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LED advances accelerate universal access to electric lighting

Les avancées dans le domaine des LED accélèrent l'accès universel à l'éclairage électrique

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ABSTRACT

A rapid increase in the performance and quality of white LED light sources has changed the dynamics of electricity access in the last 10 years, reaching tens of millions of people with electric light who previously had no viable alternatives to fuel-based lighting, which is dangerous and expensive. Eliminating fuel-based lighting is a key public health, safety, social equality, and environmental opportunity that is now achievable. Technology advances in LEDs, other super-efficient appliances, solar photovoltaic generation, advanced batteries, and coordinating information technology systems have combined to significantly expand the reach of off-grid energy systems. With support and effort, it is plausible that small "pico-solar" and "solar home" systems could serve over a billion people within a generation, providing basic but highly valued services. Continued progress can be achieved with attention to continued improvements in technology, supporting a growing range of new businesses and enterprises in energy access markets, and synergy with broader human development effort around access to clean water, financial inclusion, and fair access to resources.

RÉSUMÉ

L'accroissement rapide des performances et de la qualité des sources LED de lumière blanche a changé la dynamique de l'accès à l'électricité au cours des dix dernières années, permettant à des dizaines de millions de gens qui, auparavant, n'avaient pas d'alternatives viables à l'éclairage au pétrole, qui est dangereux et cher, de bénéficier de l'éclairage électrique. L'élimination de l'éclairage au pétrole est un enjeu clé de santé publique, de sécurité, d'égalité sociale, et une opportunité environnementale qui est à présent à notre portée. Les avancées technologiques dans le domaine des LED ainsi que d'autres appareils domestiques extrêmement efficaces, la génération photovoltaïque solaire, les batteries de nouvelle génération et les systèmes coordonnant l'information se sont associés pour étendre significativement la portée des systèmes électriques hors réseau. Avec soutien et effort, il est plausible que de petits systèmes « pico-solaires » et « maison solaire » puissent alimenter un milliard de personnes en l'espace d'une génération, procurant des services de base, mais de grande utilité. Un progrès continu peut être atteint si l'on porte attention

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à poursuivre les améliorations technologiques, qui soutiendront un nombre croissant de nouvelles activités et entreprises sur les marchés de l'accès à l'énergie, en synergie avec les efforts de développement humain autour de l'accès à l'eau propre, l'accès aux ressources financières et l'accès équitable aux ressources.

1. Introduction

For the 1.2 billion people who live without access to electricity in 2017 [1], and up to a billion more whose connection is unreliable day and night [2], the options for lighting after dark have typically been stark: kerosene lamps, candles, wood, and other fuels have been the conventional approaches for over a century. Fig. 1 shows a range of fuel-based lamp examples.

While nearly as many people live without electricity today as did in the late 1800's, when modern utilities first started business, there are now new options for reaching those who are deprived of access [3]. Based on significant and rapid changes in the capabilities and cost of solar photovoltaics (PV), batteries (often based on lithium chemistry), and efficient appliances like LED lights, a range of decentralized electricity options are now available as alternatives that extend beyond the reach of traditional regional grids. Importantly, these technologies are improving dramatically compared to fuel-based lighting. These newly available *pico-solar lamps* and *solar home systems* (*SHS*) power valuable loads including LED lighting, mobile phone charging, televisions, fans, and other small appliances. Fig. 2 illustrates a selection from among hundreds of varieties of small-scale solar energy systems that are currently available.

1.1. The high and diverse costs of fuel-based lighting

Achieving universal electricity access globally is one of the key human development challenges of this century [4]. Replacing inferior fuel-based lighting with modern lighting is a critical part of this transition and could help improve equality in access to resources, supporting important aspects of family and community life that are enabled or enhanced with adequate lighting: socializing, studying, reading, working, cooking, commerce, nighttime security, and more. In addition to the benefits of improved service, there is also a significant opportunity related to elimination of fuel-based technology systems for lighting, which impose high costs and lead to easily avoidable damages to local and global societies.

Some of the most significant damages from fuel-based lighting are public health and safety risks, resulting in thousands of deaths and hundreds of thousands of significant injuries per year through inhalation of smoke, accidental poisoning from ingestion of fuel, and burns [5–7]. Poor indoor air quality from solid fuel combustion is a significant cause of premature death globally, with a recent analysis of the global burden of disease estimating 2.2–3.6 million deaths annually [8]. While indoor cooking is the main driver for these pollution-related deaths kerosene for lighting is also a factor, albeit with significant uncertainty in the number of additional deaths attributable to lighting since most individuals using fuel-based lighting also cook with solid fuel [6,7]. Poisoning from accidental ingestion of fuel is a particular risk for children who mistake improvised fuel bottles for water, with an average mortality rate of 7% among those who are unfortunately exposed; it is

Fig. 1. Typical fuel-based lighting technology (left to right): 'Hurricane' lamp with glass wick cover, pressurized fuel lantern, and open-wick lamp made from a recycled consumer goods canister. Photos by Peter Alstone.

Fig. 2. Photomontage of a range of pico-solar and SHS products circa 2017 that are representative of the type that are produced and distributed in the global marketplace. The four photos were selected from dozens of quality-verified models that are cataloged at www.lightingglobal.org/products.

the leading cause of childhood poisoning in many countries with prevalent use of fuel-based lighting [6]. Finally, fires and explosions are a significant cause of injury, death, and property loss for people who rely on fuel-based lighting or neighbors living nearby whose homes are often caught up in the resulting fires. Fires involving significant damage to homes are doubly harmful, simultaneously injuring victims and wiping out their main stock of material wealth. Precise estimates of the number of people harmed and degree of harm due to lighting-based fires are not available, but the evidence indicates thousands of people a year are affected [6].

