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Can developing countries leapfrog the centralized electrification paradigm?

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ABSTRACT

Due to the rapidly decreasing costs of small renewable electricity generation systems, centralized power systems are no longer a necessary condition of universal access to modern energy services. Developing countries, where centralized electricity infrastructures are less developed, may be able to adopt these new technologies more quickly. We first review the costs of grid extension and distributed solar home systems (SHSs) as reported by a number of different studies. We then present a general analytic framework for analyzing the choice between extending the grid and implementing distributed solar home systems. Drawing upon reported grid expansion cost data for three specific regions, we demonstrate this framework by determining the electricity consumption levels at which the costs of provision through centralized and decentralized approaches are equivalent in these regions. We then calculate SHS capital costs that are necessary for these technologies provide each of five tiers of energy access, as defined by the United Nations Sustainable Energy for All initiative. Our results suggest that solar home systems can play an important role in achieving universal access to basic energy services. The extent of this role depends on three primary factors: SHS costs, grid expansion costs, and centralized generation costs. Given current technology costs, centralized systems will still be required to enable higher levels of consumption; however, cost reduction trends have the potential to disrupt this paradigm. By looking ahead rather than replicating older infrastructure styles, developing countries can leapfrog to a more distributed electricity service model.

Introduction

Direct electricity access eludes almost 20% of the world's population, the large majority of whom live in rural regions of developing countries, and providing universal electricity access has become a fundamental humanitarian goal of our generation (IEA, 2014a). This imperative has been formalized through the Sustainable Energy for All (SE4All) initiative that was launched by the United Nations in 2012 with the objective of achieving universal access to modern energy services by 2030. In 2013, an initial Global Tracking Framework was published, which formalized this goal and provided a consensus methodology for measuring and tracking progress toward its achievement. [1] It was estimated at the time that investments of \$60–\$160 billion dollars per year above current levels may be required in order to meet these goals (Angelou et al., 2013), and it is vital that any such investments are channeled to support technological and institutional solutions that are as forward-looking and cost-effective as possible. A second edition of the Global Tracking Framework was published in 2015 and provides an update on progress toward meeting the objectives that were established in the first edition (IEA and World Bank, 2015a). The findings of this report unfortunately indicate that the rate of progress over the two a year tracking between 2010 and 2012 falls “substantially short” of what would be required to obtain the SE4All objectives by 2030. It is therefore more important than ever that cost-effective pathways for increasing global energy access in a sustainable manner are identified and pursued.

Traditionally, nations seeking improved electricity access pursue centralized electrification. This strategy requires large upfront infrastructure investments in order to take advantage of economies of scale at large coal, natural gas, nuclear or hydroelectric generation facilities and has seen tremendous success over the past century throughout the developed and developing world. However, due to cost reductions of new distributed technologies such as rooftop solar panels, small wind turbines, and energy storage, the economics that motivated a centralized approach are changing. This is particularly the case in regions where electricity consumption is low and the costs of grid expansion are high (Levin and Thomas, 2012). In the developed world, the rapid introduction of utility-scale renewable generation is driving down wholesale electricity prices and reducing revenues for large nuclear, coal, and natural gas generators, while at the same time increasing the

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[1] The Global Tracking Framework also established two goals in addition to achieving universal access to modern energy services. These are doubling the global rate of improvement in energy efficiency and doubling the share of renewable energy in the global energy mix. While all three are worthy pursuits, the first is of primary relevance to this work.

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cost of ensuring system reliability (Ela et al., 2014). Consumers are also increasingly adopting decentralized generation technologies and reducing their reliance on the traditional centralized grid model. This combination of factors may force a fundamental shift in way the utilities and governments approach the long-term planning and development of power systems infrastructure.

In the developing world, centralized power systems have still yet to reach a significant portion of the population. Furthermore, even those who do have access to electricity receive no tangible benefit if such access is not affordable, reliable, or functioning (Mainali et al., 2014). Throughout the developing world, many poor families reside in "electrified" regions but still lack electricity for economic reasons. Electric grids are also often extremely unreliable in the developing world due to generation capacity shortages, poor transmission and distribution infrastructure, and a host of other operational issues. In many developing countries, outages can be an almost daily occurrence and many homes and businesses maintain backup diesel generators even when they have grid access (The World Bank, 2012). While many of these problems could be addressed through additional generation and infrastructure investments, such investments have not materialized for a variety of reasons. Therefore, many consumers continue to be reliant on costly personal generators to guarantee reliable access to electricity. Because of these complexities, the concept of "energy access" does not have a universally agreed upon definition and the binary metrics that are commonly used to evaluate energy access programs can often be misleading (Angelou et al., 2013). For example, one metric used in India considers an entire village to be electrified if only 10% of the homes have access to electricity but does not consider isolated homes powered by individual solar home systems (SHS) to be electrified (Palit and Chaurey, 2011). Similarly, many people who do not have direct access to electricity – electricity in the home – still have reasonable access to cell phones, battery-powered lights, and other electronic devices that may be charged at distributed charging stations. Many of these challenges are exacerbated by the fact that data on energy access and usage are scarce in many developing countries. This makes it harder to for policy makers to identify high-priority areas for public intervention and also to evaluate the effectiveness of programs that are designed to increase energy access. With this understanding in mind, the SE4All initiative has also proposed a multi-dimensional methodology to measure energy access across five consumption tiers and eight energy attributes (Angelou et al., 2013; Angelou and Bhatia, 2014). This methodology extends well beyond the traditional metrics annual energy consumption and a binary energy access indicator, incorporating a range of other factors into a multi-tier classification of energy access. The considered attributes initially included peak availability, duration of availability, evening supply, affordability, legality, and quality of access. These have been further expanded in the second edition of the Global Tracking Framework to also include reliability and health and safety (IEA and World Bank, 2015a).

Moving beyond the traditional definition of energy access toward one that accounts for reliability and affordability, it becomes clear that centralized and distributed electrification strategies are not always perfect substitutes for one another (Murphy et al., 2014). As a result, distributed approaches may be preferred in some regions even when centralized strategies appear to be the lowest cost option (Levin and Thomas, 2014a). Centralized approaches may still dominate in some regions; however, at a national scale, it will likely be the case that a socially and economically optimal power system will contain both centralized and distributed components. Therefore, developing countries have a unique opportunity to leapfrog the traditional centralized model and transition directly to a more distributed approach to electrification, particularly in regions that are not currently electrified. A comparison can be drawn to the rapid adoption of cellular telephone technologies throughout much of the developing world over the past decade, which bypassed the traditional landline model.

Policy makers are increasingly becoming aware of the potential for distributed electrification strategies to provide services in regions that have traditionally been too costly to serve with grid expansion (Narula et al., 2012). However, distributed rural electrification programs are generally poorly integrated with their grid-based counterparts (Urpelainen, 2014), and often are not afforded the same level of large-scale institutional support. In South Asia for example, it has been observed that most distributed rural electrification programs are grant and donor driven, but the few that have received significant institutional support at the state or national level tend to be the most successful (Palit and Chaurey, 2011). Grid-based electrification programs that are developed through the centralized utility model are also easier to subsidize than the more disaggregated, community-scale approaches that are often pursued by distributed programs. This effect has been quantified in Laos where subsidies for grid-based electrification usually exceed 70% of total costs, while those for distributed electrification average only 26% of total costs (Martin and Susanto, 2014). In rural regions of Thailand, homes receive 50 kWh of free electricity from the grid each month at a cost to the government of over US$30 million; this level of government sponsored financial support is simply not available for distributed electrification programs (Martin and Susanto, 2014). In Ghana, a similar "lifeline" tariff is offered, which charges all customers who consume less than 50 kWh in a month a flat fee of approximately $1.25 (World Bank, 2010), well below cost recovery in rural regions.

