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Powering a Home with Just 25 Watts of Solar PV

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April 14, 2015

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List of Acronyms

AC	Alternating current
Ah	Ampere-hour
BLDC	Brushless direct current (in reference to brushless DC motors)
BOS	Balance of system
CCFL	Cold cathode fluorescent lamp
CFL	Compact fluorescent lamp
CRT	Cathode ray tube
DC	Direct current
Global LEAP	The Global Lighting and Energy Access Partnership
GSM	Global System for Mobile Communications
IDCOL	Infrastructure Development Company Limited
h	Hour
in	Inch
in^2	Square inch
klm	kilolumen
$kWh/m^2/day$	kilowatt-hour per meter squared per day
LCD	Liquid crystal display
LED	Light emitting diode
$LiFePO_4$	Lithium iron phosphate (in reference to lithium iron phosphate batteries)
lm	lumen
lm-h	lumen-hour
lm/W	lumen per watt
NiMH	Nickel-metal hydride
PAYG	Pay-as-you-go (in reference to energy systems that involve PAYG payment systems)
PV	Photovoltaic
SHS	Solar home system
TV	Television
U.S.	United States
USA	United States of America
W	Watt
W/in^2	Watt per square inch
Wh/day	Watt-hour per day
W_p	Watt-peak

Powering a Home with Just 25 Watts of Solar PV: Super-Efficient Appliances Can Enable Expanded Energy Access Using Off-Grid Solar Power Systems

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Abstract: Highly efficient direct current (DC) appliances have the potential to dramatically increase the affordability of off-grid solar power systems used for rural electrification in developing countries by reducing the size of the systems required. For example, the combined power requirement of a highly efficient color TV, four DC light emitting diode (LED) lamps, a mobile phone charger, and a radio is approximately 18 watts and can be supported by a small solar power system (at 27 watts peak, Wp). Price declines and efficiency advances in LED technology are already enabling rapidly increased use of small off-grid lighting systems in Africa and Asia. Similar progress is also possible for larger household-scale solar home systems that power appliances such as lights, TVs, fans, radios, and mobile phones. When super-efficient appliances are used, the total cost of solar home systems and their associated appliances can be reduced by as much as 50%. The results vary according to the appliances used with the system. These findings have critical relevance for efforts to provide modern energy services to the 1.2 billion people worldwide without access to the electrical grid and one billion more with unreliable access. However, policy and market support are needed to realize rapid adoption of super-efficient appliances.

One Sentence Summary: When super-efficient appliances are used in off-grid solar power systems, the total cost of providing off-grid electricity services can be reduced by as much as 50%.

1. Introduction

Highly efficient direct current (DC) appliances are enabling dramatic advances in the utility and affordability of off-grid solar power systems for rural electrification in developing countries. Advances in light emitting diode (LED) technology, including falling prices and efficacy improvements, have already sparked development of a rapidly growing commercial market for "pico-solar" systems (i.e. solar photovoltaic systems with modules smaller than 10 peak watts [W_p]) for off-grid lighting and mobile phone charging. An estimated 7.5 million quality verified pico-solar products have been sold in Africa over the past five years as of December 2014, and sales are growing at a rate that exceeds 100% annually (Lighting Africa, 2015). Pico-solar market commercial activity is also robust in South Asia (Navigant, 2014). Efficiency gains in other household appliances, including flat panel televisions (TVs) and fans, in combination with LED lighting, have the potential to catalyze similar market growth for larger solar home systems (SHSs) that have solar photovoltaic (PV) modules ranging from 10 to over 100 W_p. These efficiency gains and the associated increase in off-grid solar system affordability have relevance for the approximately 1.2 billion people globally without grid electricity access and an additional one billion with unreliable electricity. Improved access to the services enabled by electricity access can have immediate effects on economic activity and quality of life (Casillas & Kammen, 2010; Alstone, et al., 2015).

2. Off-Grid Solar Power for Rural Electrification

Small solar power systems, including SHSs and solar lanterns, have been used to provide electric power for small appliances since the 1970s (e.g. see Cabraal, et al., 1996; Nieuwenhout, et al., 2000; Jacobson, 2004). Systems typically consist of one or more PV modules, a storage battery, a charge controller, appliances, and balance of system (BOS) components such as wiring, switches, and mounting hardware (Cabraal, et al., 1996; Jacobson, 2004). Typical appliances for small off-grid solar systems for household electrification include lights, TVs, radios, mobile phone chargers, and – in hot locations – fans (Nieuwenhout, et al., 2000; Jacobson, 2007). Many small systems rely exclusively on DC electricity, although some systems employ an inverter to power alternating current (AC) appliances.

The initial cost of systems has long been a barrier for adoption. Several approaches have been utilized to reduce the initial cost barrier, including piecemeal purchasing strategies, micro-finance loans, and – most recently – pay-as-you-go (PAYG) schemes (Banks and Hankins, 2004; Jacobson, 2004; Siegel and Rahman, 2011; Winiecki, et al., 2014). While these strategies have contributed to off-grid solar affordability by spreading the costs of the system out over time, falling system prices have also contributed substantially to system affordability.

3. Off-Grid Solar System Cost Trends

Historically, the price of solar PV modules was the dominant factor determining system cost. However, PV module prices have declined sharply over time, decreasing by more than 85% over the last decade (Giannakopoulou, 2014). As a result, they now often account for less than one-quarter of the overall cost of an off-grid solar home system (IDCOL, 2015). While the price of PV cells has been relatively stable for the past year, many in the industry expect module prices to resume their decline, albeit at a slower rate, within a year (Feldman, 2014).

Beyond PV modules, other factors that contribute to the cost of off-grid solar systems include pricing for storage batteries, charge controllers, electrical supplies (wires, switches, over-current protection, and others), and labor for system assembly and – where applicable – installation. Lead acid batteries are a mature technology, and prices have been relatively stable in many markets (Jaffe, 2014). In recent years the price of lithium-based batteries has declined sufficiently to allow for their use in pico-solar products. This improves the performance and durability of the systems considerably, but the use of lithium batteries has not contributed to a reduction in the initial price of the systems. The price of most other BOS components has been stable or – in some cases such as copper wire – increasing (Solarbuzz, 2012; Davis and Shirtliff, 2014).

