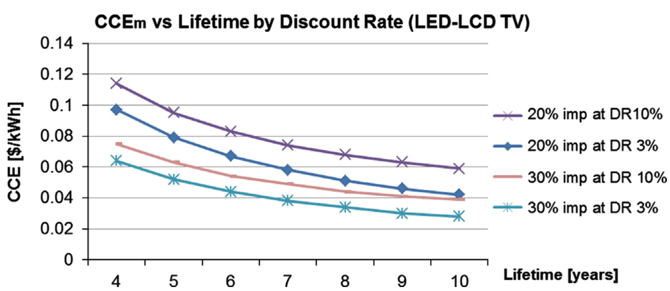


Fig. 6. Sensitivity to lifetime and discount rates of the cost per unit of conserved electricity (CCE_m) for reflective polarizers.
Assumption: daily usage=5 h. *Note*: imp=improvement potential, DR=discount rate.

expected to represent over 95% of the LED–LCD TVs through 2011 (DisplaySearch, 2011a), we focus here on 1D dimming that can be commonly applied to LED and CCFL backlights. Based on Shiga et al., 2008, we assume that 1D dimming for all types of backlights can reduce LCD TV power consumption by at least 20% on average.

To employ 1D dimming in LED–LCD TVs, manufacturers need to use a chipset that analyzes image signals at an additional cost of $2–$4, and drive integrated circuits (ICs) that control the dimming algorithm, at an additional cost of $0.8–$1.5 per drive IC.[19] For edge-type backlight units, dimming-supportive light guide panels (LGPs) are needed, entailing possible additional costs.[20] We assume that incremental costs for dimming in CCFL–LCD TVs are not higher than that for dimming in LED–LCD TVs.

Table 5 shows annualized incremental CCE by product class for dimming. The selected product groups have a CCE_m with a range of $0.03 per kW h to $0.07 per kW h, and a CCE_p with a range of $0.03 per kW h to $0.09 per kW h. Unlike reflective polarizers, the incremental costs for implementing backlight dimming may vary across manufacturers, with some related uncertainty in the range of the costs. Fig. 7 shows CCE_m for LED–LCDs versus lifetime at various combinations of discount rates and efficiency improvement potential.

[19] Based on DisplaySearch, 2011d and interviews with industry experts, if these TVs are already featured with ABC, both the net incremental cost and the savings potential will be lower, keeping the CCE roughly constant.
[20] Dimming-supportive LGPs are assumed 10% more expensive than normal LGPs.

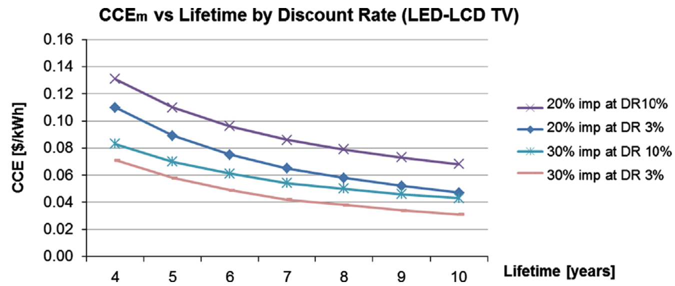


Fig. 7. Sensitivity to lifetime and discount rates of cost per unit of conserved electricity (CCE_m) for 1D backlight dimming.

4.8. Option 3: Ambient light sensor and occupancy sensor

Ambient light sensors and occupancy sensors are commercially available and their material cost does not vary with screen size or resolution. As discussed in Section 3, more research is needed to estimate the effect of these options on household TV energy consumption. According to the TV industry[21], the material cost of an ambient light sensor is in a range of $0.6 and $1.0 per unit as of 1st quarter of 2012. The total incremental cost of ABC for a TV unit is estimated to be less than the cost that is required for 1D dimming discussed above. The net incremental cost of ABC to TVs with dimming capability would be even lower, depending solely on ambient light sensors. If we assume that an additional 10% energy saving is possible for the selected TVs with dimming capability, the CCE_m and CCE_p for the ambient light sensor are less than $0.033 per kW h (assumptions: discount rate=5%, economic lifetime=8 years, daily usage=5 h).

