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Adoption of energy-efficient televisions for expanded off-grid electricity service



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ABSTRACT

Even though they dominate the global television (TV) market, light-emitting diode backlit liquid crystal display (LED-LCD) TVs have received little attention for use with off-grid household-scale renewable energy systems, primarily because of high up-front costs. However, technological advances and price declines mean that these TVs can now provide the same level of electricity service as standard LED-LCD TVs offer but at lower total energy cost. Moreover, LED-LCD TVs are inherently direct-current (DC)-powered devices and therefore well suited for use with off-grid solar home systems. We estimate that DC-powered energy-efficient LED-LCD TVs can decrease the retail purchase price of solar home systems by about 25% by allowing use of 50% smaller photovoltaics and battery capacities than would be needed for the same energy system to power a standard LED-LCD TV. We recommend that policies such as awards, bulk procurement, incentives, and energy labels be considered to facilitate the adoption of these energy-efficient TVs in off-grid settings.

1. Introduction

Televisions (TVs) are among the most commonly used household appliances. Estimates indicate that more than 80% of the world's 1.9 billion households owned TVs in 2014 (Digital TV Research, 2014). Although TV penetration in developed economies is already saturated, TV ownership in developing countries is still low, e.g., estimated at less than 40% in sub-Saharan Africa (Digital TV Research, 2014); as a result, demand for TVs is high in these countries, including in off-grid regions where an estimated 1.2 billion people worldwide lack access to electricity and in unreliable-grid regions where an additional 1 billion people reside (Global LEAP, 2016a; International Energy Agency (IEA), 2015). A recent market survey of anticipated off-grid consumer demand found that TVs were in the top three household end uses (along with light emitting diode [LED] lamps and mobile phone chargers) (Global LEAP, 2015a). Another recent analysis estimated that the number of off- and unreliable-grid households for TVs in Asia and Africa would grow from about 50 million in 2015 to about 200 million by 2020 as the distribution of energy systems increases (Global LEAP, 2016a).

In regions with no grid connectivity, deployment of small solar power systems can be a key short-term electricity supply strategy.

Falling solar home system (SHS) prices (driven by decreases in the cost of photovoltaic panels and batteries) and several market approaches (including piecemeal purchasing strategies, micro-finance loans, and pay-as-you-go schemes) have increased off-grid solar systems' affordability over time (Phadke et al., 2015). Research also indicates that a primary driver of uptake of off-grid power systems is desire for TVs (Jacobson, 2007). Use of highly efficient appliances could dramatically increase solar system affordability because efficient end uses can be served by a smaller system than would be required to power less-efficient versions of the same products. For example, a highly efficient color TV, four LED lamps, a mobile phone charger, and a radio that together require approximately 18 W [W] can be supported by a small solar power system with 27 W peak [W_p] (Phadke et al., 2015).

In particular, flat-panel TVs, such as liquid crystal display (LCD) TVs, are appropriate for direct current (DC) power systems because these TVs inherently convert alternating current (AC) input to DC inside the system. As their prices and unit power consumption have dramatically decreased, these products have begun dominating global TV sales (Park et al., 2013a). Research also indicates that incremental costs and prices of efficiency in TVs have declined rapidly (Desroches and Ganeshalingam, 2015). Regardless, primarily because of high up-front costs, flat-panel TVs have received little attention for use with off-

Abbreviations: A, ampere; ABC, automatic brightness control; AC, alternating current; Ah, ampere hour; BOS, balance of system; CCFL, cold cathode fluorescent lamp; cd, candela; CRT, cathode ray tube; DC, direct current; LEAP, Lighting and Energy Access Partnership; IEC, International Electrotechnical Commission; in², square inch; kWh, kilowatt-hour; LCD, liquid crystal display; LED, light-emitting diode; LED-LCD, LED backlit LCD; Li, lithium; m², square meter; PV, photovoltaic; SHS, solar home system; USB, universal serial bus; V, volt; W, watt; W_p, watt peak

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grid, household-scale, renewable energy systems, and the number of DC flat-panel TV products available in the off-grid market is limited. In some cases, off-grid households use inverters to enable residents to install widely available AC-powered TVs even though this results in power conversion losses (from DC provided by the energy system to AC produced by the inverter to power the TV and back to DC in the TV system). The efficiency gains from LED technology, which has been rapidly adopted in lighting products and TVs, could make off-grid solar power systems feasible and affordable in developing economies (Casillas and Kammen, 2010; Phadke et al., 2015).