Over the last decade, Brazil has embarked upon an aggressive and fairly successful universal electrification campaign. However, the current focus on grid-expansion has reached its economic limits due to the extremely high costs of grid-expansion in the rural Amazon region. Off-grid approaches are likely necessary to reach many of the 500,000 households that still lack electricity access. Electrified homes in these regions are currently supplied by isolated diesel generators and mini-grids that exist outside of the institutional electrification framework in Brazil (van Els et al., 2012). As a result, it has been difficult for the Brazilian government to provide direct, or indirect, subsidies for these distributed approaches to rural electrification. In an effort to address these issues and achieve truly universal electrification, the government has recently expanded their program to provide support for smaller third-party organizations that are able to serve these rural populations with distributed technologies (Gómez and Silveira, 2015). Such an institutionally centralized approach to implementing distributed electrification technologies may enable the Brazilian or other governments to more effectively cross-subsidize energy access in regions that are costly to serve through grid expansion. For additional discussion on the Brazilian electrification program, see (Zerriffi, 2008; Gomez and Silveira, 2010) and for the cases of several national rural electrification programs, including Brazil, see (Zerriffi, 2011).

By offering or mandating low tariffs for grid electricity in rural regions, governments are either explicitly or implicitly providing subsidies for centralized, grid-based approaches to electrification. In situations where electricity consumption levels are low or grid connection costs are high, the grid subsidy may exceed the entire cost of electricity provision through a distributed technology such as a solar home system (Levin and Thomas, 2014b). We therefore present an analysis of the unsubsidized costs of electricity provision through both a centralized grid and through distributed SHS technologies. We first review SHS costs that have been reported in a number of different countries in recent years as well as the costs associated with grid expansion, showing that both of these costs can vary significantly in different geographical regions. We then develop a general analytic framework for analyzing the choice between grid expansion and implementing distributed electrification technologies.

A number of studies have examined the choice between grid expansion and distributed electrification technologies by conducting detailed analyses of specific regions and also more generally (Parshall et al., 2009; Deichmann et al., 2011; Szabó et al., 2011; Levin and Thomas, 2012, 2013; Sanoh et al., 2012; Kemausuor et al., 2014). Rather than performing a detailed original case study analysis of electric infrastructure development in a particular location, we instead develop a broader analytic framework that can be used to identify potential economic tipping points between these two centralized and decentralized electrification paradigms. We then draw upon grid expansion costs that have been previously calculated for three specific regions to demonstrate this framework. For simplicity and to demonstrate proof of concept, we consider just one distributed electrification technology, a SHS. However, this framework could easily also be applied to analyze other distributed technologies or a hybrid approach utilizing village-scale solar arrays, wind turbines, or small hydroelectric generators with power distribution through localized micro-grids.

Materials and methods

All cost data reported in this paper have been converted into 2015 U.S. dollars based on the United States Consumer Price Index (CPI). Cost data that were originally reported in a local currency were converted to U.S. dollars based on the conversion rate at the time those costs were reported.[2] These were then adjusted into cost year 2015 dollars based on the CPI. As many currencies fluctuate significantly versus the U.S. dollar, in some cases, this can lead to different values than would be obtained by converting directly from the local currency at present conversion rates.

Solar cost review

Solar power generation has seen rapid growth throughout the world over the past decade, as the cost of manufacturing continues to fall as institutional support grows. In the industrialized world, Germany provides the earliest example of this growth and solar photovoltaic (PV) technologies provided 6.9% of Germany's net electricity consumption in 2014 (Wirth, 2015). The United States still lags behind Germany in terms of solar generation – solar technologies provided less than 1% of U.S. generation in 2014 – but has seen significant growth in recent years (EIA, 2015a). Approximately 18,000 MW of new grid-connected solar capacity was added in the United States between 2008 and 2014 (MITEI, 2015), and total installed capacity is projected to double from 20,000 to 40,000 MW over the next 2 years (SEIA, 2014). Bangladesh has led the charge toward solar development in the developing world, thanks in large part to Grameen Shakti and its efforts to reduce institutional barriers by providing microfinancing for individual SHSs. Through continued support from the Rural Electrification and Renewable Energy Development Project, it is expected that 2.5 million people in rural Bangladesh will be reached by a SHS by 2018 (World Bank, 2014). Similar growth is now being witnessed in India and interest has also been growing throughout Africa and the rest of the world.

Module and BOS

The installed cost of distributed solar generation systems can be broken into two primary components, the cost of the PV module itself, and the so-called balance-of-system (BOS) costs, which include the system inverter, controller, other hardware, installation, permitting, regulatory compliance, and a range of potential other soft costs. In the developed world, distributed solar PV systems are typically installed in buildings that already have a connection to the grid, and the additional cost of integrating the solar generation is included in the BOS costs. In this arrangement, the energy generated by the PV system is used to offset consumption from the grid, usually during peak hours when the sun is shining, and the grid connection is available to provide power during periods when solar power is not available. This is often not the case in the developing world, where solar PV systems are increasingly being considered as a standalone alternative to grid expansion in regions that do not currently have access to the grid. Therefore, a complementary storage system is also required to ensure that power is available throughout the day and night.

Due to technological advancements, increased demand, and growing economies of scale, the cost of solar modules has decreased dramatically in recent years. In the United States, the cost of a solar module was approximately $4.00 per peak watt (Wp) in 2008 and by 2014 that cost had decreased by almost 85% to $0.65/Wp (MITEI, 2015). As solar PV modules have increasingly become global commodities, similar cost reductions have been experienced around the world.

BOS costs vary much more significantly from region to region and are also dependent on the size of the installation. In the United States, these costs have been estimated to be roughly $1.15/Wp for utility-scale applications and $2.60/Wp for residential applications, although actual costs may be higher or lower in areas that are more or less supportive of solar development. All told, cost estimates for typical installed systems in the United States are therefore roughly $1.80/Wp for utility-scale applications and $3.25/Wp for residential applications. Actual reported prices for installed systems are somewhat higher for residential systems, exceeding $4.00/Wp, a difference that can be largely attributed to imperfect competition in the solar installation market. In Germany, where solar markets are more advanced, BOS costs are generally lower than in the United States, as low as $1.40/Wp for residential applications, for an average reported installed cost of roughly $2.05/Wp in 2013 (MITEI, 2015). Consumer prices may be further reduced by subsidies that are available for solar technologies in the United States and Germany; however, our analysis focuses on unsubsidized costs.

In the developing world, residential and small commercial consumers more frequently purchase a bundled SHS which typically include all necessary components, installation, appropriate battery storage, and in some cases energy efficient appliances such as LED lighting, fans, radios, or televisions. These systems are growing in popularity around the world, but costs can vary wildly. It is also difficult to draw direct cost comparisons between SHS costs in different areas as they are commonly delivered through rental agreements or various financing mechanisms, and total system costs may depend on the details of these arrangements.

