Universal Access to Electricity: Closing the Affordability Gap

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Annu. Rev. Environ. Resour. 2015. 40:261–83

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

This article's doi:
10.1146/annurev-environ-102014-021057

Keywords

universal access, renewable energy, decentralized mini-grids, solar photovoltaic, batteries, grid management, rural household, appliance, cost of electricity, efficiency, affordability gap, technology breakthroughs

Abstract

Access to electricity changes lives but only when people can afford electricity-powered services to meet their basic needs, and this is more than just two light bulbs and a fan. Decentralized renewable energy (RE) minigrids, particularly solar photovoltaic (PV) minigrids, can cost-effectively electrify a large share of currently unelectrified rural populations. But the cost of using appliances with this electricity is still much higher than what the poor can afford without deep subsidies. This affordability gap stunts the sustainability and growth of RE minigrids. Significant improvements in the economics of supplying electricity with minigrids, combined with higher-efficiency appliances, are needed to reduce the effective cost of using electricity in decentralized RE minigrids. These would bridge the affordability gap and improve business opportunities and value to users, investors, and service providers and thus create market-driven expansion to overcome the acute lack of funding that they currently face. Technology breakthroughs that can help in this respect include (*a*) significantly cheaper solar PV components to reduce up-front costs of solar PV minigrids; (*b*) significantly more affordable and energy-efficient appliances; (*c*) better-performing bulk storage at a significantly lower cost; (*d*) affordable and easy-to-use grid management solutions, and (*e*) a utility in a box for a simpler, cheaper, and faster way to set up minigrids.

Contents

1. INTRODUCTION

Energy is the life blood of development owing to its ability to power appliances and provide services that are essential for basic human needs. But more than one billion people, concentrated mostly in rural Asia and sub-Saharan Africa, lack electricity. The problem is expected to worsen in sub-Saharan Africa as population growth outpaces the increase in electrification and continues to be concentrated in rural areas where the distance from the grid and very low incomes pose challenges to electrification. Extending the grid to reach these populations is not the preferred choice for financial and other practical reasons. Instead, decentralized renewable energy (RE) minigrids are a more cost-effective option for reliable full-fledged electrification. Although much of South Asia will have electricity through grid extension, it is likely that most of rural Africa and some parts of rural South Asia will need decentralized RE minigrids. Solar photovoltaic (PV) and rechargeable battery technologies are expected to play critical roles in realizing the promise of decentralized RE minigrids. However, even if electricity were made available to rural unelectrified populations through decentralized solar PV minigrids, and even if the appliances to provide services for basic needs were affordable, the cost of using these appliances at the prevailing costs of electricity and appliance efficiency would be too high for rural users. This affordability gap prevents these minigrids from becoming financially self-sustaining and, in the face of severe funding gaps, limits their expansion and their ability to provide access to electricity for rural populations. In addition to reforms in policies and market institutions, technology breakthroughs that reduce the cost and complexity of providing electricity through these minigrids, as well as those that make relevant appliances much more efficient, can help realize the promise of universal access to electricity through RE minigrids. This review discusses these issues and how they can be resolved.

Recent years have seen an increase in proliferation of pre-electrification appliances, e.g., solar-powered lights and mobile phone chargers. Although this has benefits, low-income households need more comprehensive services to use appliances, such as refrigerators, televisions (TVs) [or other information and communication technology (ICT) devices], fans, and other tools, to meet the basic needs for safe, healthy, and comfortable living conditions, as well as for productive livelihoods. In Section 2, we look at a portfolio of appliances to meet these needs for a typical rural household and conclude that they would consume 80 kWh on average each month (1–5).

Section 3 discusses the lack of access to electricity and how decentralized RE minigrids can play a crucial role in providing access to rural areas, and therefore, to a significant share of the one billion people who are otherwise expected to remain without electricity as far out as 2030 (6–12). In Section 4, we touch upon why solar PV and rechargeable batteries are essential for realizing the promise of decentralized RE minigrids. Solar PV is the most widely applicable technology with the lowest barriers to adoption in developing rural regions. Rechargeable batteries are needed for a reliable and continuous supply of electricity in RE minigrids and especially in decentralized ones (11, 13–16).