Two additional factors, the value of the Chinese currency and the cost of labor in China, have provided upward pressure on the price of many solar products and systems. The Chinese Yuan has gained 10% in value relative to the United States (U.S.) dollar over the past four years, making exports from China relatively more expensive (USForex, 2015). Additionally, the cost of wages in manufacturing in China has increased at an average rate of 14% annually since 2004, making components and systems manufactured in that country relatively more expensive than before (Trading Economics, 2015).

While the net effect of these trends on the future price of SHSs is uncertain, it seems unlikely that the aggregate cost of off-grid solar systems will decline sharply over the coming decade as a result of changes in system component prices. Nonetheless, the cost of delivering basic household electrical service using solar off-grid systems has great potential to drop substantially as a result of energy efficiency gains in key appliances commonly used in off-grid solar systems. In fact, rapid growth in the market for pico-solar products has been driven, in large part, by dramatic LED lighting efficacy gains that have contributed to increased performance and lower prices.

4. LED Efficacy and Price Gains and the Pico-Solar Market

LED lighting technology has experienced dramatic gains in efficacy and affordability over the past five years. Data from the U.S. Department of Energy (2010a; 2014) indicate that LED package prices have dropped by an order of magnitude since mid 2009 while the efficacy of light output has doubled from about 70 lumens per watt (lm/W) to over 135 lm/W for warm white LEDs[1].

The result of these gains has enabled dramatic performance gains and price declines in the pico-solar market. The results presented in Figure 1 indicate product pricing for an illustrative set of pico-solar products that all deliver the same level of service (i.e. 120 lumens [lm] of light output for four hours [h] per day). The first two products shown are solar lanterns based on compact fluorescent lamp (CFL) technology for the years 2009 and 2014, respectively. The next four products presented are based on LED technology for the years 2009, 2012, 2014, and 2017 (projected). As shown, products based on CFL and LED technology had similar pricing as of 2009. Since then, the price of LED-based products has declined sharply while the price for CFL products has experienced a more modest decline.[2] While a number of factors influence product pricing, the cost and efficacy of LEDs are the primary drivers for the price reduction for that

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[1] Warm white LED packages have a correlated color temperature (CCT) of 2580-3710 K and color rendering index >80. They provide a more yellow-white color as opposed to the blue-white of cool white LEDs that have a CCT of 4746-7040 K.

[2] In practice, the use of CFL technology for off-grid solar lamps has declined sharply since 2009, so the values presented for the 2014 CFL product are merely illustrative.

product type. Increased efficacy influences the price by enabling the same level of lighting service (in lumen-hours [lm-h] per day) to be delivered using a smaller, less costly PV module and battery. The decline in the price of off-grid lighting products has also been influenced by the price of PV modules, but, in the case of LED-based products, this contribution has been less significant than the price reduction associated with efficacy gains. In the illustrative example shown in Figure 1, falling PV costs resulted in a reduction in the retail price of LED-based products of approximately $3.23 from 2009 to 2014, while LED price and efficacy gains accounted for savings of $23.57 on the retail price. Note that the cost of the battery was influenced by a switch to higher performance lithium battery technology, the use of which has become widespread in pico-solar products due to its durability, efficiency, cycle life, and energy density (and hence size) advantages over lead acid battery technology. The BOS cost was also influenced by rising production costs. These two factors undermined the gains associated with LED price and efficacy improvements, but only to a small degree. Similar gains are expected going forward, as indicated by the projection to 2017 provided in Figure 1.

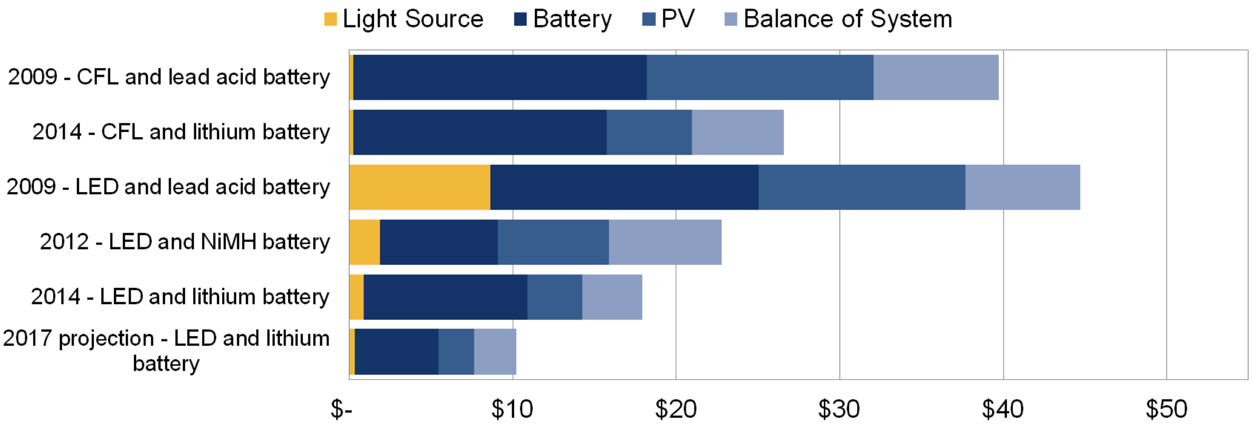

Figure 1. Retail price of pico-solar off products that provide lighting service of 120 lm for four hours per day.[3]

In practice, manufacturers of pico-solar products have not developed products that fully realize the cost reductions represented in Figure 1. Instead, companies have sought to strike a balance between increasing product performance and utility and decreasing product price. For example, many companies have increased the level of lighting service delivered by a particular product type while simultaneously reducing its price. Moreover, many products now include additional services such as mobile phone charging that also add to the cost of the product.