The organization that has been at the forefront of the rapid SHS penetration in Bangladesh, Grameen Shakti, offers systems that vary in capacity from 10 to 135 Wp and in cost from $7.70/Wp to $3.71/Wp (Grameen Shakti, 2015). These systems all include inverters and controllers, appropriately sized battery storage, a number of appliances, a 20 year warranty on the solar panel, and a 5 year warranty on the battery. In India where SHS markets are also becoming mature, similar SHSs are being delivered through financing schemes coordinated by the Ministry of New and Renewable Energy (MNRE) and the National Bank for Agriculture and Rural Development (NABARD). In 2011, the indicative costs for these systems were roughly $7.13/Wp–$6.96/Wp for systems ranging in capacity from 10 to 200 Wp (NABARD, 2011). SHS costs are generally somewhat higher in other regions of the world with less mature markets. Smaller systems are typically more expensive on a per unit basis. A review of "pico PV systems" – those with 10 Wp capacity or less – in various locations throughout the world found costs to be roughly $21.20/Wp in 2015 dollars (Lysen, 2013).

Reported SHS unit costs in a range of other locations in the developing world are detailed in Table 1 and Fig. 1. These reflect actual reported costs from different real-world programs and price lists, as opposed to generic modeling assumptions that have been made for various studies and analyses. When possible, the listed year represents the year in which the specific project was installed or the listed price was offered. However, some data sources do not explicitly provide this information, in which case we default to the publication year of the reference. Additional care should be exercised in comparing these costs, as systems may include different storage capacity or appliances. In some cases, administrative costs may be incorporated into the listed system cost, while in other cases, these may be incorporated into financing costs that are

[2] http://www.xe.com/currencytables/

Table 1
An overview of reported solar home system costs around the world.

Year	Country	PV capacity (Wp)	System cost ($)	Unit cost ($/Wp)	Battery capacity (Ah)	Battery cost ($)	Battery unit cost ($/Ah)	Battery cost (% of total)	Storage to generation ratio (Wh/Wp)	Source
2015	Bangladesh	10	$77.02	$7.70	15	–	–	–	1.50	(Grameen Shakti, 2015)
2015	Bangladesh	50	$250.32	$5.01	60	–	–	–	1.20	(Grameen Shakti, 2015)
2015	Bangladesh	100	$449.29	$4.49	100	–	–	–	1.00	(Grameen Shakti, 2015)
2015	Bangladesh	135	$500.64	$3.71	130	–	–	–	0.96	(Grameen Shakti, 2015)
2009	Bangladesh	50	$405.15	$8.10	–	–	–	–	–	(Urmee and Harries, 2009)
2013	Cambodia	40	$474.30	$11.86	48	–	–	–	1.20	(Pode, 2013)
2013	Cambodia	78	$1009.80	$12.95	78	–	–	–	1.00	(Pode, 2013)
2009	Cambodia	40	$555.00	$13.88	–	–	–	–	–	(Urmee and Harries, 2009)
2009	Ethiopia	10	$315.73	$31.57	–	–	–	–	–	(Breyer et al., 2009)
2009	Fiji	100	$1,618.38	$16.18	–	–	–	–	–	(Urmee and Harries, 2009)
2012	Ghana	15	$404.44	$26.96	12	–	–	–	–	(Ghana Ministry of Energy, 2012)
2012	Ghana	50	$808.89	$16.18	65	–	–	–	–	(Ghana Ministry of Energy, 2012)
2012	Ghana	100	$953.33	$9.53	100	–	–	–	1.00	(Ghana Ministry of Energy, 2012)
2007	Ghana	14	$609.50	$43.54	–	–	–	–		(Pode, 2013)
2007	Ghana	100	$1690.50	$16.91	–	–	–	–		(Pode, 2013)
2011	India	10	$71.30	$7.13	7	–	–	–	0.70	(NABARD, 2011)
2011	India	50	$356.50	$7.13	60	–	–	–	1.20	(NABARD, 2011)
2011	India	100	$713.00	$7.13	120	–	–	–	1.20	(NABARD, 2011)
2011	India	210	$1461.66	$6.96	120	–	–	–	0.57	(NABARD, 2011)
2010	India	35	$281.90	$8.05	40	$56.38	$1.41	20%	1.14	(Chaurey and Kandpal, 2010)
2010	India	70	$552.05	$7.89	70	$112.76	$1.61	20%	1.00	(Chaurey and Kandpal, 2010)
2009	India	50	$549.45	$10.99	–	–	–	–	–	(Urmee and Harries, 2009)
2012	Kenya	40	$645.84	$16.15	–	–	–	–	–	(Abdullah and Markandya, 2012)
2008	Morocco	80	$1,358.02	$16.98	150	$506.41	$3.38	37%	1.88	(Carrasco et al., 2013)
2009	Nepal	30	$388.50	$12.95	–	–	–	–	–	(Urmee and Harries, 2009)
2015	Nicaragua	55	$600.00	$10.91	107.5	$141.00	$1.31	24%	1.95	(Ranaboldo et al., 2015)
2015	Nicaragua	250	$2035.00	$8.14	210	$300.00	$1.43	15%	0.84	(Ranaboldo et al., 2015)
2015	Nicaragua	2500	$18268.00	$7.31	2100	$3000.00	$1.43	16%	0.84	(Ranaboldo et al., 2015)
2009	Sri Lanka	50	$532.80	$10.66	–	–	–	–	–	(Urmee and Harries, 2009)
2007	Tanzania	14	$234.37	$16.74	–	–	–	–	–	(Pode, 2013)
2007	Tanzania	70	$965.53	$13.79	–	–	–	–	–	(Pode, 2013)
2009	Vietnam	40	$555.00	$13.88	–	–	–	–	–	(Urmee and Harries, 2009)
2009	Uganda	75	$1939.69	$25.86	150	$286.42	$1.91	15%	2.00	(Kyezira et al., 2009)
2009	Uganda	14	$556.70	$39.76	70	$81.06	$1.16	15%	5.00	(Kyezira et al., 2009)
2011	Various	10	$212.00	$21.20	–	–	–	–	–	(Lysen, 2013)

considered separately. Some prices may also reflect a certain degree of subsidization, but unfortunately, most of the sources used to compile these cost data do not specifically discuss potential subsidies or other programmatic support. A regulatory environment that is supportive of distributed solar can also reduce BOS costs, and therefore, the total cost of a project, as is evident from the difference in installed costs for solar in the U.S. and Germany. Such indirect cost reduction factors are also not explicitly discussed in most of these data sources.

Storage

It is more difficult to estimate the cost contribution from the storage component of a SHS as costs are often reported only for the system as a

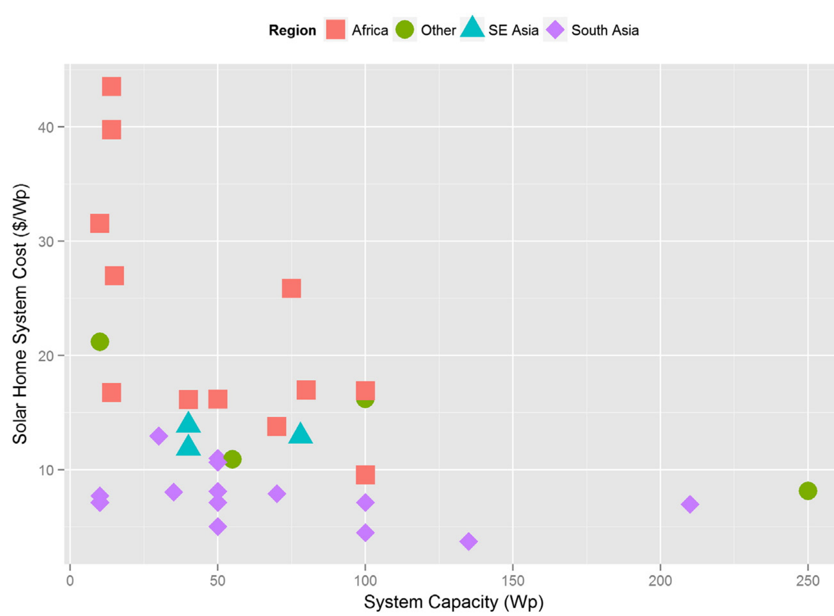

Fig. 1. Reported SHS unit costs in several different regions as a function of system capacity. Costs are generally lowest in South Asia, which reflects the relatively maturity of these SHS markets as well as potential direct or indirect subsidization.