Fuel-based lamps also have disproportionate climate change impact given the low levels of service provided to users [9]. While the CO_2 emissions from fuel combustion are one contributor, the warming from kerosene open-wick lamps is significantly amplified by the emission of black carbon particles, a primary constituent in the air pollution plume from fuel-based lamps [10]. Any black carbon that is not inhaled by nearby users (leading to health-related harm) or deposited on indoor surfaces will eventually migrate to the atmosphere, where the particles strongly absorb sunlight with a warming potential 1000's of times higher than the equivalent mass of CO_2 [11]. Compared to many pollutants, black carbon has a very short residence time in the atmosphere (on the order of days to weeks), meaning that the radiative forcing effects are regionally focused around the source of emissions instead of being evenly distributed from long-term atmospheric mixing. Many sources of black carbon (like factories, wildland fires, combustion of biomass for cooking, and diesel vehicles) are emitted along with high-albedo co-pollutants that mitigate some or all of the warming effect by reflecting sunlight in the atmosphere, which has led to relatively wide uncertainty in the overall effect of black carbon pollution sources on the global climate [11]. In the case of open-wick lamps for fuel-based lighting, however, the emissions do not include these reflective particles [10]. Thus, recent estimates have concluded that eliminating fuel based lighting presents a near-term mitigation opportunity to reduce emissions equivalent to approximately 240,000 Gt CO_2/year [12], which is equivalent to 80 coal power stations [13] or about 4% of U.S.A. annual emissions in terms of CO_2 equivalent (U.S. EPA GHG inventory 2014).

Fuel-based lighting is not only harmful but also expensive for users, often representing 2–5% of their household spending with a regressive tendency towards poorer people spending higher fractions of their scarce resources on fuel [14]. The service levels from fuel-based lighting are often insufficient for meeting users' needs as well, in spite of the cost. Aside from pressurized kerosene lamps, which have light output on the order of 500–1000 lm that are comparable to typical grid-connected electric lamps, fuel-based lamps provide relatively low light levels (5–20 lm for open wick lamps and 10–50 lm for hurricane lamps) [15,16]. In practice, users report difficulties using the lamps for many tasks and must limit their use to avoid steep costs of operation [6,16–18]. This paradox of high costs for low service has a root cause in the low efficiency of combustion for producing light. The fuel-to-light efficacy is approximately 0.05 lm/W for open flame lamps [19], 100 times worse than incandescent light bulbs and 1000–2000 times worse than modern LED light sources.

In one way, however, fuel based lighting can seem inexpensive: the relatively low initial cost of entry that belies the long-term costs. The typical initial cost of the kerosene-burning off-grid lamps range from a few dollars for open wick lamp to tens of dollars for hurricane lamps with glass covers, to twenty or more dollars for a pressurized kerosene lamp [20]. These costs are only a small fraction of the total cost of service though, when the ongoing cost of fuel is accounted for. Overall, the global spending on fuel for lighting is significant, with various estimates ranging from $20–40 billion annually [9,21], on the order of $20–100 per year for each household where the lamps are in use depending on the country [21].

Based on current levels of spending on fuel-based lighting, the financial payback (if kerosene use is eliminated altogether) is on the order of weeks to months for many decentralized energy systems that include modern lighting. Taken together, the economic, health, safety, and environmental hardships imposed by fuel based lighting – and the improvements in quality of life associated with switching to electric lighting – present a clear opportunity for joint progress on climate and equality through expansion of electricity access [3].

1.2. Advances in off-grid solar

In response to the needs and opportunities presented, there are a range of efforts to deploy pico-solar lamps and SHS in regions where electricity access rates are low, with particular focus in Sub-Saharan Africa, South Asia, and parts of Latin America and the Asia-Pacific. While expansion of access through grid connections has steadily reduced the number of people without electricity access in many areas, in Sub-Saharan Africa, where 600 million are off-grid, population growth is faster than grid expansion [21]. Projections based on assumptions of business-as-usual levels of expansion indicate stable to increasing numbers of people without electricity over the next 20 years [13], but recent growth in the scale and reach of organizations offering decentralized electricity systems indicate potential to out-perform the business as usual approach [21]. Electrification beyond the central grid (both with mini-grids and SHS) is now the focus of a range of public and private sector initiatives and organizations that have recognized this new opportunity for progress.

The current scale of pico-solar and SHS reach is 10's of millions of users served, with annual growth on the order of 30% [21]. The current activity and growth rates are consistent with a trajectory that could result in significant progress towards universal access to basic electricity within 30 years. Some compare the growth of off-grid solar to the spread of mobile phones [22], which are a similar decentralized technology that compete with fixed infrastructure systems (grid power and fixed-line telephones) that have failed to reach the majority of the population in many areas. In Africa, the International Telecommunications Union estimates there are now over 750 million mobile phone subscriptions (77 per 100 persons) [23], which provide highly valued information technology services across the continent [24].

The businesses that are active in producing and distributing off-grid solar products include design, marketing, and global distribution firms, production facilities, transportation, and national and local distribution (much like other electronics goods sectors). At last count, in 2016, there were more than 100 companies actively marketing pico-solar and SHS products, with additional firms starting up and existing firms expanding into new regions.

Given the inherently modular and scalable nature of LED lighting, PV, modern batteries, there are a wide range of possible configurations and scales of systems being deployed and made available in rural and urban markets. These range from very inexpensive (5–10 USD retail price) lamps powered by $\sim$1 W or less of solar PV to more expensive (100–500 USD retail price) solar home systems with 10–20 W or more of PV, powering a set of lamps and other devices. The images in Figs. 3a–3e show a range of these devices in use across the globe, in homes and businesses of people who would otherwise need to use fuel-based lighting or other inferior alternatives.