The rapid sales growth in the market for pico-solar products that occurred over the past five years (Fig.2) was enabled, in part, by the rising product performance and the falling product prices (Fig.1) that resulted primarily from LED technology gains. An analysis of normalized

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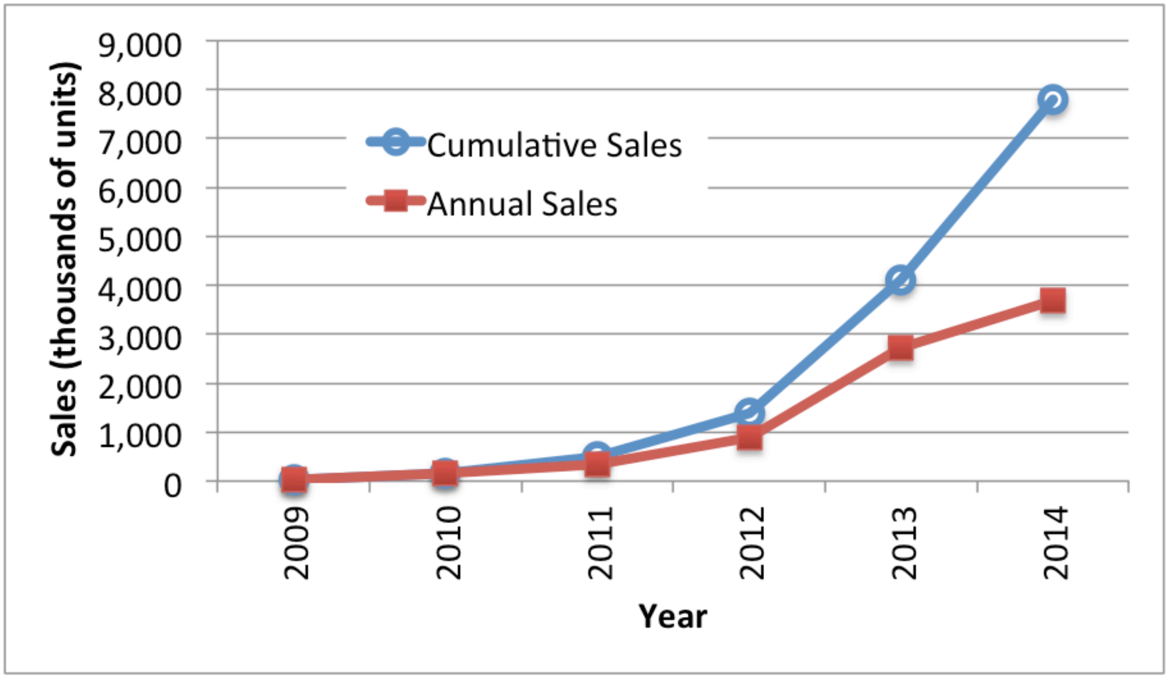
[3] Each product uses battery technologies that were or are common at the time, apart from the 2014 CFL product. The CFL and LED products from 2009 utilize a sealed lead acid battery, the 2012 LED product uses a nickel metal hydride (NiMH) battery, and the 2014 and 2017 LED products use a lithium iron phosphate ($LiFePO_4$) battery. The 2014 CFL product with a lithium battery is provided for comparison. All products utilize crystalline silicon PV modules and the stated lighting technology (CFL or LED). Note that, as of 2014, very few commercial products were using CFL technology. See Appendix A for a summary of additional assumptions.

wholesale prices for LED-based pico-solar products that were tested through the Lighting Global quality assurance program indicates a 70% price decline from 2011 to 2014 (Lighting Global, 2014).[4] Other key factors associated with market growth include improved product quality, development of distribution supply chains, increased access to finance within the sector, and growing consumer awareness.



Source: Lighting Africa, 2015

Figure 2. Commercial sales of Lighting Global quality verified pico-solar products in Africa from 2009-2014

5. Beyond Lighting: Super-efficient DC Appliances for Solar Home Systems (SHSs)

Energy efficiency is a key factor contributing to the takeoff of the pico-solar market, and it can similarly support improved affordability for larger off-grid solar systems such as SHSs and DC mini-grids. SHSs are widely used for rural electrification in a number of countries, with countries such as Bangladesh, India, Kenya, Indonesia, and Nepal having relatively large markets (Gauntlett, 2014).

Common appliances used in households with a solar home system are lights, TVs, radios, fans, and mobile phone chargers (Nieuwenhout, et al., 2000; Jacobson, 2007; Siegel and Rahman, 2011). Most radios and mobile phone chargers used in off-grid systems consume relatively little energy, so the bulk of the energy is typically allocated to lighting, TV viewing, and – where relevant – fan use. Gains similar to those discussed above for LED lighting are, of course,

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[4] Product prices were normalized by the average lighting service (lm-h/day) of their product category. For example, for single light products with no mobile charging capability, the average lighting service of all products was 340 lm-h/day. The other two categories were single light products with mobile charging (500 lm-h/day) and multi-light products (1230 lm-h/day). The price of each individual product was normalized based on providing the average level of lighting service of its product category. Prices were also been adjusted for inflation to December 2014 dollars on a per month basis.

applicable for lighting associated with these larger systems. There is also great potential to realize substantial efficiency gains for DC appliances such as TVs and fans. The potential gains associated with the use of efficient appliances vary by the type of device, as illustrated in the section that follows.

6. Technical Potential to Reduce Power Requirements by Energy Efficient End-uses

The technical potential to reduce electricity consumption for appliances typically used in solar home systems is substantial. The sections that follow include information about appliance efficiency trends for commercially available lights, TVs, and fans.

Lighting: For smaller size lights typically used in off-grid applications, LED technology has emerged as the most efficient lighting technology. Typical warm white LED package[5] efficacy (measured in lm/W) has doubled from 70 lm/W in 2009 to 135 lm/W in 2013 (US–DOE, 2010a; US–DOE, 2014). Large additional gains are expected over the coming years according to U.S. Department of Energy projections. LED packages are expected to achieve efficacies of 169 lm/W by 2015 and 197 lm/W by 2017 (US–DOE, 2014). Further, their costs per kilo-lumen (klm) have dropped by over 70% from \$18 per klm in 2010 to \$5.1 in 2013 and are projected to drop further to \$0.7 per klm by 2020 (US–DOE, 2011a; US–DOE, 2014).