whole. The relative cost of storage also depends upon several factors, namely the technology that is used (i.e. lead–acid or lithium–ion) and the storage capacity of the battery. Broadly speaking, an SHS for residential or small commercial applications in the developing world will typically include a 12 volt lead-acid battery with approximately 12 Wh (1 Ah) of storage for each Wp of solar panel generation capacity. Table 1 also shows the component of total SHS cost that is attributable to the battery for several systems where such a cost breakdown was reported. The storage to generation ratio provides a measure of the relative size of the storage component of each system. It would likely be expected that batteries in systems with high storage to generation ratios would account for a relatively larger portion of the total system cost. The storage capacities of systems without this cost breakdown are also included to provide examples of typical battery sizing for a SHS in different regions. These data indicate that storage costs can be highly variable. For example, the storage component of the 80 Wp system analyzed in Morocco accounted for a much higher share of total costs than the storage component of the 75 Wp system analyzed in Uganda, despite both systems having the same storage capacity. The primary causes of such discrepancies are not immediately clear from the information that has been made available. We assume for our analysis that the storage component accounts for 20% of the total SHS cost and must be replaced every 5 years. Therefore Table 1 should be considered to provide a broad comparative overview of reported SHS prices in various parts of the world. If precise cost information is desired for a specific location, it would be prudent to conduct a more detailed review and develop an understanding of the subsidies and other forms of support that may be involved.

Grid expansion cost review

Transmission and distribution

The cost of extending a centralized grid to connect a new structure will depend on a variety of factors, such as the length of the connection, local geography, materials costs, labor costs, and many more. Of particular importance are the line voltage and capacity, which directly and significantly impact the cost of new transmission and distribution infrastructure. A survey in 2000 found that the cost of a "typical" kilometer of grid extension line into rural areas centered around $9730 to $11,120, but varied significantly in different countries, from as low as $3058 in India to nearly $25,020 in Mali (World Bank, 2000). The reported cost reached $30,580 in parts of the United States when accounting for the costs of right-of-way clearance, an expense that was not included in most other survey results. These costs cover the voltage and capacity ranges that are typically used for rural electrification in each specific country. It is likely that different countries typically develop lines with different characteristics, which would contribute to the cost differences seen between countries. For example, the low cost in India was primarily attributed to the use of relatively smaller conductors and locally sourced materials. As another example, labor costs account for roughly half the total cost in the U.S. but are in the range of 10%–20% of total costs in developing countries.

The Energy Technology Systems Analysis Programme of the International Energy Agency has also summarized cost ranges for transmission and distribution infrastructure that have been discussed in other studies (ETSAP, 2014). The find costs of roughly $247,000/km for both a bipolar high voltage direct current (HVDV) line and a double AC line. They also present cost ranges as a function of line capacity for both long range transmission lines, $746/km-MW to $3318/km-MW, and lower voltage distribution lines, $1491/km-MW to $6636/km-MW. They also find that investment costs in transmission account for 4%–15% of the total cost of electricity deliver, while investments in distribution account for 27%–34% of the total cost. HVDC converter stations are estimated to cost $247 million, while AC substations are estimated to cost $78 million, or between $10,700/MW and $24,000/MW. The variation of costs between different countries and geographies is not discussed in detail.

Parshall et al. determined the cost of grid extension in Kenya in 2007 to be $16,213/km for medium-voltage lines, $12,203/km for low voltage lines, and $171 for the fixed cost of connecting each new structure, plus costs for internal household equipment ranging from $94 to $422 (Parshall et al., 2009). Installed costs for transformers ranged from $2591 for less than 20 kW to $6038 for up to 80 kW. The authors estimated an average grid connection cost of $2185 per household for a realistic penetration scenario, with the costs for a number of more remote regions exceeding $4600 per household.

Deichmann et al. build upon this analysis, further estimating the cost of higher voltage lines to be $95,400/km for 132 kV and $203,520 for 220 kV in Kenya (Deichmann et al., 2011). In a similar analysis of Ghana, Kemausuor et al. assumed costs of $25,250/km for medium-voltage lines, $12,120–$17,170 for low-voltage lines, $153/kW for transformers and $323 for equipment and installation per connected household (Kemausuor et al., 2014). This analysis estimated the cost of grid expansion into the relatively remote region of Northern Ghana to be $2424 per household when including initial costs and 10 years of recurring costs. Under the assumption that annual recurring costs are 1% of the total capital cost and are time-discounted, the upfront connection cost is approximately $2303 per household.

An analysis of grid extension in Senegal assumed costs of $16,640/km for medium-voltage lines, $12,480/km for low-voltage lines, $1040/kW for transformers and $274 per household for connection costs (Sanoh et al., 2012). A case study of Leona, a rural community in Senegal that is the site of a Millennium Village Project, found the cost of grid extension to be approximately $838 per household, less than the estimated average cost throughout rural Senegal, which was $1090 (Sanoh et al., 2012).

The costs of grid connection on a per capita basis are also strongly dependent on population density, settlement patterns, and the coverage of existing infrastructure. Nigeria for example is densely populated and already has a widespread transmission network. As a result grid expansion tends to be most cost-effective supply option for those who currently lack electricity access. Ethiopia on the other hand has a number of densely populated urban areas, but the overall population density of the country is lower than that of Nigeria. In addition, existing transmission and distribution infrastructure is less developed and as a result distributed generation technologies may potentially play a more prominent role in future development strategies. This effect is quantified by an analysis presented in the 2014 Africa Energy Outlook, which projects that the electrification rate in Nigeria could increase from 45% to 85% by 2040, whereas the electrification rate in Ethiopia would increase from 23% to only 60% under similar assumption (IEA, 2014b). Most of the remaining 40% without access would be located in rural areas. Similar effects are apparent even within single countries. The 2015 India Energy Outlook projected that urban electrification will be essentially universal in India by 2030; however, some 60 million people in rural areas will still lack electricity access (IEA, 2015b).

Generation

The body of literature estimating the costs of electricity generation from various technologies is far too extensive to review exhaustively here and such costs can vary significantly depending on location and global fuel prices. However, we do provide a short review of several relevant studies. Many centralized generation units in the developing world use oil-based products as a fuel source. Such generation is relatively expensive compared to the larger hydroelectric, coal, nuclear, and natural gas combined cycle plants more commonly employed in the developed world, which typically have levelized costs on the order of $0.08–$0.10/kWh (Kost et al., 2013; Salvatore, 2013; EIA, 2015b). The levelized cost of a small (<50 kW) diesel generator has been estimated to be on the order of $0.17–$0.21/kWh, while the levelized cost of a larger (1–10 MW), utility-scale generator was estimated to be $0.15–$0.17/kWh. These costs are based on a global market price for diesel fuel of $0.75/L (U.S. Gulf Coast Ultra-Low Sulfur No. 2) (Kost et al., 2013). The cost of providing electricity through a national grid is also highly dependent on both fluctuations in global energy prices and the energy mix of the country; the current trend of low oil prices ($0.36/L in November 2015) may reduce these generation costs. However, as natural gas fuel prices are typically correlated with oil prices, it is unlikely that low oil prices will lead to oil-based electricity generation being cheaper than natural gas-based generation.