In this paper, we assess the technical potential and cost to reduce the electricity consumption of small LED backlit LCD (LED-LCD) TVs using commercially available technology and evaluate whether these TVs offer the potential to reduce the cost of TV use in off-grid energy systems. The remainder of the paper is organized as follows: Section 2 presents an overview of the off-grid TV market. Section 3 discusses TV energy consumption trends. Section 4 describes our data sources, assumptions, methodology, and analysis results regarding the potential to reduce the cost of TV use in off-grid energy systems by improving TV efficiency. Section 5 presents our conclusions.

2. Overview of off-grid TV market

An estimated 1.2 billion people worldwide lack access to electricity (the “un-electrified” population) and an additional 1 billion people have unreliable electricity access (the “under-electrified” population) (International Energy Agency (IEA), 2015). Of the global population, 17% is un-electrified. The majority of off-grid households are in sub-Saharan Africa and India (International Energy Agency (IEA), 2015). Although it is estimated that more than 80% of the world’s households own TVs, TV ownership in developing countries is estimated to be low, e.g., less than 40% in sub-Saharan African countries (Digital TV Research, 2014). It is difficult to break down current TV sales between grid-connected and off-grid regions in developing countries, but we estimate that TV penetration in off-grid rural areas is low.

LCD TVs are estimated to account for more than 95% of new TV shipments in both emerging and developed economies (DisplaySearch, 2014a; Park et al., 2013a; Park et al., 2014). In new TV shipments, cold cathode fluorescent lamp (CCFL) backlit LCD TVs have been replaced by LED-LCD TVs, which account for nearly 100% of LCD TVs (DisplaySearch, 2014a; Park et al., 2013a). Cathode ray tube (CRT) TVs were estimated to account for less than 3% of shipments in emerging economies in 2014, and no new shipments of these products were expected from 2016 onward (DisplaySearch, 2014b; Park et al., 2014).

Very little research has focused on the off-grid TV market (defined here as comprising both un- and under-electrified populations) because it is currently a niche market with uncertain growth potential. Demand for DC TVs in off-grid regions is currently driven by existing distributors of solar power systems and low-power energy products (Dalberg Research, 2013). However, un- and under-electrified households could become a large appliance market as economies grow and electricity access improves. In particular, increasing opportunity for off-grid populations to access digital TV content is expected to support future demand for TVs in off-grid regions. For example, the direct-to-home industry, which provides TV content by satellite, is growing, largely to serve rural customers who do not have access to cable service (Dalberg Research, 2013; Digital TV Research, 2014; DVB.org, 2015). Although current TV penetration in off-grid rural areas is still low, a recent analysis estimated that the number of off- and unreliable-grid households seeking TVs in Asia and Africa would grow from about 50 million in 2015 to about 200 million in 2020 as the distribution of energy systems increases (Global LEAP, 2016a). Recent market transformation programs promote and help consumers identify energy-efficient, quality-assured, off-grid TVs. For example, the Global Lighting and Energy Access Partnership (LEAP) Outstanding Off-Grid TV competition recognized several TV products based on a combina-

tion of expert evaluation and quantitative assessments of energy and cost (Global LEAP, 2014a, 2016b).

3. TV energy consumption trends

This section gives a picture of commercially available energy-efficient TVs and analyzes technical improvements that are feasible in the short term. We do not analyze long-term technical efficiency improvements that would require research and development investment.

3.1. Electricity consumption by AC LCD TVs

Rapid improvements in cost and efficiency of LED technologies have driven the adoption of LED backlights for LCD TVs and other applications. In addition to improving LED performance, other viable options for improving LCD TV efficiency include optimized combinations of optical films in LCDs, improved LCD panel transmittance and brightness control functions, and energy-efficient power electronics (Park et al., 2013a, 2014). Major TV manufacturers have been offering new designs of LED-LCD TVs at lower prices than previously to decrease the price gap between conventional CCFL-LCD TVs and LED-LCD TVs. Price reductions are also made possible by decreasing the maximum luminance level, adjusting color-reproduction capability, and introducing “low-cost LED direct backlighting”¹ (Park et al., 2014).

TV manufacturing is highly globalized and concentrated, so a given size of TV will be similar in different regions of the world (Park et al., 2013a). Therefore, we can use the energy consumption of TVs sold in major economies such as the U.S. and Europe to represent the energy consumption of TVs elsewhere. For example, ENERGY STAR-qualified TVs can represent the majority of TVs sold in the U.S. because their market penetration is significant, i.e., nearly all LCD TVs met ENERGY STAR requirements in 2015 (US EPA, 2015a).² Fig. 1 shows on-mode power consumption trends of recent U.S. ENERGY STAR-qualified LCD TVs (less than 45 in.). Recent 23- and 24-in. LCD TVs, regardless of backlight technology, consume 15–34 W in on mode (United States Environmental Protection Agency (US EPA), 2013a; US EPA, 2015b).