The final LED lamp price is higher than the aforementioned LED package price. In 2013, an average price of 60 W equivalent LED lamps in the U.S. market was \$16 per klm (US–DOE, 2014), and from later 2013 onward, lighting manufacturers in the U.S. have been providing 60 W equivalent A-line LED lamps in the range of \$8 and \$20, i.e., \$10-\$25 per klm, partly including utility rebate (Tweed, 2013; GE Lighting, 2014). In November 2014 an average global retail price of 60 W equivalent LED lamps was estimated to be \$20.5 per klm (LEDinside, 2014). 40-60 W incandescent bulb replacement LED lamps consume 9-11 W compared to 10-15 W of a CFL (US–DOE, 2014; Tweed, 2013).

TVs: Liquid crystal display (LCD) technology has significantly reduced power requirements compared to cathode ray tube (CRT) TVs (Park et al., 2011). CRT was the original image rendering technology for TVs. An LCD, one of the flat panel display technologies, is a non-emissive display that uses a backlight, e.g. cold cathode fluorescent lamp (CCFL) or LED, as a light source (Park et al., 2011). As backlight source efficiency has improved, LCD TV efficiency has also increased. Although the final luminance available to the viewer is typically less than 10% of the initial luminance available from the backlight source, LCD TVs consume about 50% less power than traditional CRT TVs of similar screen size, and efficiencies are projected to improve further as backlighting and other component technology improves. LED technologies, aforementioned for general illumination, have already significantly penetrated into mobile device, monitor, laptop, and TV products (US-DOE, 2011b). Recently LED backlit LCDs were assessed to be at least 20-30% more efficient than the conventional CCFL backlit LCDs that are currently the least expensive TV technology. LED backlit LCDs have been expected to capture nearly the full backlighting market by 2016 (Park et al., 2011, 2013a, 2013b, 2014). Further, technologies such as efficient optical films can improve TV efficiency by more than 20% at incremental manufacturing costs less than \$5 for small sized TVs. DC-powered TVs are

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[5] An LED *package* refers to an assembly of one or more LEDs that includes wire bond or other type of electrical connections (thermal, mechanical, or electrical interfaces) and optionally, an optical element. An (integrated) LED *lamp* refers to an integrated assembly composed of LED packages, a LED driver, an ANSI standard base, and other optical, thermal, mechanical, and electrical components.

expected to have several additional advantages in terms of energy efficiency and are more applicable to off-grid areas relative to conventional AC TVs (Park et al., 2013a; Park et al., 2013b). The Global Lighting and Energy Access Partnership (Global LEAP) Awards tested a number of DC TVs designed for use off-grid to identify the world's highest quality, most energy-efficient, and affordable off-grid TV (Global LEAP Awards, 2014). The tested DC TVs had on-mode power consumption figures ranging from .05 to 0.1 watts per square inch (W/in^2) (M. Jordan, personal communication, October 27, 2014). In comparison, CRT TVs typically have power consumption figures ranging from 0.25 to 0.4 W/in^2 (TV.com, 2006; Park et al., 2011), which is about four times the power per unit area required by the tested DC TVs. Based on these findings, we estimate that a 19-inch (in), 10 W (i.e., 16:9 aspect ratio, approximately 154 square inches [in^2] of viewable screen area, and 0.065 W/in^2) LED backlit LCD TV can replace a 19-in, 60 W (i.e., 4:3 aspect ratio, approx. 173 in^2 of viewable screen area, and 0.35 W/in^2) CRT TV.

Fans: The best commercially available fan technology employs efficiency improvements associated with blade design, motors, drives, and controls and achieves up to 50% efficiency improvement compared to the status quo (Waide & Brunner, 2011). Using brushless DC (BLDC) motors, which utilize permanent magnets and are electronically commutated, instead of the induction motors that are typically used, can improve ceiling fan efficiency by 50%. Improving the design of fan blades can improve the ceiling fan efficiency further by 15% (Sathaye et al., 2013). The incremental cost of doubling the efficiency of a typical ceiling fan, e.g. by using a BLDC motor, is about $10 (Sathaye et al., 2013). As a result of the combination of the use of a BLDC motor and efficient blade design, a 30 W ceiling fan can replace a 70 W one and provide the same service (air delivery) at the incremental manufacturing cost of $14 out of a total cost of $50 (Sathaye et al., 2013). Similar efficiency gains have been observed in smaller table fans. For example, high efficiency table fans with blade diameters on the order of 10 to 12 in and power consumption on the order of 6 to 8 W are available for sale in Bangladesh and other Asian markets. This compares with 10 to 15 W for similarly sized conventional fans.

Table 1 summarizes key technologies assessed above. Similar opportunities exist for other electricity services such as refrigeration. For example, the energy consumption of typical small refrigerators can be reduced by as much as 40-50% by using commercially available technology (Garbesi, et al., 2011; US-DOE, 2010b).

With the exception of refrigerators, all of the technologies discussed above operate intrinsically on DC electricity. When they are used in grid-connected households, an AC-to-DC converter (often referred to as a “power supply”) is used. This conversion would not need to take place in off-grid systems (although in cases without voltage-matched appliances, DC-DC conversion is required). AC-to-DC conversion typically leads to 18%, 15%, and 13% electricity loss for lights, TVs, and ceiling fans, respectively (Garbesi, et al., 2011). In the case of refrigerators, it is possible to design them using either AC or DC electrical components.