The average production cost in Africa has also been reported to be $0.18/kWh as of 2013 (AFDB, 2013). The Kenyan Ministry of Energy has also estimated that centralized generation costs will stabilize around $0.17 per kW/kWh by 2018 (Zeyringer et al., 2015). A continent-wide modeling analysis of power system expansion in Africa found the cost of new generation in Africa to vary from $0.13/kWh in Southern Africa to $0.37/kWh in North Africa, with an average of $0.25/kWh (Sanoh et al., 2014). One modeling analysis in Kenya assumes LCOEs for various candidate centralized generation projects including $0.07/kWh for geothermal, $0.10/kWh for wind and hydro, $0.11/kWh for nuclear, $0.12/kWh for natural gas, and $0.14/kWh for coal (Kenya Ministry of Energy, 2011), while another in Uganda utilizes a proxy cost of $0.17/kWh for electricity from the grid (Murphy et al., 2014). The cost of electricity from a diesel generator was found to vary between $0.28/kWh and $0.33/kWh depending on capacity, with a diesel cost of $0.98/L. For compressed natural gas as a fuel source the generation cost varies between $0.14/kWh and $0.16/kWh at the prevailing cost of $2.00 per diesel gallon equivalent (Oladokun and Asemota, 2015). Another analysis found the LCOE of an optimized hybrid power system with small diesel generators, storage and solar PV to be $0.50/kWh based on a diesel price of $1.20/L. The LCOE of the optimal hybrid system increases to $1.60/kWh for a diesel fuel cost of $3.00/L (Ouedraogo et al., 2015).

A recent report by the International Energy Agency and the Nuclear Energy Agency provided a limited review of levelized generation costs in three non-OECD countries, China, Brazil, and South Africa (IEA/NEA, 2015). In China, the LCOE of a combined-cycle natural gas plant was determined to be $0.095/kWh at a 7% discount rate. The LCOE of coal was reported to be $0.078/kWh in China and $0.082/kWh in South Africa, both with a 7% discount rate. However, the applicability of these data to the developing world may be limited (Khatib, 2016). Another report on the cost of energy generation around the world found there to be an extremely wide range of average LCOE values for hydroelectric generation, $0.19/kWh to $3.14/kWh for small projects (<10 MW) and $0.24/kWh to $3.02/kWh for larger projects (WEC/BNEF, 2013). It includes limited analysis of the developing world, but does find the LCOE of onshore wind generation to vary between $0.047/kWh and $1.13/kWh in India, $0.49/kWh and $0.93/kWh in China, and $0.55/kWh and $0.99/kWh in Brazil. A study specific to sub-Saharan Africa projected the LCOE of several centralized generation technologies in various countries in 2020 (Castellano et al., 2015). It estimates the LCOE of natural gas to range from $0.047/kWh to $0.065/kWh, with the disclaimer that natural gas may not be widely available as a fuel source in all countries. The LCOE of coal is projected to be between $0.059/kWh and $0.071/kWh in the three countries with 94% of the coal resource capacity in the region, South Africa, Botswana, and Mozambique. Throughout the rest of the region the cost is projected to fall between $0.073/kWh and $0.086/kWh. Large-scale wind generation in countries with high wind speeds was found to have an LCOE between $0.107/kWh and $0.142/kWh. The LCOE of hydro can vary significantly depending on location, between $0.059/kWh and $0.083/kWh in East Africa and more than $0.13/kWh in West Africa. Proposed generation facilities at Inga Falls in the Democratic Republic of Congo (DRC) – discussed further below – have been projected to have a LCOE as low as $0.025/kWh.

The International Renewable Energy Agency developed a systems planning model that has been utilized to develop long-term infrastructure development plans for West Africa and Southern Africa (IRENA, 2013a, 2013b). These analyses include levelized cost assumptions for a number of different generation technologies. The values that follow are the same for both regions and exclude all transmission and distribution costs. The levelized cost of diesel generation is assumed to be $0.291/kWh for large, centralized generators and $0.604/kWh for small, distributed generators (<1 kW). Open-cycle natural gas turbines with a domestic fuel supply are assumed to have a levelized cost of $0.141/kWh and natural gas combined-cycle units, a levelized cost of $0.090/kWh. The levelized costs of utility scale solar and bulk wind generation with a 30% capacity factor are $0.121/kWh and $0.102/kWh, respectively, and of large and small hydro, $0.062/kWh and $0.107/kWh, respectively.

The Democratic Republic of Congo has roughly half of the all the hydroelectric potential in sub-Saharan Africa, including the massive resource at Inga Falls (Castellano et al., 2015). There are currently two generation units in operation at Inga Falls. The 351 MW Inga I unit was completed in 1972 and the 1424 MW Inga II was completed in 1982. However, utilization of both of these units is currently relatively low due to poor maintenance and political instability. A third unit, Inga III, with 4755 MW of capacity has been proposed and construction is set to commence in the near future (Taliotis et al., 2014). A series of additional units have also been discussed, which would bring the total generation capacity of the site to 42 GW, roughly equal to the current generation capacity of all of sub-Saharan Africa (excluding South Africa). One modeling analysis found that the large hydro resources at Grand Inga and throughout Central Africa can be exported to anywhere in Africa for a delivered cost of no more than $0.20/kWh, including $0.13/kWh in Egypt and $0.09/kWh in South Africa (Sanoh et al., 2014).

It is clear that centralized generation costs are highly variable depending on a variety of factors including fuel mix and resource availability. We assume a baseline centralized generation cost of $0.10/kWh to roughly represent a system where baseload electricity is provided by natural gas or coal, with costs potentially offset in either direction by lower cost large hydro generation, or higher cost diesel generation for peaking. We do not wish to imply that this cost assumption can be universally applied throughout the developing world. In many developing countries where there is more reliance on diesel generators, average costs may be somewhat higher, while in those countries with abundant natural gas, coal or hydro resources average costs may be somewhat lower. We therefore also consider two sensitivity scenarios with average generation costs of $0.05/kWh and $0.25/kWh to reflect potential variations in this important input parameter.

Methodology

We now present an analysis that considers the true cost of energy service provision, as a function of the capital costs of a SHS and grid connection, rather than assuming fixed, subsidized grid tariffs. This methodology is then used to analyze the choice between pursuing grid expansion and investment in distributed SHSs. Specifically, we determine the "breakeven electricity consumption level" for a given SHS capital cost and grid connection cost, at which point the cost of delivering electricity through each approach is equivalent. Therefore, all else equal, the centralized approach would be more cost-effective for greater consumption levels and the distributed approach would be more cost-effective for lower consumption levels. Due to the previously outlined variation in costs for both SHS and grid expansion in different regions on the world, we frame our analysis to explore the full range of potential values across both these parameter dimensions. This provides a more general framework for understanding the choice between pursuing distributed versus centralized electrification strategies across regions and cost scenarios.

True cost of electricity from the grid

The true cost of electricity provision through the grid is calculated as a function of the per structure grid connection cost, based on the fixed parameters shown in Table 2. This cost of provision can be broken into two components, the fixed cost of the transmission, distribution, and substation investments that are required to extend the grid, and the levelized cost of generation for each unit of electricity that is provided. The fixed cost is calculated as a function of the per structure grid connection cost as follows.