3.2. Electricity consumption in DC LCD TVs

One of the technical differences between AC and DC TVs is the AC-to-DC conversion in the former. An estimated 5–15% of electricity is lost in this conversion (Garbesi et al., 2011; Park et al., 2011), and losses can be even greater than this.³

The Global LEAP Outstanding Off-Grid TV Awards (<http://www.globalleapawards.org/>) tested a number of DC TVs designed for off-grid use to identify the world’s highest-quality and most energy-efficient and affordable off-grid TVs. The 9 DC TVs tested in 2014 were

¹ “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 the sides (or edges) of the display. LED-edge backlit TVs are the mainstream technology particularly for small and medium screen sizes because their manufacturing costs are lower than those of LED-direct backlit TVs. LED-edge backlit TVs also have a better aesthetic profile, i.e., a slimmer body. Some medium and large screen sizes use LED-direct backlight for high-end products because these devices can employ local dimming technology that can independently control each LED lamp, resulting in higher contrast ratio and better picture quality (Park et al., 2011).

² U.S. ENERGY STAR Version 6 and Version 7 requirements for TVs went into effective on June 1, 2013 and October 30, 2015, respectively. The market penetration of ENERGY STAR-qualified LCD TVs in 2013 and 2015 was 84% and 89%, respectively (US EPA, 2013b, 2015a).

³ We tested a 19-in. AC-DC-compatible TV model sold in Kenya by measuring on-mode power consumption. The on-mode power consumption (13.2W) in AC input is about 35% higher than the consumption in DC input (9.8W). The TV model we tested had a power factor (defined as actual power to apparent power) of 0.44 in on mode. Low power factor appliances with a stand-alone off-grid power system could require more power than high power factor appliances do, while consumers in grid-connected systems are not charged for such unused power.

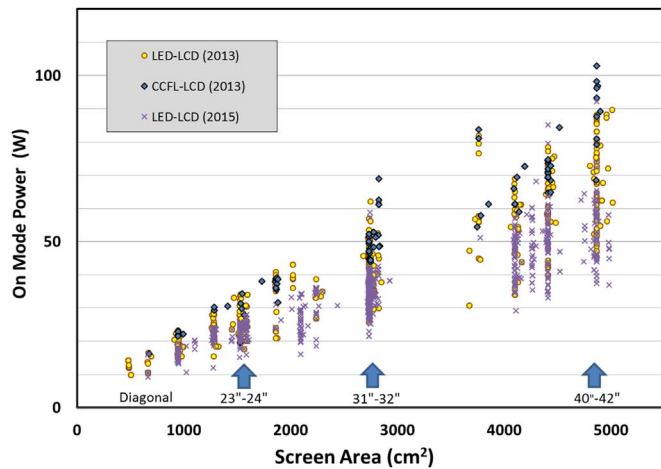


Fig. 1. On-mode power consumption of U.S. ENERGY STAR-qualified LED-LCD TVs. On-mode power consumption of ENERGY STAR-qualified TVs with no automatic brightness control (ABC) or with ABC enabled at 300 lx (2013) and 100 lx (2015). Source: Authors' work based on (United States Environmental Protection Agency (US EPA), 2013a) and (US EPA, 2015b)

Table 1

On-mode power consumption of AC- and DC-powered TVs.

	DC TVs	AC TVs
Region	Developing countries ^a	USA
Data source	Global LEAP Awards	ENERGY STAR Most Efficient
Year	2014	2015
Screen size (diagonal)	15–23 in.	15–24 in.
On-mode power performance	0.05 – 0.10 W/in ²	0.06 – 0.11 W/in ²
Power consumption translated for a 23-in. TV ^b	11.3 – 22.6 W	13.6 – 24.8 W

^a Global LEAP Awards nominees were required to provide a brief written explanation, in English, of how the product warranty is serviced in two of the following six countries: Bangladesh, India, Indonesia, Kenya, Nigeria, Uganda.

^b Authors' calculation based on Global LEAP (Global Lighting and Energy Access Partnership Global LEAP, 2013) and (US EPA, 2014).