The off-grid solar sector has grown significantly in the last decade as the cost of production has decreased and new features and capabilities have become possible with advances in technology. Fig. 4 is a photograph taken in Kenya in 2014 during field research that documented retail market availability for off-grid lighting devices [25]. The photo highlights the wide range of solar off-grid lighting devices available and how the reach of mobile phones is an important driver for off-grid solar. These links between information technology and energy access are multi-pronged. Many solar devices (including most of those shown in the photo) can recharge mobile phones, allowing users to avoid recharging services that incur high fees and driving demand for the energy systems. Furthermore, mobile phones and information technology are instrumental for coordinating the supply chains that deliver solar to market. Also, in some cases users have the option of paying for their solar energy system with mobile payments that are linked to their cell phone. In Fig. 4, for example, the man in the foreground is coordinating orders and deliveries of products via his mobile phone and the salespeople in the background are showing their tablet computer that is used to track sales to our research team.

2. Off-grid energy technology deployment

Three key drivers that are enabling off-grid solar to close the electricity access gap are improvements in technology, new business models, and global institutional and regulatory support. Over the last decade, advances in LED lighting technology have played a critical role in bringing down the cost of service, alongside similar improvements in solar, battery, and supporting technology systems. In parallel there has been an expansion in new business models and deployment approaches, with private sector businesses and new organizations launching across a range of regional and economic contexts. Many in the developing world utilize newly ubiquitous information technology for micro-payments and coordination of their supply

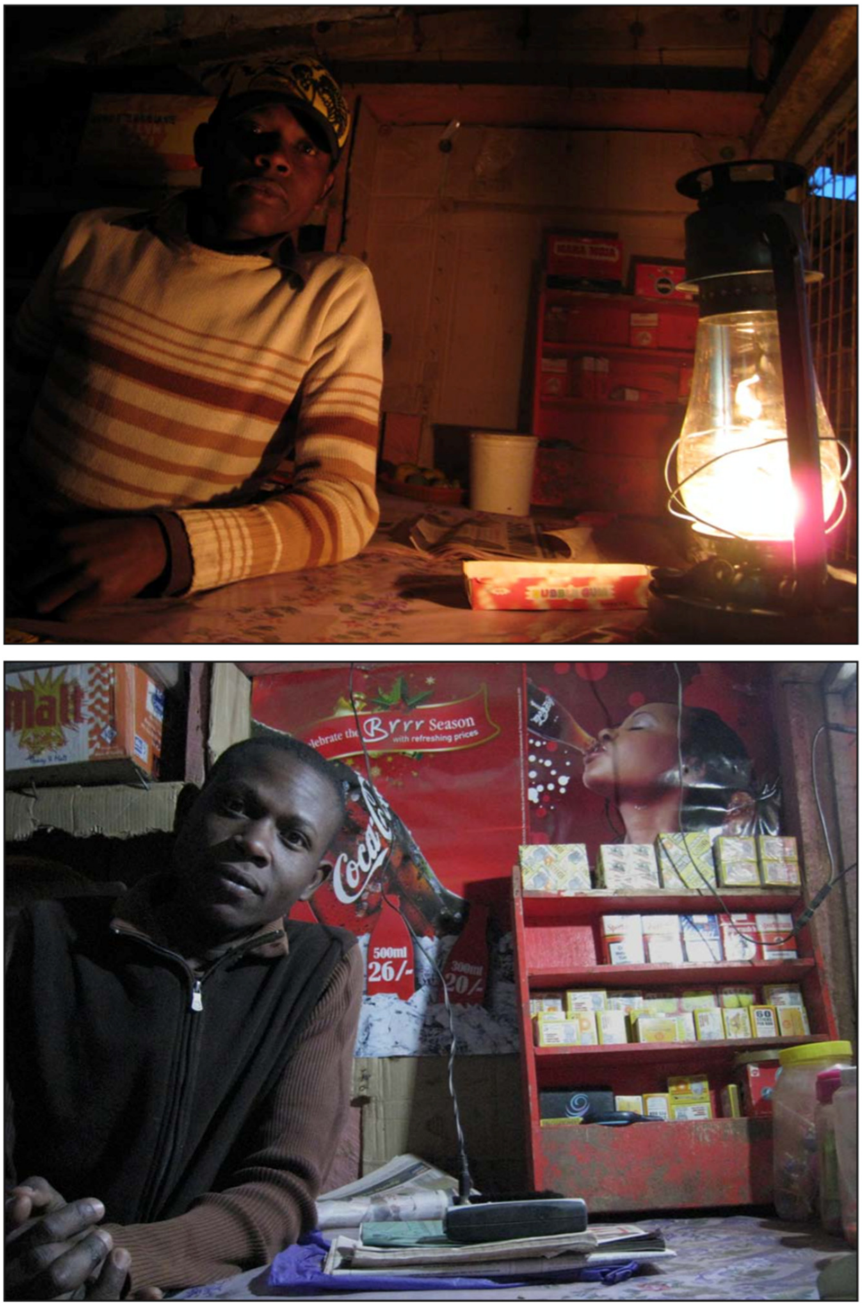

Fig. 3a. In Kenya, before and after photomontage of a shopkeeper who previously used a hurricane lamp, and later adopted solar LED lighting (photos: P. Alstone).

chains [26]. Recognizing the need for global coordination and support of this new framework for providing electricity everywhere, even in the absence of an electricity grid, a range of national and international institutional efforts have emerged as well that focus on policy, market transformation, regulatory frameworks, and other areas.

2.1. The critical role of LED light sources

A fundamental technology enabling decentralized energy is LED lighting, which has dramatically improved in terms of efficacy, quality, and durability over the past decade, with continued progress expected going forward (as described in the special issue, to which this article is a contribution). Compared to incandescent and compact fluorescent bulbs (the incumbent alternative for small-scale off-grid light, ∼10–50 lm/W), LED light at 100+ lm/W requires far less electricity to deliver equivalent light. Alternatively, LEDs can provide superior and expanded service for the same electricity budget (i.e.