To annualize the fixed cost of grid extension, an annual capital payment (p) first is calculated for a given grid connection cost using a standard fixed-payment amortization formula.

$$p_g = i_g \cdot \frac{C_g}{1-(1+i_g)^{-N_g}} \tag{1}$$

These payments are assumed to occur annually over the loan term, while maintenance costs are assumed to occur over the entire lifetime of the system. Eq. (2) therefore represents the present value of the time-discounted cost stream of grid expansion, assuming that the system lifetime is longer than the loan term.

$$PV_g = \sum_{t=1}^{N_g} \frac{p_g + m_g}{(1+r_g)^t} + \sum_{t=N_g+1}^{T_g} \frac{m_g}{(1+r_g)^t} \tag{2}$$

The annualized cost of grid connection is the quantity (x_g) that satisfies Eq. (3). This can alternatively be thought of as the cost that when applied during each year of the lifetime of the transmission system will have a present value equal to the present value of the original time-discounted cost stream.

$$PV_g = \sum_{t=1}^{T_g} \frac{x_g}{(1+r_g)^t} \tag{3}$$

Solving for x_g yields

$$x_g = \frac{PV_g}{\sum_{t=1}^{T_g} (1+r_g)^{-t}}. \tag{4}$$

This is similar to a levelized cost of electricity calculation, except here the costs are levelized over a number of years of grid operation, as opposed to a number of kilowatt-hours of electricity generation. The annualized cost (AC_g) of energy provision through the grid is therefore this fixed cost plus the variable cost of generation multiplied by the annual energy consumption level (y).

$$AC_g = x_g + c \cdot y \tag{5}$$

True cost of electricity from a solar home system

The true cost of electricity from a SHS is similarly calculated as a function of the unit capital cost of the system, in dollars per Wp. This cost is then combined with ongoing maintenance and battery replacement costs and levelized over the lifetime electricity generation of the system to arrive at a levelized cost of generation as follows.

The methodology for calculating this levelized cost is similar to the method presented above for grid expansion, although many key parameters differ. For example, loans for an individual SHS would typically have higher interest rates and shorter terms than those made available to utilities and governments for large capital investments in grid expansion. The parameter assumptions presented in Table 3 reflect this assumption. However, as previously discussed, it is also possible for governments to take a centralized approach to implementing distributed energy systems, in which case more favorable financing terms may be available. This possibility will be analyzed in more detail later.

An annual loan repayment amount (p_s) is calculated according to a standard fixed-payment amortization formula.

$$p_s = i_s \cdot \frac{C_s}{1-(1+i_s)^{-N_s}} \tag{6}$$

Similar to the grid calculation, a cost stream that includes maintenance and battery replacements can then be constructed. The present value of this cost stream is calculated as in Eq. (7).

$$PV_s = \sum_{t=1}^{N_s} \frac{p_s + m_s + b}{(1+r_s)^t} + \sum_{t=N_s+1}^{T_s} \frac{m_s + b}{(1+r_s)^t} \tag{7}$$

An SHS may also be provided through a rental program or other similar arrangements, where a regular payment is made in exchange for use of the SHS, potentially including maintenance and battery replacement. While the following analysis will focus on a loan-based model, Eq. (7) could easily be adjusted to represent a different monthly or annual cost stream. For a more detailed analysis and discussion of different financing mechanisms that may be used see Levin and Thomas (2014b).

The levelized cost of a SHS is the quantity (L_s) that satisfies the following relation, where z is the annual quantity of electricity generated by the system. This can similarly be thought of as the cost that when applied to each unit of generation will have a present value equal to the present value of the original time-discounted cost stream (PV_s).

$$PV_s = \sum_{t=1}^{T_s} \frac{L_s \cdot z}{(1+r_s)^t} \tag{8}$$

$$L_s = \frac{PV_s}{z \cdot \sum_{t=1}^{T_s} (1+r_s)^{-t}} \tag{9}$$

Table 2
Grid cost parameters. These parameters are original input assumptions based upon a review of multiple different sources. These values were chosen to be broadly applicable across a range of scenarios. Actual values will vary depending on the specific technology and geographic location being considered, as well as a range of other project-specific factors. Therefore, all results that follow should be considered in the context of all input assumptions.

Parameter	Value	Symbol
Grid connection cost ($/structure)	–	C_g
Loan term (years)	30	N_g
Interest rate	10%	i_g
Discount rate	5%	r_g
Annual maintenance (% of capital cost)	1%	m_g
Lifetime (years)	50	T_g
Levelized cost of centralized generation($/kWh)	0.10	c

Table 3
SHS cost parameters. These parameters are original input assumptions based upon a review of multiple different sources. Actual values will vary depending on the specific technology and geographic location being considered. Battery cost assumptions are for lead–acid batteries, which are currently more commonly used in SHS applications due to lower costs. However, cost reduction for lithium–ion batteries may alter this dynamic the future.

Parameter	Value	Symbol
Capital per Wp	–	C_s
Interest rate	20%	I_s
Loan term (years)	5	N_s
Discount rate	5%	R_s
Annualized battery replacement cost[3]	4% of capital/year	b
Battery replacement frequency (years)	5	–
Lifetime (years)	20	T_s
Annual maintenance (% of capital cost)	1%	M_s
Capacity factor	20%	–

The annualized cost (ACs) of energy provision through a SHS is therefore simply this levelized cost multiplied by the annual energy consumption level (y).

$$AC_s = L_s \cdot y \tag{10}$$

Breakeven energy consumption

Grid expansion requires a fixed upfront investment in transmission and distribution infrastructure, but typically has the benefit of a lower levelized cost for each unit of generation. Therefore, broadly speaking, grid expansion is more cost-effective when energy consumption is high and a SHS is more cost-effective when energy consumption is low. This tradeoff can be directly compared to determine a breakeven energy consumption level, at which the cost of energy provision through both grid expansion and a SHS is the same. This approach has also been used in conjunction with a network expansion algorithm to identify priority locations for distributed generation infrastructure (Levin and Thomas, 2012). Therefore, if actual energy consumption is less than this amount, an SHS would be the cheaper option whereas if actual energy consumption is greater that this amount, grid expansion would be cheaper. Eq. (11) equates the costs of energy provision from each approach as defined in Eqs. (5) and (10), with Y being the breakeven annual energy consumption level.

$$x_g + c \cdot Y = L_s \cdot Y \tag{11}$$

Solving for Y yields

$$Y = \frac{x_g}{L_s\text{-}c}. \tag{12}$$

As the cost of grid expansion (x_g) increases, the breakeven energy consumption level also increases, while the opposite holds for increasing SHS costs. If the levelized cost of electricity from a SHS (L_s) is less than the levelized generation cost of a centralized plant (c), then the breakeven energy consumption level becomes negative, implying that it would never be cost-effective to pursue a centralized electrification strategy.

Results and discussion

We now apply the parameter assumptions outlined in Tables 2 and 3 and cost data for several different regions to demonstrate a potential application of this analytical framework.

When all other parameters are held constant, x_g becomes a simple linear function of the per structure grid connection cost (C_g). Applying the values presented in Table 3 yields the following relation, where C_g is in dollars per structure and x_g is in dollars per year.

$$x_g = .099 \cdot C_g \tag{13}$$

Similarly, when all other parameters are held constant, L_s becomes a simple linear function of the unit capital cost of the SHS (C_s). Applying the values presented in Table 3 yields the following relation, where L_s is in dollars per kWh and C_s is in dollars per Wp.

$$L_s = .093 \cdot C_s \tag{14}$$

Eq. (12) thus becomes

$$Y = \frac{.099 \cdot C_g}{.093 \cdot C_s\text{-}.10}. \tag{15}$$

Under these parameter assumptions, we now analyze three specific regions that were discussed in "Grid expansion cost review" section: Leona, Senegal, Northern Ghana, and rural Kenya. These regions are assumed to have per structure grid connection costs of \$838, \$2302, and \$4600, respectively.