In Section 5, we analyze the affordability of decentralized solar PV minigrids and conclude that there is a significant affordability gap with current technologies. This is to say that, even if decentralized solar PV minigrids were made available, and even if appliances for basic needs were affordable, the cost of electricity to provide basic services with existing appliances is too high for low-income users. If we look at the poorest four billion people who largely reside in rural areas, the highest income bracket comprises people who make \$3–5/day. Their monthly electricity budget is expected to be \$7.50 on average, and the prevailing cost of electricity in solar PV minigrids with storage is \$0.24/kWh on average. At these rates, the effective cost of consuming 80 kWh (the typical monthly household consumption needed for basic services) is \$20—almost three times what these users can afford. To bridge this seemingly intractable gap, two things must happen: The cost of electricity must fall sharply, and appliances must become more efficient. This relationship is demonstrated by the isoquant in **Figure 1**. This gap, and the improvements needed to bridge it, will be much higher for those who make less than \$3–5/day. The underlying assumptions for **Figure 1** are described in the sidebar titled Sources of the Assumptions for **Figures 1** and **8**. This isoquant is discussed again in Section 5 with a complete analysis of the figure (4, 5, 10, 11, 14, 17, 18).

The affordability gap makes RE minigrids less sustainable and severely limits their expansion because of funding shortfalls. Section 6 concludes with a summary of technology advances. These can improve the economics of electricity supply and usage in decentralized RE minigrids, the value of these minigrids to consumers and investors, and expansion through stronger and self-sustaining market-driven demand in rural areas (6, 10, 11, 19–23). Desirable breakthroughs would reduce the cost and complexity of delivering electricity and make relevant appliances much more efficient. In summary, these advances would include the following:

1. A suite of components that significantly reduce up-front costs of solar PV minigrids (10, 14, 21, 24–27)
2. Appliances for household use and income generation that are significantly more affordable and energy efficient than those on the market today (30–34)
3. Better rechargeable battery technologies for bulk storage in minigrids, with improved performance at a significantly lower cost (11, 12, 15, 16, 35)
4. Affordable and easy-to-use grid management solutions for RE minigrids (8, 11, 36)
5. A utility in a box to make it simpler, cheaper, and faster to set up and operate RE minigrids.

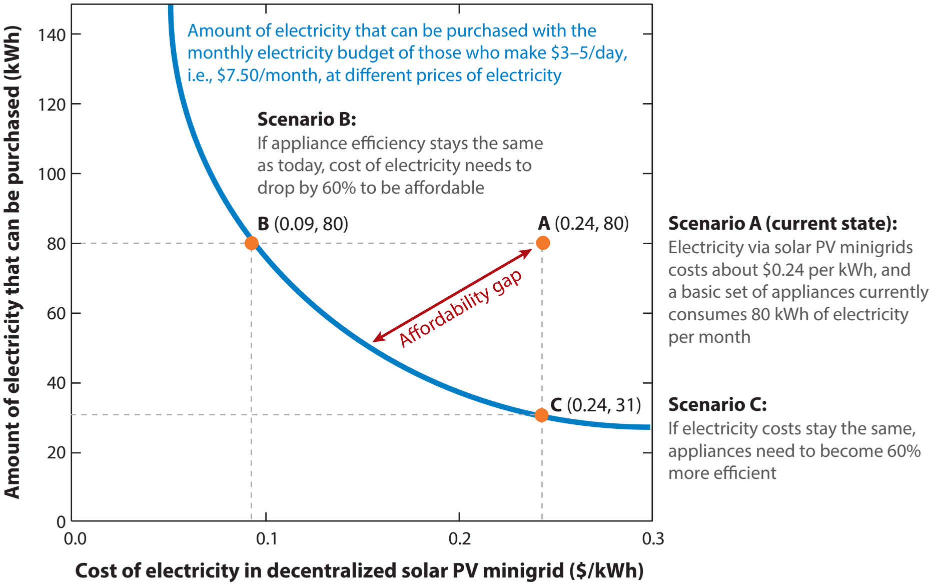

Figure 1

An isoquant curve representing combinations of reductions in cost of electricity versus the amount of electricity consumed by appliances to fit the monthly energy budget of populations earning $3–5 per day. The effective cost of electricity in decentralized minigrids [$0.24 per kWh including storage in solar photovoltaic (PV) minigrids] is too high to support the basic services (which consume 80 kWh using currently available appliances) for low-income users. The affordability gap is 60% for those making $3–5/day, so the cost of electricity needs to drop or the efficiency of the corresponding portfolio of appliances needs to improve by 60%, or both need to happen for a similar combined effect. For those making less than $3/day, these improvements need to be greater to bridge the affordability gap. This analysis is based on the assumptions in the sidebar titled Sources of the Assumptions for **Figure 1** and **Figure 8**—and not on actual observation of usage owing to lack of access and affordability of both electricity and appliances for low-income rural populations. A detailed analysis leading up to this conclusion is provided in References 4, 5, 10, 11, 14, 17, and 18.