The CCEs for the three technical options are less than residential electricity prices of many countries. Thus, TV efficiency can be cost-effectively improved beyond the BAU trajectory using these, or equivalent efficiency improvement options. 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 (Fig. 8).

5. Policy insights to accelerate adoption of efficient TVs

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, least cost or only efficiency improvement options available. We do not endorse any specific technology nor advocate prescription of proprietary technology for a standards-setting process or design of incentive programs, but merely discuss certain technologies to illustrate the magnitude of cost-effective savings available.

In order to design policies to effectively encourage the efficiency improvement of TVs, it is important to first estimate the effect of efficiency improvements that will take place even in the absence of additional policy intervention (i.e., BAU options in Table 1) and then assess how further efficiency improvements can be facilitated cost effectively. Based on the discussion in Section 3, we assume that the average energy consumption of CCFL–LCD and LED–LCD TVs will reduce by 30% and 55% from 2010

[21] The cost information was obtained from a top-tier manufacturer, but the identity of the expert we interviewed and the manufacturer source are kept confidential at the interviewees' request.

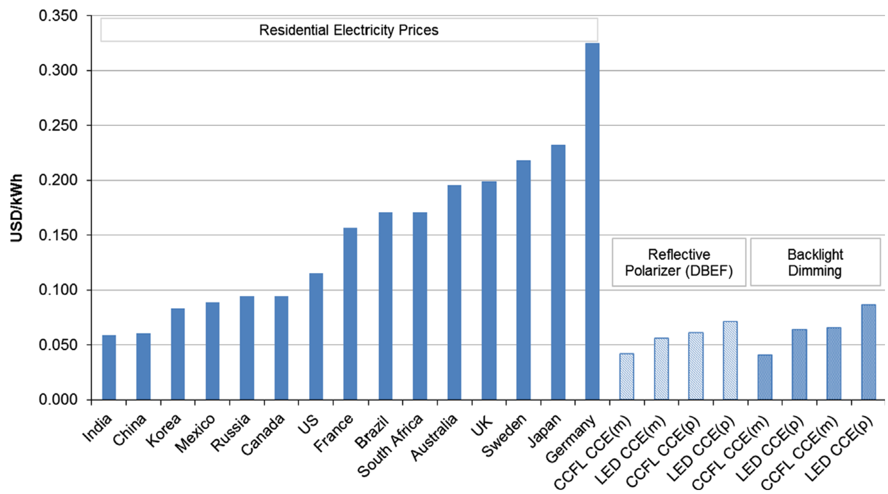


Fig. 8. Average Residential Energy Prices and Cost of Conserved Electricity (CCE)
Assumptions: discount rate = 5%, economic lifetime = 8 years, daily usage = 5 h.
Source for energy prices: International Energy Agency (IEA), (2011); United States Energy Information Administration (US EIA), (2010); McNeil et al., (2008); Rosen and Houser, (2007).

Table 5
Cost of conserved electricity (CCE)[a] for 1D backlight dimming.

Screen size	Backlight	$\Delta P_{on\text{-}mode}{}^{b}$ per unit (W)	$\Delta C_m{}^{c}$ per unit ($)	$CCE_m{}^{d}$ ($/kW h)	$\Delta C_p{}^{e}$ per unit ($)	$CCE_p{}^{f}$ ($/kW h)
32"	CCFL	12.3	6.1	0.042	10.0	0.069
	LED	8.2	6.7	0.069	9.0	0.093
42"	CCFL	17.9	6.3	0.030	7.0	0.033
	LED	12.6	7.2	0.048	10.0	0.067
Weighted average	CCFL	12.9	6.1	0.041	9.7	0.065
	LED	9.4	6.8	0.064	9.3	0.086

See Table 4 for descriptions of caption a to f.

levels by 2015, respectively, even without additional policy intervention. In addition to these BAU improvements, LCD TVs, particularly small- and medium-sized entry level models, can reduce power consumption using cost effective options with $CCE_m < \$0.08$/kW h, such as reflective polarizer, backlight dimming, and equivalent technology. Moreover, although we did not fully analyze ambient light sensors and occupancy sensor in the cost-effectiveness analysis, these options are being adopted to some TV models. Although more research would be needed to accurately estimate the actual effect of ambient light sensors and occupancy sensors on energy savings, in this paper we assume that an additional 15% efficiency improvement through ambient light sensors and occupancy sensors in LCD TVs is possible, extrapolating from the estimated savings from dimming (Desroches and Garbesi, 2011; Park et al., 2011).