Table 1. Selected technologies for efficiency improvement in lights, TVs, and ceiling fans

End use	Efficiency technologies	Description	Power reduction and other benefits
Lighting	▪ LEDs	LEDs are on the order of 1000 times, 6 times, and 1.3 times more efficient than kerosene-based lights, incandescent, and CFLs, respectively (US–DOE, 2014; Mills, 2005)	A 10 W LED lamp can replace a 60 W incandescent or a 13 W CFL, and has 30 and 2.5 times the rated life, respectively.
TV	▪ LED backlight ▪ Efficient optical films ▪ Dimming technology ▪ DC powered system	In general, LED backlit LCD TVs are 50%+ more efficient than CRT TVs. Efficient backlight sources, optical films, local dimming technology, and DC powered systems can further improve the typical LED-LCD TV efficiency by more than 40% (Park et al., 2011, 2013a & 2013b)	A 19 in, 10 W DC-powered LED-LCD TV can replace a 60 W CRT TV of similar screen size. DC LED-LCD TVs provide better picture quality, require less space, and do not need an AC to DC converter in the TV set.
Fans	▪ Brushless DC motors ▪ Efficient blades	Brushless DC motors are 50% more efficient than the typical induction motors used in ceiling fans. Better blade design can improve the efficiency of a ceiling fan by 15% (Sathaye et al., 2013) Similar efficiency gains are expected from table fans.	A 6 W DC motor powered table fan can replace a 10 W standard table fan and provide the same service (air delivery). Further, these DC fans do not require an AC to DC convertor.

7. Solar Home System Design and Cost Analysis

To estimate the savings that can be realized through the use of super-efficient appliances, we estimated the retail cost of purchasing a solar home system (SHS) and an associated set of appliances. The results presented in Figure 3 illustrate three scenarios that provide the same level of service to the end-users. A summary of the level of service provision is given in Table 2. Note that the scenarios presented here only represent one example. Similar results also apply over a range of system sizes, appliance types, and applications, including systems that include fans, refrigerators, and water pumps.

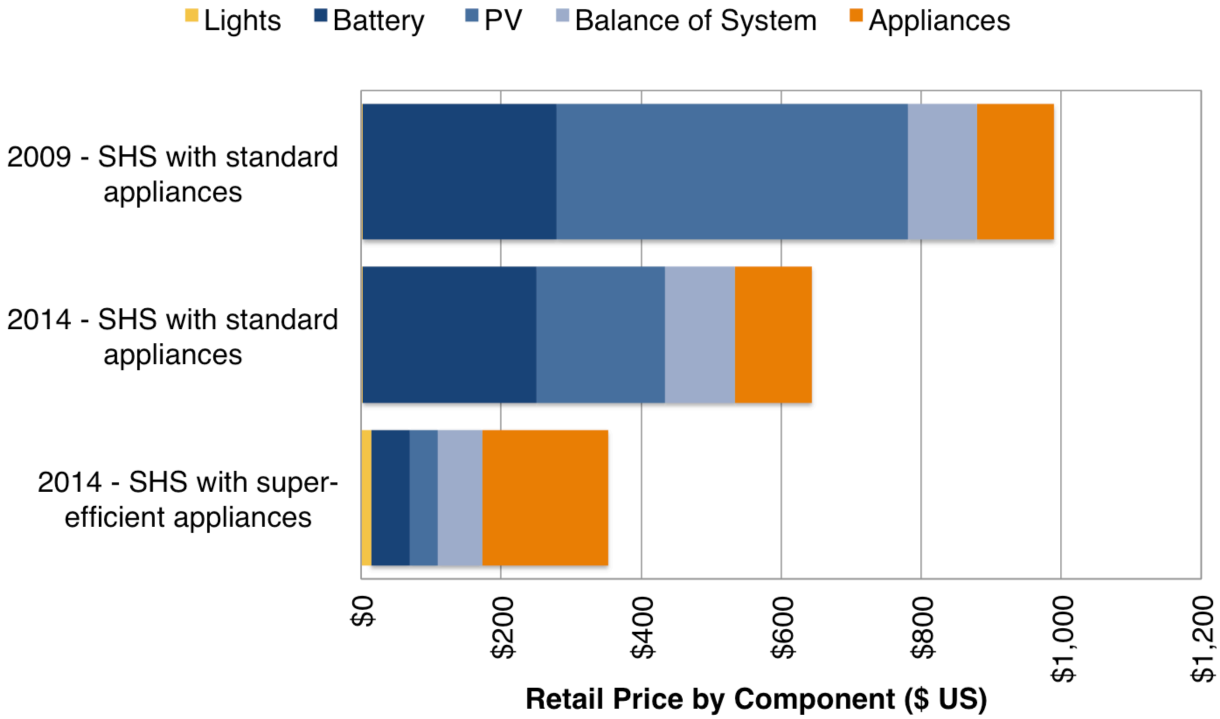

Figure 3. Retail purchase price for three solar home systems that provide identical levels of service. See Tables 2 and 3 for additional information about the three scenarios presented.

Table 2. Level of service provided by the three solar home system packages presented in Figure 3, above.

Energy Service	Size	Daily Use
Lighting	600 lm	4 hours
Television	19 in color TV	4 hours
Radio	Small portable radio	6 hours
Mobile phone charging	Basic phone	1 charge per day

Several results are evident from the findings presented in Figure 3. *First*, the cost of a SHS using standard appliances declined substantially from 2009 to 2014. This was due largely to a decline in the price of PV modules used for SHSs, which dropped from about $2.00 per watt in 2009 to $0.75 per watt in 2014 on a wholesale basis (PVinsights.com, 2014; EnergyTrend, 2014; Chase, 2014). Lead acid battery price declines also contributed modestly to the reduction. *Second*, the use of super-efficient appliances provides an additional decline in overall system cost despite the higher cost of the appliances. This is due largely to the reduction in energy use, which allows for a smaller PV module and battery. The specifications of the SHS components for the three scenarios are presented in Table 3. Key design assumptions include a solar resource of 5 kWh/m^2/day, three days of battery storage autonomy, a maximum battery depth of discharge of 70%, and the following efficiency losses: 15% loss due to imperfect maximum power point tracking for the PV module, 20% loss due to battery charge – discharge, and 15% loss due to wire resistance, connector contact resistance, and other miscellaneous effects. Additional model assumptions are summarized in Appendix B.