2. ELECTRICITY CONSUMPTION LEVELS CORRESPONDING TO BASIC SERVICES NEEDED BY RURAL HOUSEHOLDS

Of the various forms of modern energy, electricity is perhaps the most vital for development because of its ability to provide services for important human needs. It is the most versatile and efficient way of consuming energy; can be easily converted to multiple forms of energy, e.g., heat, light, and mechanical energy; and is relatively loss free, nonpolluting, and easily regulated at the point of use. It can be generated centrally and distributed conveniently and efficiently across long distances, making it extremely economical. This makes it ideal for powering appliances that are central to human safety, comfort, and productivity. Although there are other factors that also contribute to underdevelopment, countries with lower electrification rates are clearly worse off in terms of human development (**Figure 2**). The lack of access to electricity forms a vicious cycle with lack of development: Less-developed countries do not have the means to invest in electrification, and the low levels of electrification limit development.

Access to electricity has been defined differently in different contexts. In some, it has meant having an electricity connection, whereas in others, it has meant a reliable supply and the ability to consume a minimum quantity of electricity. There is increasing recognition that electricity

SOURCES OF THE ASSUMPTIONS FOR FIGURE 1 AND FIGURE 8

Power consumption figures for basic services using current appliances include the following:

1. Power draw for efficient appliances (4)
2. The power draw for an irrigation pump and hours of electricity consumption for appliances are our assumptions. Typical hours of use of irrigation pumps (5)

The cost of electricity in decentralized solar photovoltaic (PV) minigrids with storage considers the following:

1. Solar PV costs as per second round of bidding for National Solar Mission in India (18)
2. Balance-of-system costs based on a standard breakdown of costs in a solar PV system (14)
3. Storage can add 50% or more to system costs for solar PV minigrids (11)

The segmentation and electricity budget of poor people include the following:

1. Segmentation of the poorest four billion people (17)
2. Typical percentage of income allocated to an energy budget and the percentage of an energy budget spent on lighting and electricity among poor people (exact numbers vary by region) (10)

These assumptions use benchmarks. Observed data (where available) vary depending on a range of factors. Consumption is influenced by the quality of electricity, subsidies, and pricing schemes for appliances and electricity. The cost of electricity varies widely by installation, availability of resources, cost of capital, and subsidies. Actual observation of costs and usage is limited by lack of access and affordability of both electricity and appliances for low-income rural populations.

access should be defined in terms of the level of amenities and services it enables. Electricity leads to development when people use it for services to meet their basic human needs, e.g., both household and livelihood needs. Thus, to be meaningful for human development, access must be measured by the value and range of services that improve the quality of life and productivity. In other words, electricity to power light bulbs, a fan, and a mobile phone is unlikely to lead to development. If the consumer does not have the necessary appliances, or if they cannot be powered by electricity even if it is available (because it is too expensive) to provide adequate services, then meaningful access is lacking. There are a number of electricity-powered services for basic development needs to reduce the burden of manual labor and physical discomfort, improve overall health and productivity, and enhance digital inclusion. An appropriate suite of appliances to meet the basic needs for development should also include a refrigerator (to preserve highly nutritious perishable food), an ICT device (TV and/or computer), and appliances to improve economic productivity (e.g., irrigation pumps).

To understand how much electricity would be consumed to meet the basic needs of a low-income rural household, we assume that they would need to use a portfolio of appliances that includes lighting, a fan, a refrigerator, an ICT device (e.g., a TV), and an appliance to generate income (e.g., an irrigation pump). Assuming the energy-efficiency levels of appliances currently on the market, the household will consume roughly 80 kWh each month (**Figure 3**) (4, 5).