Table 6 summarizes LCD TV efficiency improvements possible by adopting options discussed above. Numbers (except for market share) in Table 6 are based on 32-in. LCD TVs and the reference value (100% in gray color) is the average on-mode power consumption (with ABC-disabled) of CCFL–LCD TVs in 2010. As LED–LCD TVs are expected to account for more than 75% of global TV shipments from 2013 onward, energy efficiency programs need to account for the performance of LED–LCD TVs. Standards programs need to define much more stringent efficiency targets than are currently in place in order to exploit the maximum available cost effective energy efficiency potential and re-evaluate these targets regularly as the market evolves. A labeling or incentive program going into effect after 2012 may need to consider even more aggressive levels than, for example, the ENERGY STAR Version 6, due to the rapid evolution in TV energy efficiency.

Standards or entry levels of labeling programs setting specifications in 2013 could target an on-mode power consumption level about 15% below ENERGY STAR Version 5 while still remaining technology neutral and thereby capturing the additional savings potential (see Fig. 9). CCFL–LCD TVs can meet this level by employing cost-effective efficiency improvement options, while LED–LCD TVs will likely meet the level without any further efficiency improvement options. *Labeling and incentive programs* setting specifications for 2013 could target an on-mode power consumption level 50% below ENERGY STAR Version 5 (see Fig. 9). LED–LCD TVs (which are likely to be about 80% of the market in 2013) can achieve this level by adopting cost effective technologies equivalent in cost and energy savings terms to reflective polarizers or backlight dimming. This level is about 36% more stringent than ENERGY STAR Version 6. In fact, 20% of the models in the 2011 ENERGY STAR data set already met the proposed requirements for ENERGY STAR Version 6 (ENERGY STAR, 2011c). The most efficient models in 2012 consume about 40–42% of the power of the CCFL BAU case (100% in Table 6) (Topten.info, 2012).[22]

6. Global savings potential for efficiency improvements in LCD TVs

Based on the discussion in the previous sections, this analysis compares future TV energy consumption for three major

[22] The most efficient 32″ LCD TVs (LED-LCDs) available in the U.S and Europe for 2012 consume about 29–30 W in on-mode.

Table 6
LCD TV power consumption improvement trajectory.
Sources for energy efficiency standards: California Energy Commission (CEC), 2010; ENERGY STAR, 2012a; ENERGY STAR, 2011a.

			2010 (%)	2013 (%)	2015 (%)
Market share	CCFL–LCD		61	15	2
	LED–LCD		16	77	93
Average on-mode power consumption	CCFL	BAU	100	81	69
		BAU+1	80	65	55
		BAU+1+2	64	52	44
		BAU+1+2+3[a]	54	44	37
	LED	BAU	78	49	34
		BAU+1	62	39	27
		BAU+1+2	50	31	22
		BAU+1+2+3	43	27	19
MEPS (California)			–	109 (100)[b]	109 (100)
Voluntary label (ENERGY STAR)		Ver. 4	109 (> 70)	–	–
		Ver. 5	–	77 (> 80)	–
		Ver. 6	–	61 (> 50)	61 (> 90)
Potential level for standards[c]			–	65 (> 80)	55 (> 95)
Potential level of incentives[d]			–	< 39	< 27

[a] (1) Reflective polarizer, (2) backlight dimming, (3) ambient light sensor and occupancy sensor.
[b] Market penetration rate of TVs that meet the corresponding efficiency level is presented in parentheses ().
[c] Approx. 10–15% below ENERGY STAR Version 5 and 6—this is a level CCFL–LCD TVs can meet by employing cost-effective efficiency improvement options, while LED–LCD TVs will likely meet the level without any further efficiency improvement.
[d] Approx. 50–55% below ENERGY STAR Version 5 and 6—this is a level LED–LCD TVs can meet by employing cost-effective efficiency improvement options.