Table 3. Component specifications for the three solar home system scenarios presented in Figure 3, above. Note that the results are based on modeled data; actual system sizing would vary slightly in practice since it would need to conform to available component sizes for PV modules and batteries. In all three cases, the PV modules were assumed to be crystalline silicon and the batteries were lead acid.

System	Total Daily Load (Wh/day)	Total Connected Load (W)	PV Module Size (W_p)	Battery Size (Ah)
2009 – SHS with standard appliances	354	88	123	126
2014 – SHS with standard appliances	349	86	121	125
2014 – SHS with super-efficient appliances	77	18	27	28

Table 4 provides a summary of results for several additional scenarios. These findings confirm that the use of super-efficient appliances can result in substantial cost savings for a number of system and appliance use configurations.

Table 4. Initial retail cost savings for solar home system packages that include super-efficient appliances relative to packages that utilize standard appliances for a variety of appliance use configurations. Actual price savings will vary by market.

Solar Home System Level of Service				Total Connected Load for Super-Efficient System (W)	Percent Savings with Super-Efficient Appliances Relative to Baseline Scenario with Standard Appliances
Lights (150 lm each)	Mobile Phone Charge	Fans (12 in)	TVs (19 in)		
# of lights used for 4 h/day	# of full phone charges/day	# of fans used for 6 h/day	# of TVs used for 4 h/day		
2	-	-	-	3	24%
4	1	-	-	7	17%
4	1	1	-	13	23%
4	1	-	1	17	48%
4	2	1	1	25	41%

PV modules are expected to experience modest declines in cost over the coming years, with, for example, projected reductions by the U.S. Department of Energy on the order of 4% annually between now and 2016 (Feldman, 2014). While these reductions are important, a transition to the use of super-efficient appliances offers substantially greater potential for system cost and consumer price declines. This is especially true if the cost of super-efficient appliances themselves can be reduced through economies of scale in production.

Super-efficient appliances offer perhaps the best upcoming opportunity to reduce SHS initial purchase prices, but other trends in the off-grid energy market offer avenues for improving durability and longevity, further reducing life cycle costs. Two emerging trends related to pico-solar and SHS durability and a third trend related to business model innovation are noted below. System durability strongly influences the environmental and human development outcomes associated with the use of off-grid energy systems (Alstone, et al., 2014).

First, emerging battery technologies such as lithium iron phosphate ($LiFePO_4$) batteries are approaching price parity with lead-acid batteries; the latter battery type has had relatively stable pricing (Jaffe, 2014). Lithium batteries offer significant advantages over lead acid batteries, including increased cycle life, higher charge-discharge efficiency, and greater tolerance for deep discharge (Lighting Global, 2012). We expect that lithium batteries will begin to replace lead acid batteries in significant numbers over the coming years. Such a transition will not reduce the purchase price for systems initially, as lithium batteries still cost marginally more than lead acid batteries. However, it will result in improved system durability and a lower system life cycle cost due to longer battery replacement intervals.

Second, there has been a recent trend towards the development of plug-and-play SHS kits (Lighting Global, 2014). While these kits do not fully eliminate the need for technical assistance during installation for most off-grid customers, they can greatly reduce labor costs associated with system installation. This approach may not work effectively in all cases, but, where applicable, can provide measurable cost savings for many off-grid customers. Additionally, standardization and centralized production of complete systems can reduce component and (BOS) mismatch issues and enable more careful control of overall system quality.

Third, the innovative use of wireless communication technology is revolutionizing the marketing, sales, and financing of off-grid solar systems in some markets. Large gains in connectivity and digital access have occurred globally, including in the developing world. There is now near-ubiquitous connectivity for individuals working in supply chains for off-grid power and the majority of potential users have access to mobile phones (Nique and Arab, 2013). One emerging use of mobile technology in the off-grid solar energy sector is pay-as-you-go (PAYG) digital financing. PAYG technology extends micro-finance to previously unbanked buyers using embedded systems that can automatically enforce repayment without the need for loan servicing agents. This can lead to dramatically reduced transaction costs. A variety of combinations of payment systems ("mobile money", scratch cards, etc.) and enforcement mechanisms (remote GSM connections and keypad verification) are currently being deployed (Winiecki and Kumar, 2014). Additionally, the embedded GSM connections or intermittent connectivity used for payment enforcement in some PAYG systems present new opportunities for remote monitoring to identify service needs and better understand user behavior. More broadly, the rapidly growing conventional supply chain for off-grid energy systems, including for PAYG, relies heavily on connectivity for coordination of production, sales, and customer service that meets the needs of the off-grid poor.

8. Policies to Accelerate Adoption of Super-efficient Appliances in Off-grid Areas

Falling LED prices and increases in efficacy have helped enable rapid sales growth for pico-solar products that provide basic lighting and, often, mobile charging services for off-grid use in Africa, Asia, and other regions. This has led to significant welfare gains for users in terms of avoided expenditures for kerosene and device charging fees, improved quality of lighting, and reduced exposure to the health impacts of fuel-based lighting (Alstone, et al., 2015; Lam, et al., 2012; Mills, 2012; Pokhrel, et al., 2010; Epstein, et al., 2013; Lakshmi, et al., 2012). The widespread use of super-efficient appliances provides a similar opportunity to help greatly improve the affordability of larger off-grid solar systems for household use.

While the use of super-efficient appliances to reduce the cost of off-grid solar systems is promising, several barriers inhibit rapid deployment of the technology. First, while prices are declining in some cases, the initial cost of the appliances is generally higher than less efficient versions. In the absence of buyer awareness about the benefits of super-efficiency, this can inhibit rapid uptake.