15–23 in. on diagonal and had on-mode power consumption ranging from 0.05 to 0.1 W per square inch (W/in²) (Global LEAP, 2014b); 0.05 W/in² can be mathematically translated into about 4.8–11.3 W for 15- to 23-in. TVs with a 16:9 aspect ratio. In comparison, on-mode power consumption of the 18 “most efficient” ENERGY STAR (AC-powered) LED-LCD TVs (15–24 in. on diagonal) in early 2015 ranged from 0.06 to 0.11 W/in²; 0.06 W/in² can be translated into 5.8–13.6 W for 15- to 23-in. TVs with a 16:9 aspect ratio (US EPA, 2015c). Table 1 summarizes the specifications and on-mode power consumption of these two types of TVs. Although the two product groups may not be exactly comparable (because other specifications, e.g., network features, luminance default mode, etc., could be different), these models represent highly efficient TVs available in the U.S. and developing countries. We estimate from these data that DC LED-LCD TVs could consume about 9–16% less electricity than AC LED-LCD TVs consume.

The industry has attempted to develop energy-efficient DC LCD monitors. In 2010, 3 M demonstrated that an 18.5-in. universal serial bus (USB)-powered LED-LCD monitor could consume 40% less power than standard monitors (i.e., reducing power from 14.0 to 8.3 W). This was achieved by using a high-transmittance LCD panel and a reflective polarizer (i.e., dual brightness enhancement film) and drawing power through two USB 3.0 ports (Park et al., 2013b; Siefken et al., 2011). A USB cable's limited power-transmitting ability restricts the total amount of power that an end use may consume. Therefore, USB-powered monitors need to employ very efficient technologies. In 2011, 3 M

expanded the technology to a 23-in. USB-powered monitor, claiming power consumption of 9 W (Park et al., 2013b). Currently available USB protocols permit only 2.5 W (USB 2.0), 4.5 W (USB 3.0), and 7.5 W (USB BC 1.2) of power output, but the emerging USB power delivery protocol offers power levels up to 100 W, including 5 V (V)/2 amps (A), 12 V/1.5–3 A, and 20 V/3–5 A, which could be widely applicable to electronic products and appliances, including low-voltage DC TVs (USB, 2012).

It appears that the energy efficiency is improving in DC TVs that are appropriate for off-grid consumers. In 2015, several SHS providers introduced new DC TV models at the Global LEAP Off-Grid Appliance Networking Event in Bangladesh. DC TVs of 15.6 in. and 19 in. consumed about 7–8 W and 10–14 W in on mode, respectively. The power consumption claimed for a 23-in. DC TV model demonstrated at the event was 9 W (Global LEAP, 2015b).

4. Estimating cost and electricity-savings potential

We use a bottom-up approach to estimate the potential to reduce the energy consumed by small TVs and the potential for use of these TVs to reduce the costs of off-grid energy systems. We obtained the market data for this analysis from a review of literature including market and technical reports (e.g., DisplaySearch data and reports⁴) as well as country-specific databases (e.g., U.S. ENERGY STAR). Our analysis focuses on small (less than 25 in. in diagonal) TVs because only small TVs are likely to be affordable in off-grid settings.

4.1. Methodology and assumptions

We begin our analysis by assessing cost and price of commercially available TVs typically used in grid-connected settings (where the power source is AC) and estimate their performance in off-grid settings (where the power source is typically DC). AC TVs are not niche products, so this assessment gives us insight into the price and performance of small TVs that can be deployed at scale in off-grid regions. The analysis addresses potential market and economic efficiency improvements that are technically feasible, practical to manufacture, and therefore could be realized in the short term. Next, our analysis compares TV energy consumption for two primary scenarios: a base case, which assumes options that are commonly implemented for TV models, and an efficiency case, which assumes that selected cost-effective efficiency options are implemented for target TVs. We then assess potential impacts of energy-efficient DC LED-LCD TVs on off-grid SHS design. Finally, we consider additional savings scenarios to address variations in TV price and efficiency.

Fig. 2 shows the analysis structure. Table 2 summarizes characteristics of the baseline model and energy-efficiency improvement options. A detailed discussion follows.

4.1.1. Baseline model

The average screen size of traditional CRT TVs shipped from 2007 to 2011 in Asia (excluding Japan and China), the Middle East, and Africa is estimated to be in a range of 19–21 in. (translated into about 173–212 square inches [in²] for a 4:3 aspect ratio) (DisplaySearch, 2010, 2011a, 2012a). Although there analog TV households remain, and CRT TVs are still commercially available, there is no significant demand for CRT TVs in the global TV market and the secondary market for CRT TVs is unlikely to continue for much longer. Therefore, our baseline model, based on which we estimate cost-efficiency for off-grid use, is a single 22-in. LED-LCD TV (about 207 square inches for a 16:9 aspect ratio). The baseline model operates on AC and is assumed to consume 21 W (equivalent to 0.1 W/in²) in on mode. Power usage of 0.1 W/in² is the value of the least efficient model among Global LEAP TV Award-winning products. U.S. ENERGY STAR LED-LCD TVs (120

⁴ DisplaySearch (acquired by IHS in 2014) provides reliable information based on manufacturer surveys and analyses on the display market and related industries.