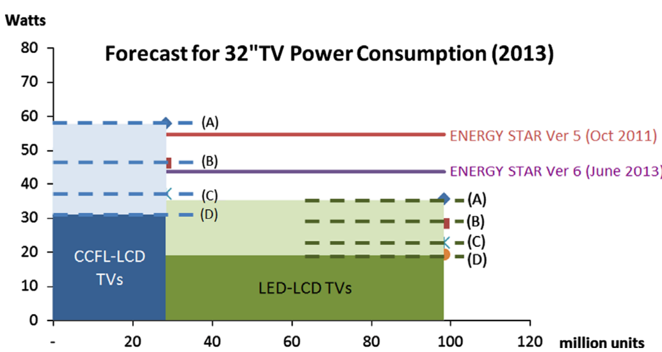


Fig. 9. Possible levels for standards, labeling and incentive programs.
(A) Estimated average power consumption in a BAU scenario.
(B) Power consumption possible with *either* reflective polarizers *or* backlight dimming.
(C) Power consumption possible with *both* reflective polarizers *and* backlight dimming.
(D) Power consumption possible with four options: reflective polarizers, backlight dimming, ambient light sensor and occupancy sensor. Each shaded area represents total power consumption by global shipments in the corresponding scenario.

scenarios: a *base case* with efficiency improvement expected in BAU (Base Case), an *efficiency case* and a *super efficiency case* with two sub-cases; one is the case with the two cost-effective efficiency improvement options (i.e., reflective polarizer and backlight dimming) and the other is the case with the other two efficiency improvement options (i.e., ambient light sensors and occupancy sensors) that can be additionally adopted by manufacturers. In addition to the three major scenarios, we include one additional case which assumes a market transition from CCFL–LCD to LED–LCD in the LCD technology with no further efficiency improvement within each technology from 2011 onward in order to give the reader a sense of the rapid improvement in TV efficiency expected even in a BAU scenario.

To calculate savings potential under these scenarios, we used the total screen area of each technology provided by DisplaySearch (2011a) (see Fig. 3), the average on-mode energy performance (in watts per screen area) for each size category and backlight technology based on the ENERGY STAR database, market shares of each product group divided by region, screen technology and size, and improvement potential discussed in Section 3 through 4.

Fig. 10 shows the results of forecasted global TV electricity consumption in on-mode. Details on each scenario follow.

1. Frozen Efficiency Case—in this case we assume that there is a large scale market transition in LCD technology, based on DisplaySearch (2011a), from inefficient (CCFLs) to efficient backlights (LEDs) *with no further efficiency improvement* within each technology from 2011 onward. Global TV electricity consumption, contributed from annual TV shipment including CRT, PDP and OLED TVs, is estimated to decrease slightly from 36 TW h per year in 2010 to 35 TW h per year in 2015 because of this large scale transition, while total *LCD TV* electricity consumption is expected to increase slightly from 27 TW h per year in 2010 to 31 TW h per year in 2015.
2. Base Case (BAU)—As discussed in Section 5, the efficiency of CCFL–LCD TVs and LED–LCD TVs can be improved by about 30% and 55% up to 2015, respectively, compared to 2010 levels. While PDP and OLED TVs are expected to improve in their unit efficiency, their collective market shares are likely to be very low (< 6%). This case reflects only LCD TV efficiency improvement potential, with other TVs' efficiency held constant through 2015.
3. Efficiency Case—this case assumes that, in addition to the improvements included in the base case, CCFL–LCD TVs have efficiency levels equivalent to those achievable by employing two cost effective options; reflective polarizers and backlight dimming. The majority of LED–LCD TVs are expected to meet the proposed level without needing further efficiency improvement. We assume that these efficient technologies for CCFL–LCD TVs can enter the market starting 2012, and in every year these models reach about 60–90% of the CCFL's market shares according to screen size. The effect of this case decreases through 2014 as CCFL backlights are expected to be phased out of the market.
4. Super-efficiency Case I—this case assumes LCD TVs with efficiency levels equivalent to those achievable by employing two cost-effective options; reflective polarizer and backlight dimming (1D). All LCD TVs employing these options from 2012to 2015 are assumed to be about 40% more efficient than LCD TV models included in the base case in the same period. In this scenario, we assume that these efficient technologies for CCFL- and LED–LCD TVs can enter the market starting 2012, and in