Fig. 3b. In Kenya, sorting tomatoes by the light of a portable LED task light in a night market (photo: P. Alstone).

Fig. 3c. In Bangladesh, installing a solar module for a solar home system on a roof (photo: A. Jacobson).

these technology advances can be deployed either as a savings based on efficiency gains or as an increase in the level of service provided; in practice, a combination of the two is the typical result). Modern LED chips also provide better durability and scalability than compact fluorescent bulbs, which were an intermediate off-grid lighting alternative and are still in wide use, although they are rapidly being replaced by LEDs. Nearly all the new lighting products on the market for off-grid applications are now LED-based.

Our research team documented the rise in availability and sales for solar powered LED lighting in three towns, in Kenya, in 2009 [27], 2012 [28], and 2014 [25] as part of a long-run market tracking effort. The results thus far illustrate the trends towards a growing market reach for LED-based lighting in off-grid contexts. In 2009 there were already significant numbers of LED-based lighting devices available, but most had a "flashlight" (or "torch") form factor and were powered by dry cell batteries or grid-based recharging. Among the off-grid lighting products available in the towns we surveyed, we saw a progression from 87% to 93% to 99% share of LED over the three study periods.

Even more striking was the rise of solar PV as an energy source over the same time frame, which went from less than 1% share in product availability in 2009 to 35% in 2014. Linked with this evolution in product design towards solar and LED based products was a shift in form factor, from 90% flashlights in 2009 to an approximately even mix between ambient

Fig. 3d. In Myanmar, a home powered by solar electricity (photo: A. Jacobson).

Fig. 3e. In India, reading by the light of a portable LED light (photo: A. Jacobson).

lights and flashlights by 2014. Overall, we documented the emergence of a new product category alongside conventional flashlights and fuel-based lighting: solar-powered LED lighting.

2.2. Integrated solar-battery-LED energy systems

There are three core technology trends that are mutually supportive in improving the performance and lowering the cost of off-grid solar energy services: the development of efficient end-use appliances and devices that reduce the power and energy budget for a given level of service provision, a decrease in the cost of solar PV modules, and the emergence of advanced battery systems, mostly utilizing lithium battery technology, that have longer lifetimes and improved charge–discharge efficiency. Off-grid solar products involving various combinations of solar PV modules, batteries, and high efficiency appliances (including LEDs and other loads) are now widely available.

Fig. 4. Off-grid solar retail sellers being surveyed by a field research team in Kenya, 2014 (photo: P. Alstone).

LED lighting is emblematic of a broader trend towards the use of "super-efficient" appliances and devices for off-grid or battery-powered operation, which now include refrigerators [29], fans [30], televisions [31], information technology devices [32], and others. It is notable that LED light source efficacy is one of the drivers improving the efficiency of handheld information and communication technology (e.g., mobile phones) and flat screen televisions, which are both highly valued by users for meeting basic energy service needs. The mechanism for this relationship is that LEDs are now available as sources for backlighting of displays, where organic LED and wide-angle chips enable compact design and high efficiency backlighting compared to cold cathode CFLs.

Advances in materials science, physics, and engineering have led to sustained and significant progress on solar photovoltaic materials and advanced batteries over the last decades. From the 1970's to the 2010's, the cost of solar modules has dropped from about \$100/W to under \$1/W. Lithium ion batteries are on a similar trend, with cells that were \$1/Watt-hour in 2010 reaching parity with lead-acid (\$0.35/Watt-hour) circa 2015 and on a pathway to fall below \$0.20/Watt-hour [33].

The required capacity (and associated cost) of solar PV and battery storage is based on the solar resource and the demand from end-use appliances that are powered. By improving the efficiency of the end-uses, it is possible to provide more energy service (e.g., more lumens of light or more hours of television or fan operation) with a given size solar panel and battery. Alternatively, the required scale of the energy generation and storage can be reduced to power a given set of loads. Thus, technology advances in PV and storage, combined with vastly improved efficiency in lighting and other devices, has led to a steep reduction in the cost of providing basic electricity services with pico-solar and SHS.

Table 1 describes a range of household energy services that are relevant and achievable with a range of off-grid solar options (and the incumbent fuel-based lighting for reference). There is a wide continuum of options for technology, ranging from very small-scale "pico-solar" lanterns with a single light point to systems that provide fixed-point lighting in multiple rooms and can power other small appliances.

Along with co-authors, we developed and reported on a techno-economic model that estimates the cost of service for pico-solar and SHS in Phadke et al. (2015) [34]. The model estimates the expected retail cost of integrated solar energy packages, combining estimates of the component-level costs and performance of solar, battery, lighting, balance of systems, and other appliances. The scope for the article included two types of solar energy system: First, a pico-solar lighting system that can provide 125 lm of lighting service for a 4-hour period (for a total lighting service of 500 lumen-hours per day) with typical solar energy resource availability, denoted as "pico-500" in the figure. The second type is a solar home system that can deliver 600 lm of light over a four-hour period (2400 lumen-hours) and power a 19-inch color television for 4 hours of viewing, a table radio for 6 hours, and a basic mobile phone recharge each day. The estimates were made for both "conventional" and "super-efficient" sets of lighting and appliances. The conventional appliance set includes compact fluorescent lighting (CFL) in the pico-solar lantern and the SHS and a cathode-ray tube color television display for the SHS. The super-efficient appliances include LED lighting and (in the case of the SHS) LED back-lit television. Fig. 5, below,

Table 1
A range of household-scale, standalone off-grid energy technology options for lighting and other services, with approximate metrics for service quantity and cost indicated.