The SE4All Global Tracking Framework established a multi-tier methodology for measuring energy access. While the Framework clearly states that a simplified electricity consumption metric does not fully encapsulate the level of energy access available to a given household, an effort was made to convert each of the five access tiers into a consumption range. These energy services available in each access tier and the associated minimum annual household electricity consumption level are outlined in Table 4. These consumption ranges were established in the second edition of the Framework (IEA and World Bank, 2015a) and differ slightly from those outlined in the first edition (Angelou et al., 2013).

Fig. 2 shows the breakeven annual energy consumption level for each region as a function of the unit capital cost of a SHS. This metric provides a means for comparing the relative cost-effectiveness of SHS deployment and grid expansion for various SHS costs and annual consumption levels. In regions to the right of each line grid expansion is the cheaper option, while for regions to the left of each line, an SHS would be the cheaper option. For example, in the case of Northern Ghana, an SHS with a \$6/Wp capital cost would be the cheaper option for electricity provision when annual consumption is less than about 500 kWh per structure per year. The breakeven consumption level with a \$6/Wp capita cost is about 1000 kWh/year in Rural Kenya. Alternatively, if annual consumption in Lenoa, Senegal is 500 kWh/year, a grid connection would be the cheaper option as long as SHS capital costs exceed \$3/Wp.

The annual energy consumption levels that correspond with reaching each tier of energy access as defined by the SE4All framework – listed in Table 4 – are also indicated in the figure. It is therefore possible to identify the SHS capital cost that enables each access tier to be reached through electricity provision from an SHS. These capital cost values are listed in Table 5 for baseline assumptions (which is represented graphically in Fig. 2), as well as for three sensitivity scenarios.

Under baseline assumptions, it is clear that SHS deployment is a lower-cost option than grid extension to achieve Tier 1 energy access in all three considered regions, and likely for Tier 2 access as well. Northern Ghana could potentially achieve Tier 3 access with SHS deployment if capital costs could be reduced to less than \$7.84/Wp; these costs are currently found in India, Bangladesh, and other more mature SHS markets. Rural Kenya could achieve Tier 4 access with SHS deployment if costs were to reach \$5.02/Wp. This cost level has been achieved for larger systems in Bangladesh and is perhaps a reasonable short to medium term target for Kenya as technologies continue to develop and markets mature. The provision of Tier 5 energy access solely through SHS deployment is not cost-effective in any of these regions given current conditions; however, it is certainly conceivable that SHS capital costs on the order of \$2.00/Wp–\$3.00/Wp could be achieved over the next decade given current SHS cost reduction trends around the world.

This baseline analysis assumes that each SHS is financed directly by the end consumer at a relatively high interest rate of 20%. However, utilities and governments can also take an institutionally centralized approach to the development of distributed technologies. In this case,

Table 4
Annual electricity consumption levels corresponding to each of five tiers of energy access, as defined by the United Nations Sustainable Energy for All initiative (IEA and World Bank, 2015a).

	Annual energy consumption (kWh per household)	Indicative electricity services
Tier 1	4.5	Task lighting and phone charging
Tier 2	73	General lighting, television, and fan (if needed)
Tier 3	365	Tier 2 and medium power appliances
Tier 4	1250	Tier 3 and high power appliances
Tier 5	3000	Tier 4 and very high power appliances

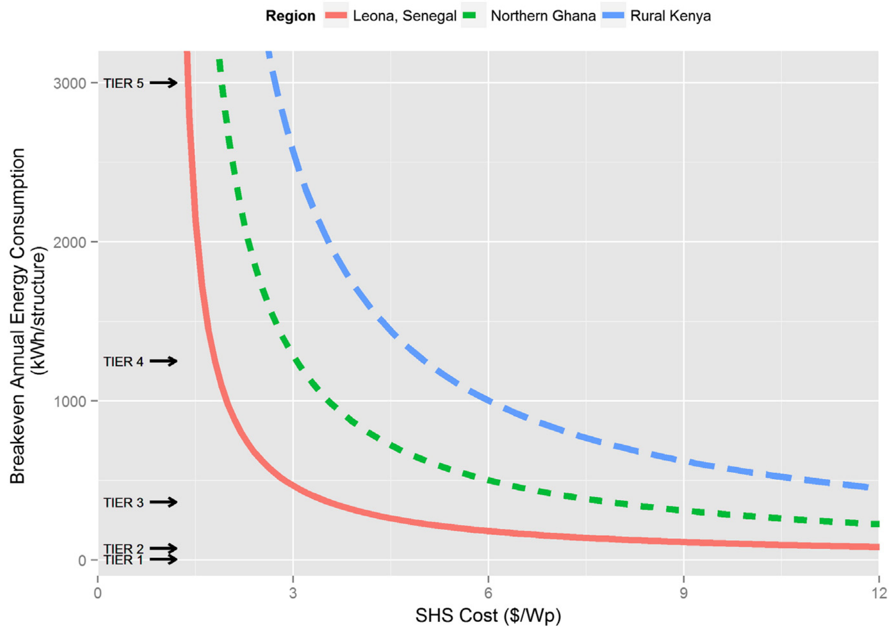

Fig. 2. Breakeven annual electricity consumption as a function of SHS capital cost for the three regions discussed in the "Grid expansion cost review" section. Electricity provision through the grid would be the cheaper option for consumption levels greater than the breakeven quantity, while provision through a SHS would be the cheaper option for lower consumption levels. These baseline results are also summarized in Table 1.

interest rates and other financing terms would likely be more favorable. Table 5 also shows a sensitivity analysis where we assume that SHSs are financed at 10% interest rate that is also applied to grid development. This causes SHS deployment to be the lower-cost electrification option even when capital costs are somewhat higher; Tier 3 access could be achieved in Northern Ghana with SHSs when costs are less than \$9.24/Wp and Tier 4 access in Rural Kenya could be achieved when costs are less than \$5.92/Wp. We also consider sensitivities around the levelized cost of electricity from the grid. The baseline assumption of \$0.10 is based upon a presumed mix of lower cost hydro or natural gas generation along with diesel generation during peak load periods, as may be common in many developing countries. However, in some regions, the centralized power system may be far more reliant on diesel generators for electricity generation, in which case the average levelized cost of electricity would be somewhat greater. Alternatively, some regions may have access to more abundant hydroelectric resources, reducing their average levelized cost of electricity. The impacts of these sensitivity assumptions are also shown in Table 5. A change in the levelized cost of centralized generation does not greatly impact the relative cost-effectiveness of SHS deployment of Tier 1 and Tier 2 access levels. This is because an overwhelming majority of the total costs of electrification and consumption are related to infrastructure investments when annual consumption is low. When the levelized cost of centralized generation is \$0.25/kWh, SHS deployment becomes cost-effective for Tier 3 consumption level in Ghana for costs up to \$9.46/Wp, and in Leona, Senegal for costs up to \$5.16/Wp. Tier 5 consumption becomes cost-effective in Rural Ghana for an SHS cost of \$4.34 or less, which is comparable to the current cost of larger systems in Bangladesh. For a levelized cost of centralized generation cost \$0.05/kWh, Tier 3 consumption levels can be cost-effectively served by SHS deployment if capital costs are less than \$7.30 in Northern Ghana, and \$14.05 in Rural Kenya.