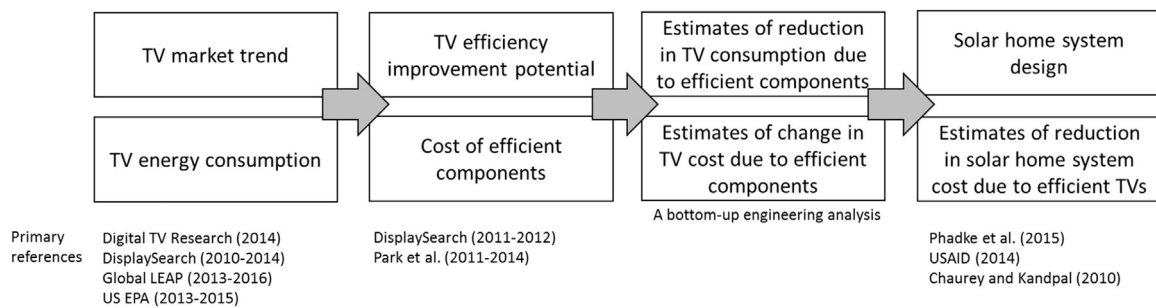


Fig. 2. Structure of the analysis.

Table 2
TV energy-efficiency improvement options.

Base Case:		
<ul style="list-style-type: none"> Standard LED backlit LCD (LED-LCD) TV Screen size in diagonal: 22 in. Screen area: 207 square inches (16:9 aspect ratio) On-mode power consumption: 21 W (0.1 W/sq.in.) Retail purchase price: \$150 		
Energy-efficiency improvement options	% energy savings	Incremental manufacturing cost (U.S. dollars)
No AC-DC conversion	5–15%	-\$4.5
Efficient optical films	20–30%	\$2.6 to \$4.3
Brightness control – ambient light sensor	10%	\$0.6–\$1.0
Brightness control – backlight dimming	20%	\$5–\$6
All options	45–57% (51%)	\$3.7–\$6.8 (\$5.3)

Note 1. The percent energy savings numbers are multiplicative (not additive) in nature.

Note 2. The baseline model runs on AC.

Note 3: () refers to the average value in the range.

models, 21.5–24 in.) range from 12 W to 28 W with an average on-mode power of 22 W (US EPA, 2015b).

TV manufacturing is highly globalized, and Asia-based manufacturers lead the global market (Park et al., 2013a, 2014). Most global manufacturers that sell their products in developing countries such as India import LCD panels⁵ from factories in the manufacturer's home country and produce finished TV sets by assembling these panels with the other TV components in facilities close to the market (Park et al., 2014). Local TV brands generally outsource LCD panels from Asian manufacturers and assemble them with other components in local facilities. Thus, because the panels for all markets generally come from Asia, analyzing the cost structure of typical LCD TVs sold in the U.S. market gives insights applicable to the situation in developing countries. The average price of 22-in LED-LCD TVs in the U.S. decreased by about 26% from 2011 to 2014 and was estimated at about \$166 (of which the manufacturing cost accounts for about 70%) in 2014 (DisplaySearch, 2011b). Based on this price decrease between 2011 and 2014, we estimate that the average price of 22-in LED-LCD TVs in the U.S. would decrease to \$150 in 2015. Actually, in 2016, 22- to 24-in LED-LCD TVs, available in the U.S. and India, sold at a price of \$110–\$150.⁶ Retailer markups vary by region and sellers and might be higher in some developing countries or off-grid regions than in other markets.

⁵ The term “panel” generally refers to an entire assembly of layers, excluding electronics such as the image circuit and the power supply unit. A flat-panel display “module,” sometimes also called a “panel,” typically refers to a panel with drive circuits (Park et al., 2013a).

⁶ Authors' estimates based on searches on www.amazon.com and www.amazon.in.

4.1.2. Efficiency improvement options: no AC-DC conversion, reflective polarizers, and brightness control

As discussed earlier, AC-to-DC conversion in AC-powered TVs typically results in an estimated 5–15% electricity loss (Garbesi et al., 2011; Park et al., 2011). The cost of power electronics in 22- to 23-in TVs and monitors is estimated to range between \$4.5 and \$15 (DisplaySearch, 2011b, 2012b). We assume that eliminating AC-DC conversion would save at least \$4.5 in manufacturing costs.