Off-grid energy technology	Description	Quantity of lighting service (lumen-hours/day)	Other energy services	Annual cost range ($USD/device/year[a])
Fuel-based lighting	Lamp with fuel reservoir, wick, or mantle, and sometimes a transparent wind screen. Widely variable fuel consumption rate	10–100+	None	$20–100
Pico-solar lantern	Single-source lamp powered by 1–2-W solar module with integrated battery	50–500	None	$2–10
Pico-solar multi-function product	Single or multi-source lighting, powered by 2–15 W solar module	200–2000	Phone charging, radio, USB appliances	$10–30+
Solar home system	10–100s of Watt solar module plus battery storage, control, and appliances	400–4000+	Phone charging, radio, USB appliances, TV, fan, fridge, etc.	$40–200+

[a] Annual costs for fuel-based lighting are for the fuel, only (the dominant cost). Annual costs for solar-based electricity systems are based on an estimate of the technology investment cost divided by an assumed lifetime of 2 years. A 2-year life is a conservative value, especially for solar home systems.

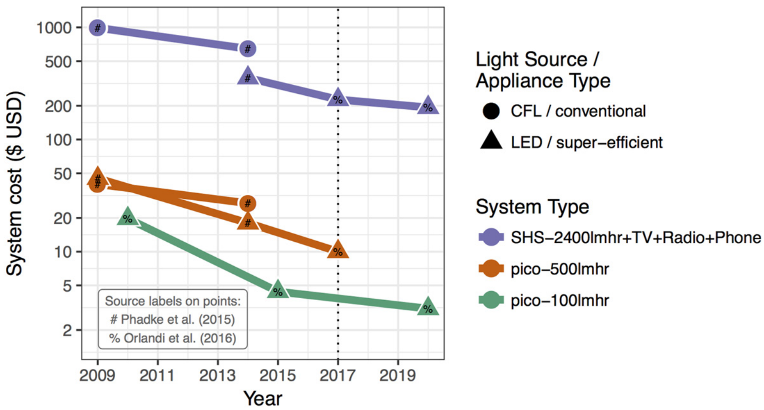

Fig. 5. A synthesis of estimates for the retail cost of various off-grid solar energy systems. The original estimates were presented in two separate papers, one published in 2015 [34] and another in 2016 [21], with the source indicated by symbols that annotate each data point. The shape and color of points is related to the class of end-use devices (conventional vs. super-efficient) and one of three types of system. The service level for each system type is held constant: a 100 lumen-hour pico-solar lamp, 500 lumen-hour pico-solar lamp, and a 2400 lumen-hour (plus other appliances) solar home system (SHS). Note the log scale on the cost axis.

combines those estimates with additional data points estimated for a report by Orlandi et al. (2016) [21] that extended the analysis by Phadke et al. to include updated estimates for 2017 and forecasts to 2020. The report by Orlandi et al. also included an estimated trajectory for very small-scale pico-solar lighting that provides 25–50 lm of service for 4 hours a night (approximately 100 lumen-hours, which is similar to the quantity of light from incumbent fuel-based lighting), denoted as “pico-100” in the figure.

The trajectory for off-grid solar energy systems illustrated in Fig. 5 shows the relative influence of demand-side efficiency vs. solar and battery advances and how the type of system changes the way these contributions manifest. The overall trend across cases is towards significantly lower costs for the same level of service. The pico-solar lamp options included in the results are ‘lighting only’ systems, which show a roughly 80% reduction in the cost of light from 2009 to 2017: from $40–45 to $10 for the pico-500 lamp and from $20 to $4 for the pico-100. The contributions of advances in solar and batteries vs. contributions from more efficient lighting (switching from CFL to LED) are approximately equal in scale [34]. For example, the change in cost from 2009–2014 for conventional pico-500 solar lamps was 33% (representing reduced costs based on solar and battery advances, from $40 to $27). Furthermore, in 2014 the cost change from switching to super-efficient design for the lamp is estimated to reduce the costs by an additional 33% (representing an overall system cost reduction for switching from CFL to LED from $27 to $18). Since then, continued advances in solar and batteries, along with higher efficacy, lower cost LED lighting, have reduced the expected cost further, to $10 for the pico-500 by 2017. Similar trends are estimated for the pico-100, with reductions from $20 to $4 overall from 2009 to 2017 (and a forecast of $3 by 2020).

SHS like the one described above include not just lighting but also other key end-uses: television, mobile phone charging, and radios. With a standard suite of services (described above), the estimated cost was about $990 with conventional appliances in 2009. By 2014, similar to the trends for pico-solar lamps, advances in the cost of solar and battery technology had reduced the expected cost of the SHS by 35%, to $640. With super-efficient lighting and other appliances, a significant

45% further reduction in cost was possible in 2014 to $350. The decomposition of costs in 2014 includes $41 for a 27-W solar PV module, $55 for a 340 Watt-hour lead acid battery, $63 for balance of systems electrical components, $15 for LED lighting, and $179 for other appliances. Details on these costs, including those for other systems and time frames, are documented in Phadke et al. (2015) [34].

Observations of the off-grid energy market confirm what one might expect, which is that after 2014–2015 nearly all of the devices and packages being produced utilize super-efficient lighting and other appliances to reduce the cost of service [25]. Before these advances, most SHS and pico-solar lamps were well outside the affordability range of most of the people who live off-grid with typical per capita earnings of $1–5/day. Continued cost reductions are one of the keys for unlocking the potential of off-grid solar because affordability is critically important for cash-poor users of the technology, most of whom do not have access to formal banking or financial services. Thus, the continued improvement in the cost and efficacy of LED lighting, along with improvements in other components, will continue to be important for advancing systems of access.