Awareness raising efforts such as awards programs and outreach campaigns offer avenues for increasing knowledge about the benefits of super-efficient appliances. Efforts to increase awareness should consider typical purchasing patterns for off-grid SHSs, as this influences the target audience for the awareness messages. In many markets, SHSs are sold on a component basis. When this approach is taken, the appliances used with the system are frequently selected by retail buyers that have little access to technical guidance or support from a person that understands off-grid solar system design. In cases where retail buyers are selecting appliances on an independent basis, they should be a primary target audience for awareness raising efforts. In other cases, SHSs are sold in packages that frequently include lights and – sometimes – other appliances such as TVs, radios, and fans. When appliances are included with the rest of the system in a package, the vendor becomes the primary audience for awareness raising efforts. Vendors do often have an incentive to specify highly efficient appliances in order to increase the affordability of the package. However, some vendors may not be fully aware of the opportunity afforded by super-efficient appliances, or they may not know how to effectively procure good quality appliances. It is, of course, much more challenging and costly to effectively reach retail buyers than it is to communicate with vendors that are further upstream in the delivery chain, so the widespread deployment of super-efficient appliances would benefit from a trend toward the inclusion of appliances in solar home system packages.

Measures that contribute to the reduction of prices are also important for accelerating adoption of super-efficient appliances. Most super-efficient off-grid appliances are at an earlier stage of development, and their pricing is therefore high, in part, because they have not achieved economies of scale in production. Government and development agency programs that involve bulk purchase of super-efficient appliances can – if designed appropriately – lead to price reductions because they enable appliance manufacturers to scale up their production. Government policies such as taxes and duties charged on appliances can also influence product pricing. Policies that actively seek to reward super-efficiency can help encourage uptake of these devices.

Regardless of whether the appliance purchases are made by governments, system manufacturers, or retail buyers, product quality assurance is important to ensure that those who are making the purchases are able to distinguish good quality products from inferior goods (Jacobson and Kammen, 2007; Akerlof, 1970). Global LEAP carried out preliminary work relevant to the development of test methods for DC appliances for off-grid use in the context of the Global LEAP Appliance Awards (Global LEAP Awards, 2014), and efforts to make additional progress are underway. Existing quality assurance efforts, such as the ones operated by the World Bank Group's Lighting Global program and the Infrastructure Development Company Limited (IDCOL) SHS program in Bangladesh, could consider building on this work by adding efficient appliances to the list of products covered by their respective programs. Additional measures, such as efficiency standards and labeling programs for off-grid appliances, might also be utilized.

Access to finance for quality-assured super-efficient appliances could help enable their use. Efforts to support finance could include measures ranging from support for establishment of working capital loan facilities that enable distributors to purchase and manage stock to consumer finance that helps retail buyers purchase higher cost appliances such as TVs. In some cases, support that enables concessional financing may be appropriate. Additional research and engagement with market actors and financial institutions is needed to identify which specific policies would be most beneficial to meet the financing needs of the off-grid appliance sector.

While there have been a number of global or regional initiatives focused on supporting the deployment of pico-solar products and solar home systems, relatively few have focused specifically on increased adoption of super-efficient appliances for off-grid use. Given the very real opportunity to help expand access to energy services in off-grid areas through the use of these devices, we encourage existing programs that are managed by governments and international development agencies to strongly consider incorporating measures that support increased use of super-efficient appliances.

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Appendix A: Pico-Solar Product Design and Cost Analysis Assumptions

This appendix includes a summary of key assumptions related to the cost analysis for pico-solar systems presented in Figure 1 in the report.

1. The load for the system is exclusively lighting. For the sake of simplicity, it was assumed that the product did not charge a mobile phone. In practice, many off-grid lighting products include mobile phone charging capabilities.
2. LED luminaire efficacies – Typical warm white LED luminaire efficacies from the US DOE Solid-State Lighting Research and Development Multi-Year Program Plan for 2010, 2013 and 2014 were used. The 2014 efficacy figure used is an estimate based on the average of the typical 2013 figure and the 2015 projection figure. The 2017 efficacy projection used the projected 2017 figure presented in the same 2014 DOE document. These figures were verified through comparison with the Lighting Global pico-solar product testing results for products tested in 2014, which averaged 87 lm/W and ranged from 25 to 158 lm/W. The figures were also verified through comparison with the Global LEAP Awards test results of DC LED luminaires (1-6 W) conducted in 2013. The average efficacy of tested products was 102 lm/W.
3. CFL luminaire efficacy – The typical CFL luminaire efficacy figures for 2009 and 2013 were used from the US DOE Solid-State Lighting Research and Development Multi-Year Program Plan for 2010 and 2014, respectively.
4. LED package costs – The typical, 1000 quantity, warm white LED package prices from the US DOE Solid-State Lighting Research and Development Multi-Year Program Plan for 2010, 2013 and 2014 were used. The 2014 cost figure used is an estimate from the average of the typical 2013 figure and the 2015 projection figure.
5. DC CFL cost – The Solid-State Lighting Research and Development Multi-Year Program Plan for 2010 and 2014 provided typical 2009 and 2013 retail CFL costs for an AC 13 W self-ballasted compact fluorescent lamp, respectively. This was adjusted to the wholesale FOB cost by assuming the retail cost is twice that of the wholesale cost. The cost of DC CFLs was then conservatively assumed to be 50% greater than the AC CFL costs due to the much lower production volumes of DC CFLs used worldwide.
6. Wholesale PV module costs – These costs were provided confidentially from a single large manufacturer of pico-solar products. The 2017 projection of the wholesale PV module cost was calculated by adjusting the 2014 figure used by the expected cost reduction percentage indicated for 2017 by Feldman (2014).
7. Battery costs – A custom data set was purchased from Navigant Consulting of historical and forecast battery pricing ranges for the size of lithium and lead acid batteries commonly used in pico-solar products. The midpoints of the ranges provided by Navigant were assumed for the battery costs. For the 2012 Nickel Metal Hydride battery cost, the 2012 cost of this battery from the Lighting Africa Market Trends Report 2012 (2013) was used.
8. BOS costs – The component cost breakdown from the Lighting Africa Market Trends Report 2012 (2013) was used to calculate the BOS cost per watt of the PV module. The BOS cost includes housing, LED driver, labor and assembly.