Higher-efficacy LEDs and highly efficient LCD panels can be adopted over time, but efficient optical films (e.g., reflective polarizers) and brightness control functions are already commercially available in selected TV models. A reflective polarizer improves TV efficiency by 20–30% regardless of backlight source (Park et al., 2013a). The cost of a reflective polarizer was \$6 in 2011 and was projected to be about \$3.7 in 2015 for 26-in. TV models (DisplaySearch, 2011c), so we estimate the cost of reflective polarizers for 22-in. TV models to range from \$2.6 to \$4.3 in 2015, adjusted by screen area.

Brightness control methods have been developed to reduce TV power consumption and improve image contrast ratio. There are two types of on-mode power management technologies for TV screens. One is automatic brightness control by a sensor that detects ambient light and dims the screen in low light conditions (Park et al., 2011). Ambient light sensors are commercially available; their materials cost ranges from \$0.6 to \$1.0 and does not vary with screen size or resolution (Park et al., 2014). The other type of brightness control entails dimming part of the backlight area depending on input image (Park et al., 2011). Park et al. (2013a) estimated the incremental cost of backlight dimming to be about \$6–\$7 for 32-in. TV models in 2012. We assume that dimming that can be used for all types of backlighting reduces LCD TV power consumption by at least 20% at an additional cost of \$5–\$6, based on Park et al. (2013a) and given the rate of TV price decrease between 2012 and 2015.

4.1.3. Solar home system design

In general, an SHS cost has four components: photovoltaic (PV) module, battery, balance of system (BOS), and appliances connected to the system. Because total SHS cost is determined mainly by the PV and battery capacities associated with total connected load, we can analyze the cost by holding constant all variables other than TV efficiency and TV cost. Key design assumptions for SHSs in this analysis include a solar resource of 5 kW-hours per square meter (kWh/m²) per day, three days of battery storage, a maximum battery depth of discharge of 50% (for lead-acid battery) and 90% (for lithium [Li]-ion battery), as well as the following efficiency losses: 20% loss (for lead-acid battery), 10% loss (for Li-ion battery) from battery charge–discharge, and about 23% loss collectively from imperfect maximum power point tracking for the PV module, wire resistance, connector contact resistance, and other miscellaneous effects. Table 3 summarizes our SHS design assumptions.

Although lead-acid batteries are cheap and commonly used for a variety of applications, they have low efficiency, a small number of life cycles, and maintenance issues so that they must be much larger in

Table 3
Solar home system design assumptions.

Characteristics	Assumptions
Battery efficiency	80% (lead-acid), 90% (Li-ion)
Battery depth of discharge	70% (lead-acid), 90% (Li-ion)
SHS efficiency losses	<ul style="list-style-type: none"> ● 15% from imperfect maximum power point tracking for the PV module ● 10% from wire resistance, connector contact resistance and other miscellaneous effects
Cost of PV module	\$0.8/W
Cost of battery	\$0.08/Wh (lead-acid), \$0.35/Wh (Li-ion)
Cost of BOS	\$1.1–\$1.4/W-PV (varying by required PV capacity)

Authors' assumptions are based on (Chaurey and Kandpal, 2010; Phadke et al., 2015), and (United States Agency for International Development USAID, 2014). Costs in the table refer to wholesale price. Note that the results are based on modeled data; actual system sizing would vary in practice.

capacity (e.g., 2–4 times) than a Li-ion battery or be replaced earlier (Akhil et al., 2013; Gretz, 2016; United States Environmental Protection Agency (US EPA), 2013a). The lead-acid battery analyzed above is roughly assumed to operate for 500–1000 cycles (or about 1.5–3 years) before its capacity drops below 80% when replacement would be considered. Conversely, the counterpart Li-ion battery is estimated to take more than 2000 cycles without replacement (i.e., more than six years). Hence, the per-cycle cost of Li-ion batteries is reasonably comparable to the per-cycle cost of a lead-acid battery. Li-ion batteries also offer several other advantages compared to lead-acid batteries, including smaller size, greater safety, and less environmental impact. The efficiency of Li-ion batteries is improving, and the price is dropping. These advantages make clear why it is important to assess emerging battery technologies, such as Li-ion batteries, as an option for SHSs. If we calculate annualized SHS costs that take equipment lifetime into account, an SHS with a Li-ion battery would be more cost competitive than an SHS with a lead-acid battery.