2.3. New business models for off-grid electricity

The technology advances that enable off-grid solar energy systems to be affordable have been developed in combination with a range of new approaches to private and public-sector deployment. Unlike grid extension, which is primarily a public sector effort, most off-grid energy systems are deployed through private sector channels, with varied levels of public support [21,35]. There is no “natural monopoly” for off-grid power systems that is analogous to the kinds of concessions and utility models that are used for the grid, which means that a variety of business models and approaches can be used within a region or town, and in the last several years the market for off-grid energy systems has grown to include over 100 firms with various approaches. With growth in the number and reach of organizations there is now an industry association for off-grid lighting as well (the Global Off-grid Lighting Association), which holds conferences, advocates for policy changes, and helps coordinate the emerging sector.

The business networks that deliver energy access service include a variety of actors, from multinational corporations to sole proprietorships and informal resellers. These networks are vast in scale, typically spanning manufacturing facilities in industrial centers of Asia, wholesale trading centers in Asia, the Middle East, and Africa, and distribution reaching to final users in urban and rural settings, some of whom reside 100’s of kilometers from the nearest highway. Some actors choose to “vertically integrate” across a range of these supply chains, with design and manufacturing coordination, dedicated distribution systems, and using a consistent retail brand. What is more common, however, is to have mixed ownership and control over portions of the supply chain, with intermediate suppliers and distributors working together. Many firms specialize in a particular role, such as retail sales in a particular region or designing and manufacturing energy systems for others to sell [21,35].

One of the most important and high-profile retail approaches for off-grid solar businesses in the last five years has been “pay-as-you-go” (PAYG), where recently expanded information technology connectivity is leveraged to offer micro-loans or fee-based off-grid energy service. While a wide variety of PAYG approaches are in use [26], a typical arrangement is that users of the devices pay a small upfront down payment to obtain a system (e.g., $30), then make small daily or weekly payments (e.g., $1/day) for a set amount of time. The payments can be made over mobile money platforms that are rapidly increasing their reach in off-grid regions (serving a similarly disruptive role in the banking sector as off-grid solar does in the electricity sector). If a customer misses a payment, the PAYG solar energy system enters a locked mode until payments are resumed. Thus, with targeted integration of information technology it is possible to offer very small solar energy systems on a loan or fee-based service basis, where before the transaction and loan enforcement costs of these approaches would have been cost prohibitive [26]. These business models mimic the fee structure of utilities, offering users the ability to pay for systems and service over time rather than requiring lump, up-front payments. The market for PAYG solar has rapidly grown [21], with increased adoption compared to cash sales [26], because fee-based or loan repayments match better with many users’ ability to pay, and leads to increased trust in the technology, a key factor for widespread adoption.

2.4. Institutional support for off-grid lighting

Institutions and public sector organizations have emerged in parallel to the advances in technology and business models that could accelerate the pace of electricity access. These efforts are often motivated by the human development imperative of energy access: improvements in health, safety, equality of service, and affordability. Over the decades, a range of goals and awareness-raising activities have been undertaken, and recently at the global level was expressed in United Nations Sustainable Development Goal Seven, which sets a target: “By 2030, (to) ensure universal access to affordable, reliable, and modern energy services” [36].

Another *United Nations* initiative, “Sustainable Energy for All” (SE4ALL), raises the profile of energy access in global development practitioner networks and is helping to more clearly define what “access” means through the “multi-tier framework” for electricity access [4]. Importantly, the framework moves beyond a concept of access that treats grid-connected households as electrified and everyone else as being off-grid by setting five different tiers of electricity access that are based on the level of energy service that is available. This more nuanced approach allows systems ranging from low-power off-grid solar products to high-power grids to be counted when considering the level of electricity access for a given household.

Pico-solar and SHS are key technologies for providing Tier 1 and 2 access (out of five Tiers), powering lighting and information technology devices (Tier 1) plus small appliances like televisions and fans (Tier 2). With a harmonized framework for measuring and reporting electricity access, the vitally important but incomplete advances in access that derive from these basic services can be tracked and planned for by national and global initiatives to reduce energy poverty.

A range of global programs and initiatives support expanding energy access, often with "on-the-ground" support that includes capacity building, access to financing for supply-chain actors, direct subsidies, and other mechanisms. Some of the prominent examples include the "Deutsche Gesellschaft für Internationale Zusammenarbeit" (GIZ), ("EnDev" program and other efforts), the United States Government (Department of Energy and Power Africa), the World Bank and International Finance Corporation (Lighting Africa, Lighting Global, etc.), the United Kingdom Department for International Development (DFID), SNV Netherlands Development Organisation, the United Nations Capital Development Fund, and others.

2.5. The quality assurance example

Quality assurance for off-grid solar and LED lighting is an example of the kind of specialized global support that is vital for growing the reach of new technology systems. Like all electronic goods, the durability of components, appropriateness of design, and quality of assembly are all critical elements for long-lasting solar LED lighting that is ultimately affordable for customers and provides valued service. During the same period that good quality pico-solar and SHS emerged, inexpensive and essentially disposable LED lights became available. These products are typically powered by single-use dry cell batteries or poorly constructed rechargeable batteries [28]. These very low-quality and short-lifespan alternatives represent an improvement compared to fuel-based lighting in terms of health and safety, but not significantly in terms of the value of service, since the effective cost of electricity when purchased in the form of dry cell batteries or fee-based recharging services is up to $100's per kWh (10–1000 times the cost of better alternatives like solar or grid service). Quality matters particularly in the marketplace for off-grid solar because users who have bad experiences with early or poor-quality versions of new technology are often hesitant to invest in further systems. This market spoiling effect has been observed in early off-grid solar markets [37], and it was one of the drivers for developing quality assurance protocols that help support good quality devices in the market [38].