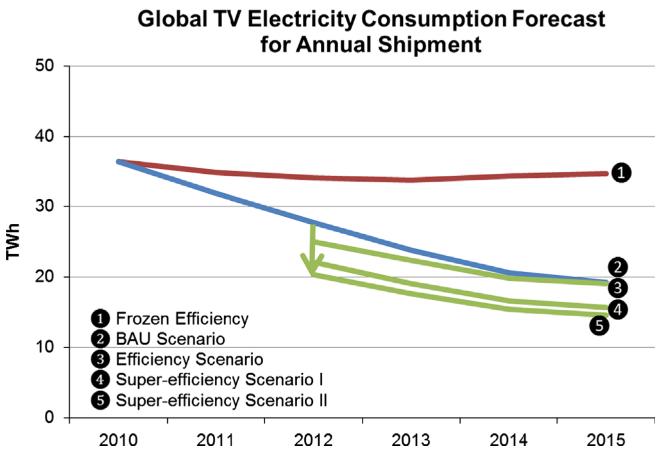


Fig. 10. Global TV electricity consumption forecast for annual shipment.

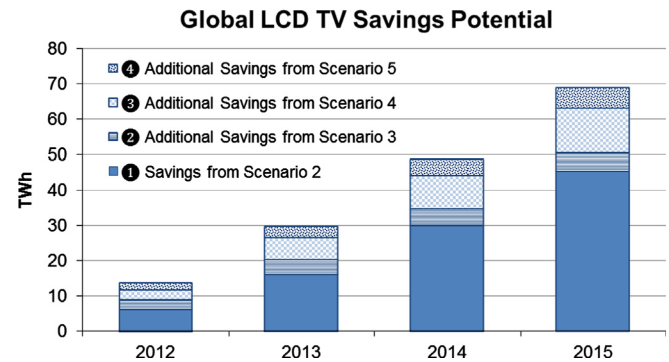


Fig. 11. ❶: Possible savings by BAU improvement.
❷: Possible savings by standards.
❸+❹: Possible savings by incentives and labeling programs.

Table 7
Summary of global savings potential in LCD TVs by Scenario.

	Scenario compared	Annual savings in 2015	Cumulative savings from 2012 through 2015	Lifetime savings (6–10 years)
Base Case (BAU)	Frozen efficiency	45	98	270–450
Efficiency Case	Base Case	5	17	30–50
Super-efficiency Case I	Base Case	18	48	108–180
Super-efficiency Case II	Base Case	23	63	138–230

Unit: TW h.

every year the most efficient designs reach about 40–100% of the market share varying by technology option.

5. Super-efficiency Case II—this case assumes Super-efficiency Case I with additional options; ambient light sensor and occupancy sensors. We assume that additional 15% efficiency improvement, based on the discussion in Section 4 and 5, can be achieved.

The energy savings potential contributed from 2012 to 2015 TV shipments by each scenario and corresponding policy programs, compared to scenario 1 or 2, are summarized in Table 7 and Fig. 11.

6.1. TV electricity consumption in selected countries

TV manufacturing is highly globalized and TVs sold in different regions of the world are very similar for any given size and display technology. Hence our analysis does not consider separate efficiency improvement options for different regions of the world, but does take into account different screen technology mixtures, screen sizes, and TV sales in each region. Average viewing time (hours per day), one of the major factors in TV energy consumption, varies with region and country (International Energy Agency—Efficient Electrical End-Use Equipment (IEA 4E), 2010).[23] With growing functionality this average viewing time may increase in the future. However, in this analysis, we applied a fixed value of 5 h per day to all selected countries to isolate the

[23] The figures for viewing hours for the UK (4.8 h), Australia (7.3 h), and the Republic of Korea (6.9 h) were based on government assumptions.