9. PV maximum power point tracker (MPPT) efficiency – The Lighting Global pico-solar product testing results indicated that the average MPPT efficiency of reference pico-solar products was 93%. This was used in the analysis.
10. Battery efficiency – The figures used were from Reddy (2010) and Lighting Global pico-solar product testing results, which indicated the average lithium battery efficiency of reference pico-solar products was 94%.
11. Other efficiency – The Lighting Global pico-solar product testing results indicated that the average circuit efficiency of reference pico-solar products was 80%. This was used in the analysis.
12. Retail cost – The retail cost was assumed to be twice the FOB wholesale cost based on the typical markup and duty and tax rates across African countries indicated in the Lighting Africa Market Trends Report 2012 (2013).

Appendix B: Solar Home System (SHS) Design and Cost Analysis Assumptions

This appendix includes a summary of key assumptions related to the cost analysis for solar home systems presented in Figure 3 and Table 3 in the report.

1. LED luminaire efficacies – Typical warm white LED luminaire efficacies from the US DOE Solid-State Lighting Research and Development Multi-Year Program Plan for 2010, 2013 and 2014 were used. The 2014 efficacy figure used is an estimate from the average of the typical 2013 figure and the 2015 projection figure. These figures were verified against the Lighting Global pico-solar product testing results for products tested in 2014, which averaged 87 lm/W and ranged from 25 to 158 lm/W. The figures were also verified against the Global LEAP Awards test results of DC LED luminaires (1-6 W) conducted in 2013. The average efficacy of tested products was 102 lm/W.
2. CFL luminaire efficacy – The typical CFL luminaire efficacy figure for 2009 was used from the Solid-State Lighting Research and Development Multi-Year Program Plan for 2010.
3. DC LED luminaire cost – This was calculated using the average wholesale costs for the 3 winning LED lamps tested in 2013 for the Global LEAP Awards. The cost was then adjusted by the percentage cost drop from 2013 to 2014 of LED lamps shown in the 2014 Solid-State Lighting Research and Development Multi-Year Program Plan.
4. DC CFL cost – The Solid-State Lighting Research and Development Multi-Year Program Plan for 2010 provided a typical 2009 retail CFL cost for an AC 13 W self-ballasted compact fluorescent lamp. This was adjusted to the wholesale FOB cost by assuming the retail cost is twice that of the wholesale cost. The cost of DC CFLs was then conservatively assumed to be 50% greater than the AC CFL costs due to the much lower volumes of DC CFLs used worldwide.
5. Television performance and cost – For the standard (conventional) television, a 19 in color TV based on cathode ray tube (CRT) technology was assumed. Based on observations of common practice and TV product availability for off-grid TV use in Sub Saharan Africa and South Asia, the TV was assumed to require AC power. A low cost, 100-watt modified sine wave inverter with an 80% conversion efficiency was used to convert DC power from the solar PV system to the AC power required by the TV. The TV was assumed to consume 60 W of AC power and have a retail cost of $70. TV pricing was based on observed retail prices for such TV sets in Kenya. The inverter was assumed to cost $40 based on retail prices from Kenya (Sollatek, 2014). For the super-efficient TV, a 19 in LCD TV based on LED-backlighting technology was assumed. The unit was assumed to consume 10 W during standard “on-mode” operation. This performance was based on units available for retail purchase in Kenya in 2014 and is consistent with test results from award winning products in the Global LEAP Awards competition (Global LEAP Awards, 2014). The retail price of the super-efficient TV was assumed to be $180 based on retail prices for units of this size in Kenya. These prices are also consistent with advertised prices for award winning products in the Global LEAP Awards (Global LEAP Awards, 2014).
6. Fan performance and cost – The cost and performance of both the standard (conventional) and super-efficient fans are based on 12 in. table fans that are available for retail purchase in the South Asian countries of India and Bangladesh. The standard fan was assumed to consume 10 W and have a retail price of $7.20 (based on a price of 450 Indian Rupees). The

super-efficient fan was assumed to consume 6 W and have a retail price of $15 (based on a price of 1200 Bangladesh Taka).

7. Mobile phone charging performance – Mobile phone charging was assumed to require 10 Wh of electricity per charge for scenarios involving both standard and super-efficient appliances. The charging energy is based on the typical charging requirements of basic mobile phones commonly available in Africa and South Asia. The cost of purchasing the mobile phone and charger were not included in the cost analysis.
8. Radio performance and cost – The power to operate a small radio was assumed to be 1 W for both scenarios (i.e. standard appliances and super-efficient appliances). While the power required to operate a radio varies by brand, size, and use patterns, low power radios are widely available and affordable in Sub Saharan Africa and South Asia. Low power consumption radios can therefore be considered for both scenarios.
9. Wholesale PV module costs – The 2009 figure was determined by using the average of High and Average figures from PVinsights PV module price data (2014). The 2014 figure was determined by using the average of the High and Average figures from the PVinsights (2014), EnergyTrend PV (2014) and Bloomberg New Energy Finance PV module cost data (Chase, 2014).
10. Lead acid battery costs – 2014 Bangladesh solar home system component prices provided by IDCOL were used. The 2009 lead acid battery cost was assumed to be 10% higher than the 2014 cost based on the trend indicated in the custom battery cost data set purchased from Navigant Consulting.
11. BOS costs – 2014 Bangladesh solar home system component prices provided by IDCOL were used to estimate the equation by which BOS cost varies with the wattage of the PV module. The BOS includes cables, other accessories, transportation and installation.
12. PV maximum power point tracker (MPPT) efficiency – The efficiency of 85% was assumed based on expert opinion. Reza Reisi, et al., (2013) indicate that off-grid MPPT efficiencies can range from 86% to 98% depending on the algorithm employed.
13. Battery efficiency – The lead acid battery efficiency used was from Reddy (2010).
14. Other efficiency – The Lighting Global pico-solar product testing results indicated that the average circuit efficiency of reference pico-solar products was 80%. This value was also used in the analysis of solar home systems. The value is consistent with the professional experience of the research team.
15. Retail cost – The retail cost was assumed to be twice the FOB wholesale cost based on the typical markup and duty and tax rates across African countries indicated in the Lighting Africa Market Trends Report 2012 (2013).