The Lighting Global Quality Assurance program is a joint initiative of the International Finance Corporation (IFC) and World Bank, and it was developed to address quality assurance and consumer protection in the off-grid solar sector. Both authors of this article played leading roles in the development of the program, in collaboration with team members. The program is an example of the type of global policy and public-sector support efforts that are key to grow a transnational energy access technology system like off-grid solar. Unlike grid-based power, where any given firm or agency typically operates a network within the boundaries of a single country, there is a strong need for off-grid solar to have globally harmonized approaches that enable centralized and low-cost manufacturing and design that serves multiple regions. The QA program includes product testing and verification that helps key actors in the market (e.g., investors, commercial banks, governments, and wholesale buyers, among others) determine which products are good quality. Along with the scale of the off-grid lighting market, the QA program has grown from a single laboratory, testing dozens of solar lighting products from the market at a time, to a network of 8 labs, a supported International Electrotechnical Commission test standard (IEC 62257-9-5), and a quality verification program that currently lists over 100 products as having met the Lighting Global Quality Standards.

The QA program's original quality standards, which were launched in 2009 through the Lighting Africa program, emphasized truth-in-advertising and product durability. The focus on truth-in-advertising rather than requiring that products meet minimum performance thresholds is intended to allow manufacturers to produce a wide range of innovative designs while still holding them accountable to deliver products that perform as claimed. Consumer research indicated that end-users were also strongly interested in durable products.

When the program began, lumen degradation of LEDs and short battery cycle life were identified as weak links for product durability. To address these, Lighting Global QA adopted low cost test methods to evaluate these parameters and took measures to support development of more durable products by manufacturers. Early market monitoring indicated that many off-grid LED lighting products had very short light source lifetimes (e.g., degradation to L70 in 100–200 hours or less) [38,39]. To address this, the QA program developed a set of technical briefing notes intended to inform manufacturers about lumen maintenance and measures that could be taken to ensure adequate durability. Within a few years, most manufacturers had identified solutions to the issue, and LED degradation is now relatively rare in the sector among reputable manufacturers. Similarly, sealed lead-acid batteries, which were widely used in small off-grid solar products when the QA program was launched, were identified as key source of product failure and consumer dissatisfaction. Fortunately, lithium-based batteries were emerging as a cost effective and more durable solution for electricity storage. Using low-cost test methods developed by colleagues from the Fraunhofer Institute for Solar Energy Systems, the QA team implemented quality standards for battery durability that contributed to a shift from lead-acid to lithium-ion batteries (including especially cells based on lithium iron phosphate chemistry) for small off-grid solar products. Today, LED lumen maintenance and battery durability are rarely the main points of failure for these devices. Instead, more mundane durability problems related to switches, connectors, and bad solder joints are more likely to contribute to early product failure. The examples serve to illustrate how targeted institutional support can support private sector deployment of a critical human development technology like basic lighting devices.

3. Conclusion

Advances in LED lighting and other super-efficient appliances have played a fundamental role, along with solar PV and battery systems, in enabling new possibilities to bring electric light to households and regions that have historically been deprived of modern energy service. For decentralized electricity systems to reach significant fractions of people who live without access, continued advances are needed in areas related to off-grid solar technology, business models for delivering systems and services to end-users, and institutions that enable market development and protect consumer interests.

The basic technology advances enabling inexpensive and reliable off-grid solar have mainly been based on spillover from technology originally developed for “grid-based” applications. This dynamic should continue if there is continued progress towards lower cost and higher performance components like LED lighting, PV modules, batteries, communications modules, connectivity, and controllers. As off-grid markets grow, there may be focused technology development opportunities as well, with needs for specialized lighting systems or modules that are tailored for use.

As the trends in the cost (lower per unit), performance (higher efficiency), and durability (longer operational life) for PV, batteries, and LED lighting continue, there will be continually changing possibilities and permutations for integrated energy systems. The progress over the last 10 years has gone from very basic, lighting-only devices to multi-function and diverse household energy systems. The coming decade promises to deliver additional advances and innovation as well.

In the context of fast-changing technology and deployment strategies, it is important that the supporting regulatory, financing, and institutional frameworks be nimble and avoid technology lock-in that could occur due to rigid policies or inflexible regulations. This calls for continued coordination and exchange through organizations that span global, regional, national, and local focus.

The cost of providing light and other services is now within reach of many, which could lead to significant gains in human health and safety, more equal access to basic energy service, and a reduced impact on the climate [3]. With continued effort to drive down the cost of basic technology components (like LED lighting) further, along with public and private sector support for decentralized off-grid energy systems, it could be possible to eliminate fuel-based lighting and provide basic electricity service to the globe without waiting for much slower-developing grid extension and connection efforts. Providing these services is a vital human need, and it deserves the focus of scientific, public policy, and business interests alike.