4.1.4. Cost-effectiveness of solar home systems with TV

For off-grid consumers, the cost of TV use consists of the up-front cost of the TV and the cost of electricity use (i.e., the cost of the SHS). We assess how the cost of using a TV with an SHS changes as TV efficiency improves and annual electricity consumption reduces. We estimate savings potential by subtracting retail purchase price (i.e., up-front cost) of the SHS with energy-efficient TV from the retail purchase price of the SHS with baseline TV. We also calculate, using Eq. (1), the cost of off-grid TV use by the annualized cost of the SHS with a TV, and we estimate, using Eq. (2), the savings of the annualized cost of the SHS with an efficient TV compared to the annualized cost of the SHS with a base-case TV.

$$ACS(\text{Annualized Cost of SHS}) = \sum_i \text{Cost}_i \left[\frac{\text{discount rate}}{1 - (1 + \text{discount rate})^{\text{lifetime}_i}} \right] \quad (1)$$

Table 4
Estimated component specifications and costs for solar home system design cases.

Scenario	TV	Battery	Total Connected Load (W)	Total Daily Load (Wh/day)	Battery storage (Ah ^a)	PV module size (Wp)	Estimated system price (\$)
Conventional Case	CRT	Lead-acid	71	283	126	102	561
Base Case	Standard LED-LCD		21	84	38	30	339
Efficiency Case I	Efficient LED-LCD		10	41	18	15	256
Efficiency Case II		Li-ion	10	41	13	13	320

The results of the conventional case are based on authors' assumptions, including 21-in. CRT (60 W in on-mode), 15% efficiency loss from DC-AC inverter, and \$50 retail price. Note that the results are based on modeled data; actual system sizing would vary in practice. Actual price savings will also vary by market.

^a Ah – ampere hour.

$$\text{Savings} = ACS(\text{with standard TV}) - ACS(\text{with an efficient TV}) \quad (2)$$

where i represents each component of an SHS, with a discount rate of 10%. We assume a battery lifetime of 2 years for a lead-acid battery and 6 years for a Li-ion battery; a TV lifetime of 10 years; and a PV and BOS lifetime of 10 years. These author assumptions are based on (Park et al., 2011; Phadke et al., 2015; United States Agency for International Development USAID, 2014), and (Zhuang et al., 2007).

4.2. Benefit of energy-efficient TVs for solar home system design

Energy-efficient DC TVs cost slightly more than less-efficient models, but their adoption contributes to reducing overall SHS cost. The total cost of an SHS with an energy-efficient DC LED-LCD TV is expected to be about 25% less than the cost of an SHS with a standard LED-LCD TV because the PV and battery capacities required with the efficient TV would be 50% less than for the same energy system with the standard TV (see Table 4). The total savings potential will grow as TV demand increases in the off-grid market along with improved electricity access, increased availability of TV content, and a decline in LED-LCD TV prices. The TV market for off-grid households is predicted to be at least 50 million units in 2020. Based on an estimated average cost savings potential of about \$80 per system, the total cost-savings potential for 50 million households is about \$4 billion. If we compared the LED-LCD TV plus SHS with a conventional CRT TV plus SHS, the benefit of the energy-efficient LED-LCD TVs would be much larger. Table 5 summarizes the component specifications modeled for the three primary LED-LCD TV scenarios and an additional case with conventional CRT TV.

Our key finding is that the cost of an off-grid SHS with a TV can be reduced by improving the TV energy efficiency because the cost of the TV efficiency improvement is smaller than the resulting SHS savings as a result of a smaller SHS being needed as the TV becomes more efficient. Although further price declines and TV efficiency advances are anticipated, it is difficult to estimate precisely how much TV price and efficiency will change the future. Another finding is that, in terms of annualized cost that considers system component lifetime, an SHS with a Li-ion battery becomes cost competitive against an SHS with a lead-acid battery (see Fig. 3). Because of possible variations in system parameters such as TV price and efficiency, we consider additional scenarios that include $\pm 20\%$ variations in efficiency of LED-LCD TVs and the lower- and higher-bound incremental costs for energy-efficient DC TVs from Table 2. Although variations in other system parameters (such as PV price, battery price, and PV and battery lifetime) change the total cost of the SHS, we do not consider these parameters because they apply to both the base case and efficiency case TVs. The lower-bound case shows a savings of \$36 per system in annualized cost. The upper-bound estimate is \$18 per system in annualized cost. Fig. 2 and Table 5 show the annualized costs of SHS designs with a TV by sensitivity scenario.

Table 5
Estimated costs and savings by additional solar home system design cases.