Table 8
Country-specific savings potential in LCD TVs for 2012–2015.

Country/Scenario	Annual savings in 2015				Cumulative savings from 2012 through 2015			
	2	3	4	5	2	3	4	5
Australia	1.3	0.2	0.6	0.8	2.8	0.7	1.5	2.0
Brazil	1.7	0.3	0.8	1.0	3.6	1.1	2.2	2.8
China	10.5	1.0	4.0	5.3	22.9	3.4	10.8	14.3
Canada	1.0	0.1	0.3	0.5	2.2	0.3	0.9	1.3
EU	6.8	0.2	2.4	3.1	15.1	0.9	6.5	8.5
India	2.4	0.4	1.1	1.4	5.0	1.2	2.8	3.6
Japan	1.4	0.1	0.5	0.7	3.2	0.2	1.4	1.9
Korea	1.1	0.2	0.5	0.6	2.2	0.6	1.2	1.6
Mexico	1.0	0.2	0.5	0.6	2.2	0.6	1.3	1.7
Russia	1.8	0.2	0.6	0.8	3.8	0.7	1.5	2.2
South Africa	0.2	0.1	0.1	0.1	0.5	0.2	0.3	0.4
US	8.1	0.7	2.7	3.7	17.5	2.6	7.4	10.1
Total	37.4	3.7	14.0	18.6	80.9	12.5	37.8	50.3
Global	45.4	5.1	17.8	23.5	97.9	17.0	48.0	63.5

2: Base Case, 3: Efficiency Case, 4: Super-efficiency Case I, 5: Super-efficiency Case IIUnit: TW h per year.

effect of technological options on electricity consumption and savings from this consumer-oriented variable.

Table 8 summarizes LCD TV savings potential by scenario which is contributed from predicted 2012–2015 TV shipments in selected countries,[24] representing about 80–85% of the global TV shipments. The selected countries can save 18.6 TW h out of 23.5 TW h per year in 2015 by scenario 5, compared to the BAU case.

7. Conclusions

Our analysis estimates that there will be a significant decrease in on-mode energy consumption for newly sold TVs globally, because of the large-scale transition toward LED–LCD TVs and rapid efficiency improvement in TVs, in spite of the projected growth in screen size and TV sales. We also find that TV consumption can be cost effectively reduced even further beyond the improvements likely because of this transition.

These findings have the following implications for energy efficiency market transformation programs: First, as a result of the transition to LED–LCD TVs and technology improvement within LED–LCD TVs, more than 80% and 50% of TVs will be able to meet ENERGY STAR Version 5 and 6 requirements, respectively

[24] Super-efficient Equipment and Appliance Deployment (SEAD)'s member governments. More information on SEAD is available from its website at http://www.superefficient.org.

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 as technology evolves. If in every year the efficient designs discussed in this paper reach an average of 40–90% of the market varying by technology type and efficiency improvement option, the energy savings potential would be up to 23.5 TW h per year in 2015.

Future research on TV energy efficiency should also discuss other recent TV technology trends such as 3D TVs and smart TVs, which were not fully included here, as these trends are still developing and their future direction and impact is still uncertain. Although the trend toward incorporating 3D or network functions in TVs will be likely to result in increase in power consumption in 3D or network modes, all of the options for increasing the efficiency discussed in this paper can be equally applied to the new TVs.

Acknowledgments

We wish to thank the reviewers of this article as well as the report, *TV Energy Consumption Trends and Energy-Efficiency Improvement Options* (LBNL5024-E), on which this paper is based. This work was funded by the Bureau of Oceans and International Environmental and Scientific Affairs, U.S. Department of State, and administered by the U.S. Department of Energy in support of the Super-efficient Equipment and Appliance Deployment (SEAD) Initiative through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. Any errors or omissions are the authors' own.

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