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References

[1] IEA, World Energy Outlook 2016, Organization for Economic Co-operation and Development & International Energy Agency, 2016.
[2] AGECC, Energy for a Sustainable Future: Report and Recommendations, UN Secretary-General’s Advisory Group on Energy and Climate Change, 2010.
[3] P. Alstone, D. Gershenson, D.M. Kammen, Decentralized energy systems for clean electricity access, Nat. Clim. Change 5 (2015) 305–314.
[4] SE4ALL, Global Tracking Framework, Sustainable Energy for All, 2013.
[5] E. Mills, Health Impacts of Fuel-Based Lighting, Lumina Project, 2012.
[6] E. Mills, Light for Life: Identifying and Reducing the Health and Safety Impacts of Fuel-Based Lighting, United Nations Environment Program, 2015.
[7] N.L. Lam, K.R. Smith, A. Gauthier, M.N. Bates, Kerosene: a review of household uses and their hazards in low- and middle-income countries, J. Toxicol. Environ. Health Part B 15 (2012) 396–432.
[8] A.J. Cohen, et al., Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015, Lancet 389 (2017) 1907–1918.
[9] E. Mills, The specter of fuel-based lighting, Science 308 (2005) 1263–1264.
[10] N.L. Lam, et al., Household light makes global heat: high black carbon emissions from kerosene wick lamps, Environ. Sci. Technol. 46 (2012) 13531–13538.
[11] T.C. Bond, et al., Bounding the role of black carbon in the climate system: a scientific assessment, J. Geophys. Res., Atmos. 118 (2013) 5380–5552.
[12] A. Jacobson, N.L. Lam, T.C. Bond, Black Carbon and Kerosene Lighting: An Opportunity for Rapid Action on Climate Change and Clean Energy for Development, The Brookings Institution, 2014. Available at: http://www.brookings.edu/research/papers/2013/04/climate-change-clean-energy-development-hultman. (Accessed 27 September 2014).
[13] J. Koomey, et al., Defining a standard metric for electricity savings, Environ. Res. Lett. 5 (2010) 14017.
[14] R. Bacon, S. Bhattacharya, M. Kojima, Expenditure of low-income households on energy, Extr. Ind. Dev. Ser. 16 (2010).
[15] E. Mills, Technical and Economic Performance Analysis of Kerosene Lamps and Alternative Approaches to Illumination in Developing Countries, Lawrence Berkeley National Laboratory, 2003.
[16] P. Alstone, A. Jacobson, E. Mills, Illumination Sufficiency Survey Techniques: In-situ Measurements of Lighting System Performance and a User Preference Survey for Illuminance in an Off-Grid, African Setting, Lumina Project, Lawrence Berkeley National Laboratory, 2010.
[17] P. Johnstone, A. Jacobson, E. Mills, M. Mumbi, Self-Reported Impacts of LED Lighting Technology Compared to Fuel-Based Lighting on Night Market Business Prosperity in Kenya, Lumina Project, Lawrence Berkeley National Laboratory, 2009.
[18] E. Mills, A. Jacobson, The Off-Grid Lighting Market in Western Kenya: LED Alternatives and Consumer Preferences in a Millennium Development Village, Lumina Project, 2007.
[19] P. Alstone, P. Lai, E. Mills, A. Jacobson, High life cycle efficacy explains fast energy payback for improved off-grid lighting systems, J. Ind. Ecol. 18 (2014) 722–733.
[20] K. Radecsky, P. Johnstone, A. Jacobson, E. Mills, Solid-State Lighting on a Shoestring Budget: The Economics of Off-Grid Lighting for Small Businesses in Kenya, Lumina Project, 2008.
[21] I. Orlandi, N. Tyabji, J. Chase, Off-Grid Solar Market Trends Report, Bloomberg New Energy Finance/Lighting Global, 2016.
[22] B. McKibben, The Race to Solar-Power Africa, The New Yorker, 2017.

[23] International Telecommunications Union, ICT Facts and Figures 2017, 2017.
[24] J.C. Aker, I.M. Mbiti, Mobile phones and economic development in Africa, J. Econ. Perspect. 24 (2010) 207–232.
[25] N. Turman-Bryant, P. Alstone, D. Gershenson, D. Kammen, A. Jacobson, The Rise of Solar, Lighting Global, 2015.
[26] P. Alstone, D. Gershenson, N. Turman-Bryant, D. Kammen, A. Jacobson, Off-Grid Power Systems and Connectivity, Lighting Global, 2015.
[27] P. Johnstone, J. Tracy, A. Jacobson, Market Presence of Off-Grid Lighting Products in the Kenyan Towns of Kericho, Brooke, and Talek, Lighting Africa, 2009.
[28] M. Harper, P. Alstone, A. Jacobson, A growing and evolving market for off-grid lighting, Light. Afr. 1 (2013), https://www.lightingglobal.org/news/type/market-analysis-reports/.
[29] A. Gopal, G. Leventis, A. Phadke, S. de la Rue du Can, Trading appliance efficiency for electricity subsidies: the potential in emerging economies, in: Proceedings of ECEEE 2013 Summer Study, 2013.
[30] N. Shah, N. Sathaye, A. Phadke, V. Letschert, Costs and benefits of energy efficiency improvement in ceiling fans, in: Proceedings of 2013 International Conference for Energy Efficiency in Domestic Appliances and Lighting, 2013.
[31] W.Y. Park, A. Phadke, N. Shah, V. Letschert, TV Energy Consumption Trends and Energy-Efficiency Improvement Options, Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA, USA, 2011.
[32] J.G. Koomey, S. Berard, M. Sanchez, H. Wong, Implications of historical trends in the electrical efficiency of computing, IEEE Ann. Hist. Comput. 33 (2011) 46–54.
[33] M. Liebreich, Bloomberg New Energy Finance Summit Keynote, 2017.
[34] A.A. Phadke, et al., Powering a Home with Just 25 Watts of Solar PV: Super-Efficient Appliances Can Enable Expanded Off-Grid Energy Service Using Small Solar Power Systems, Lawrence Berkeley National Laboratory, 2015.
[35] N. Turman-Bryant, P. Alstone, D. Gershenson, D. Kammen, A. Jacobson, Quality Communication, Lighting Global, 2015.
[36] United Nations, Transforming Our World: The 2030 Agenda for Sustainable Development, 2015.
[37] E. Mills, J.L. Tracy, P. Alstone, A. Jacobson, P. Avato, Low-cost LED flashlights and market spoiling in Kenya's off-grid lighting market, Energy Effic. (2014) 1–15, https://doi.org/10.1007/s12053-014-9294-2.
[38] E. Mills, A. Jacobson, The need for independent quality and performance testing for emerging off-grid white-led illumination systems for developing countries, Light Eng. 16 (2007) 5–24.
[39] T. Mink, P. Alstone, J. Tracy, A. Jacobson, LED Flashlights in the Kenyan Market: Quality Problems Confirmed by Laboratory Testing, Lighting Africa, 2010.