Scenario	PV cost	Battery cost	TV price	TV efficiency	Annualized system price (\$)	Savings compared to Base Case
Base Case	\$0.8/W	\$0.08/Wh (Lead-acid)	\$150	21 W	\$85	\$0
Efficiency Case I	+20% efficiency and lower incremental cost Normal efficiency and incremental cost +20% efficiency and higher incremental cost		\$155	8 W	\$49	\$36
			\$158	10 W	\$56	\$29
			\$172	12 W	\$64	\$21
Efficiency Case II	+20% efficiency and lower incremental cost Normal efficiency and incremental cost +20% efficiency and higher incremental cost	\$0.35/Wh (Li-ion)	\$155	8 W	\$52	\$33
			\$158	10 W	\$59	\$26
			\$172	12 W	\$67	\$18

Assumptions: Discount rate 10%; Battery lifetime 2 years for a lead-acid battery and 6 years for a Li-ion battery; TV lifetime 10 years; PV and BOS lifetime 10 years; TV daily usage 4 h; LED-LCD TV standby-mode power consumption 0.5 W.

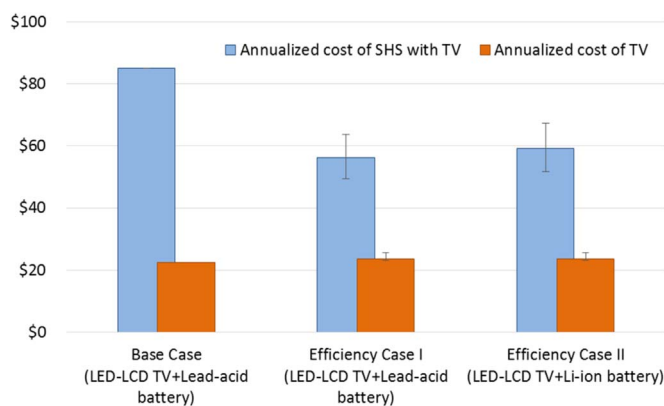


Fig. 3. Annualized cost of solar home systems and TVs by scenario. Assumptions: Discount rate 10%; Battery lifetime 2 years for a lead-acid battery and 6 years for a Li-ion battery; TV lifetime 10 years; PV and BOS lifetime 10 years; TV daily usage 4 h; LED-LCD TV standby-mode power consumption 0.5 W.

5. Summary and conclusions

We find that LED-LCD TV energy consumption can be reduced by about 50% by deploying commercially available, cost-effective efficiency technologies, including DC-only systems. This efficiency improvement reduces total SHS cost by about 25% because it allows use of 50% smaller PV and battery capacities compared to a base case. Our analysis estimates that adoption of efficient DC LED-LCD TVs could significantly decrease modeled retail SHS price even though these TVs cost more than standard LED-LCD TVs. If the projected off-grid TV market of 50 million households in developing countries were to benefit from the average per-system cost savings potential of about \$80, the total cost savings from SHS purchases in these off-grid regions would be about \$4 billion. Another finding is that, in terms of annualized cost that considers system component lifetime, an SHS with a Li-ion battery becomes cost competitive against an SHS with a lead-acid battery.

These findings have the following implications for energy-efficiency policies and programs in off-grid regions:

First, as a result of the global transition to LED-LCD TV technology, price declines and efficiency advances in these TVs will enable increased use of SHSs in off-grid regions and lower total SHS costs for the same level of electricity service. However, although the use of energy-efficient TVs can reduce the total cost of off-grid energy systems, the up-front cost of LED-LCD TVs is generally higher than the cost of less-efficient conventional LED-LCD TVs (as well as inefficient traditional CRT TVs). Policies and programs, such as awards

and labeling, should consider ways to increase public awareness of the benefits of energy-efficient DC TVs.

Second, to facilitate reduction in LED-LCD TVs prices, policy measures need to reward energy-efficient, quality-assured TV products. As discussed earlier, it is still difficult to find DC LED-LCD TVs from global TV manufacturers, mainly because these TV products are at an early stage of development, and the potential economies of scale are uncertain. Government policies that reward energy-efficient TVs would help accelerate the penetration of these TVs in the market.

Third, to facilitate further reduction in home energy system costs, policies need to address the adoption of commercially available, cost-effective efficiency improvements in TVs. LED-LCD TVs with selected technological options can provide specific energy and cost-savings benefits to off-grid systems with no significant incremental cost increase for the TV products themselves.

The off-grid appliance and energy system market is young and highly distributed. TV demand in the off-grid market is expected to grow as electricity access improves and LED-LCD TV prices continue to decline. Further research on off-grid TV energy efficiency should discuss country- or region-specific energy and cost-savings potentials of energy-efficient DC TVs as well as technical issues such as interoperability and quality assurance that were not addressed in this study.

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