Table 5
The SHS capital cost that is required to provide each SE4All energy access tier at lower cost than a grid connection is shown under baseline assumptions, as well as for three sensitivity scenarios. A high cost implies more favorable conditions for SHS deployment, while a low cost implies more favorable conditions for grid expansion. This is because the listed cost represents the cost at which a consumer would be financially indifferent between obtaining a SHS or a grid connection. Therefore, a high value means that an SHS is the overall least-cost option even when the SHS itself is relatively expensive.

Electricity consumption tier	Leona, Senegal	Northern Ghana	Rural Kenya
	SHS deployment is more cost-effective than centralized generation when the capital cost of a SHS (\$/Wp) is less than the value shown.		
Baseline			
Tier 1	\$200.67	\$549.59	\$1096.68
Tier 2	\$13.38	\$34.89	\$68.62
Tier 3	\$3.54	\$7.84	\$14.59
Tier 4	\$1.80	\$3.05	\$5.02
Tier 5	\$1.38	\$1.90	\$2.72
10% SHS interest			
Tier 1	\$236.37	\$647.36	\$1291.77
Tier 2	\$15.76	\$41.10	\$80.82
Tier 3	\$4.17	\$9.24	\$17.18
Tier 4	\$2.12	\$3.60	\$5.92
Tier 5	\$1.62	\$2.24	\$3.21
\$0.25/kWh centralized			
Tier 1	\$202.29	\$551.21	\$1098.30
Tier 2	\$15.00	\$36.51	\$70.23
Tier 3	\$5.16	\$9.46	\$16.21
Tier 4	\$3.42	\$4.67	\$6.64
Tier 5	\$3.00	\$3.52	\$4.34
\$0.05/kWh centralized			
Tier 1	\$200.13	\$549.05	\$1096.14
Tier 2	\$12.84	\$34.35	\$68.08
Tier 3	\$3.00	\$7.30	\$14.05
Tier 4	\$1.26	\$2.51	\$4.48
Tier 5	\$0.84	\$1.36	\$2.18

Conclusions

Over the past century, the concept of universal electrification has been synonymous with universal access to a grid connection. Distributed energy systems have largely existed to complement this centralized framework. The emergence of lower cost distributed technologies has created a fundamental shift in how energy services are being consumed, and a comprehensive national scale grid is no longer a necessary condition of universal access in a country or region.

Comprehensive energy planning should consider long-time horizons over which cost parameters will likely change. The decision to extend the grid requires significant upfront investment that may commit a region to a centralized electricity delivery mechanism for years or decades to come. Distributed approaches may be implemented more gradually, scaling as demand increases and reacting to potential future cost reductions. It is clear that distributed SHSs can play an important role in achieving the SE4All goal of universal access to modern energy systems by providing populations in currently un-electrified regions with Tier 1 or Tier 2 access. However, it is also often argued that while an SHS may be cost-effective for small consumption levels, as consumers gain access to electricity for the first time their demand will increase, eventually to the point where grid extension would have been more cost-effective. Therefore, the long planning horizons and large upfront costs of grid expansion are often justified in part by the argument that such infrastructure is necessary to support demand growth over time. In the current economic paradigm, centralized systems are still a vital component of the transition up the energy ladder to Tier 4 and Tier 5 access levels. Localized mini-grids powered by wind, solar or small hydroelectric generators may also become an increasingly attractive alternative that combines elements of purely centralized or decentralized development plans, i.e. shorter implementation time than a comprehensive national scale centralized generation and transmission system (but longer than an individual SHS) and lower generation costs than a SHS (but potentially greater than those from a large centralized unit).

Yet, the costs of distributed generation technologies have experienced dramatic reductions in recent years and this trend shows no signs of abating. Rooftop solar systems (without storage) are approaching grid parity in parts of the developed world, and the large majority of distributed installations are taking place on structures that are already connected to the grid (i.e. have zero grid connection cost). The cost of large, utility-scale wind and solar generation has also decreased rapidly in recent years, and additional future cost reductions can likely be expected. At the same time, the costs of traditional centralized generation facilities, such as nuclear, coal, natural gas, and hydro as well as transmission infrastructure have remained relatively constant over recent decades. As demand for distributed systems increases, markets will mature and larger systems will be installed. Both of these effects should drive economies of scale to help reduce the average system cost on a per unit (dollars per Wp) basis. Alternatively, as currently un-electrified regions receive access to electricity for the first time, it is reasonable to expect that their demand for energy services will continue to grow, making centralized systems more attractive. System planners must balance the tradeoff between these two effects when planning the development of power infrastructure that may be in operation for decades to come as costs and demands continue evolve and fluctuate over time.

Batteries represent a significant portion of the total cost of a SHS, but energy storage also provides additional services that are not inherently available through a grid connection. While energy storage is an essential component of an SHS, due to the intermittent nature of solar illumination, energy storage is not strictly necessary for those who consume electricity through a grid connection. However, energy storage provides additional tangible value for grid-connected consumers. Many consumers with a grid connection in unreliable regions also choose to maintain energy storage or backup diesel generators to provide service during power outages. When a direct economic comparison is made this additional cost is generally attributed to a SHS which includes storage, but it is not usually factored into the costs of consuming electricity through the grid. Additionally, a SHS is typically sold as part of a package that includes appliances that consumers would otherwise have to purchase separately for their grid-connected home or business.

Centralized electrification strategies based on grid-expansion may still be the optimal means of providing energy services throughout much of the world (Levin and Thomas, 2012). However, there are cases where a distributed approach is justified for economic, social, or geopolitical reasons. For example, national-scale electric grids require massive, concentrated capital investments that must be coordinated through a centralized entity and implemented over years or even decades. This is a challenging proposition under the best of circumstances and the lack of long-term institutional stability in parts of the developing world only serves to increase the challenge. Distributed technologies can be disseminated on regional or local scales much more quickly and require less centralized coordination. This increased speed of implementation may generate significant socio-economic benefits for populations that will otherwise continue to lack affordable and reliable access to basic energy services. Many consumers may be willing to pay a premium for the earlier access, increased reliability, autonomy, and environmental benefits that are afforded by an SHS compared to electricity provided through a centralized grid. Moreover, the implementation of distributed electricity services outside of the centralized utility business model could provide opportunities for innovation in the development of electricity service business models, energy efficient direct current appliances, and energy storage approaches. However, it can also be difficult for individual consumers to gain access to the capital required for a SHS purchase. Therefore, innovative business and financing models are also needed to support technology adoption (Palit and Chaurey, 2011; Bhattacharyya, 2013; Levin and Thomas, 2014b). While not directly considered in our analysis, localized micro-grids powered by solar arrays, wind turbines, or small hydroelectric generators may also offer a promising hybrid approach to achieving energy access goals in an efficient and cost-effective manner.

Distributed approaches to electrification are increasingly receiving institutional support from governments and aid agencies in the form of direct subsidies or programmatic support. However, this support still often falls short of what is available for the development and operation of a centralized electrification system and distributed electrification programs may be operated independently of grid expansion efforts, rather than as a single coordinated program (Palit and Chaurey, 2011; van Els et al., 2012; Martin and Susanto, 2014; Urpelainen, 2014). Many rural consumers pay grid tariffs that are well below cost-recovery for those regions and as a result are implicitly subsidized directly by their government or utility, or cross-subsidized by consumers in urban areas. An integrated approach to new power infrastructure development with commensurate levels of financial and institutional support for distributed approaches to energy service provision could propel developing countries to become leaders in next-generation energy technologies.

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