3. DECENTRALIZED RENEWABLE MINIGRIDS AND THEIR POTENTIAL FOR UNIVERSAL ACCESS TO ELECTRICITY

Despite its importance, developing regions suffer from a lack of electricity. Currently, 1.3 billion people, mostly in rural sub-Saharan Africa and South Asia, lack access [based on the International

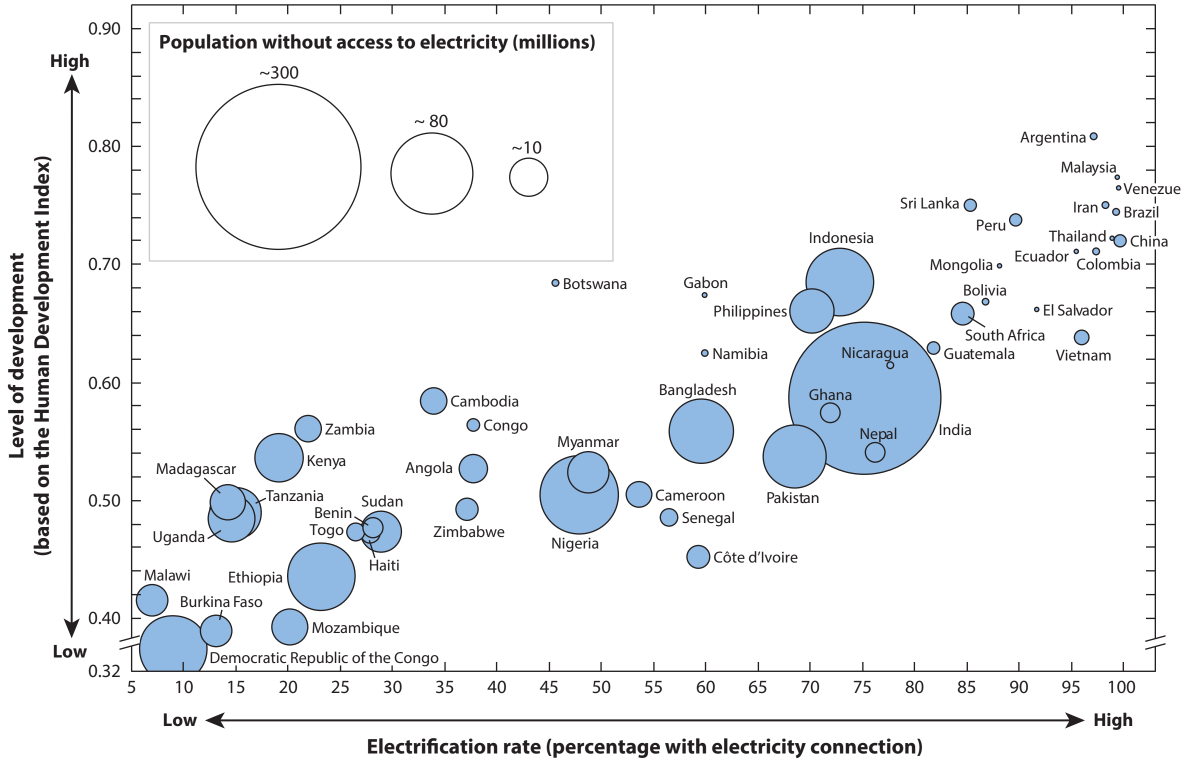

Figure 2

The Human Development Index of countries versus percent of population with electricity. Note that the International Energy Agency defines electrification as the annual consumption of at least 250 kWh of electricity in rural areas and 500 kWh in urban areas for a household of five (1, 2). These are the levels of electrification that were used to create this figure.

Energy Agency (IEA) definition of electrification; see Ref. 6]. This represents one-fifth of the world's population (6). Developing Asia[1] has the largest number of people without electrification (675 million out of a regional population of 3.6 billion), and sub-Saharan Africa has the highest percentage of population without electricity (72%). In these regions, more than 80% of the people without electricity live in rural areas. In aggregate, the IEA's optimistic scenario (a scenario in which all countries fulfill their current commitments to policy and investments for expanding electricity infrastructure projects) projects that there will still be one billion people without access to electricity in 2030 (**Figure 4**). Most of those without access will still be those living in rural areas, but the numbers would have increased in sub-Saharan Africa and fallen in Asia (6).

Decentralized RE minigrids offer considerable advantages, compared with both grid extension and stand-alone systems, for serving remote rural populations. Electricity is typically generated in large power plants with hundreds of megawatts (MW) of capacity by converting energy from coal, natural gas, water in dams and reservoirs, and nuclear fuels, and it is delivered (almost instantly), using a very large centralized power grid, to users across large geographical areas. Transmission

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[1] Please note that some of the source material used for this section combines data for all of developing Asia (which includes all of South Asia, as well as countries from Southeast Asia), whereas others isolate the data for South Asia. Hence, some exhibits show the data for developing Asia, and others show it for South Asia.

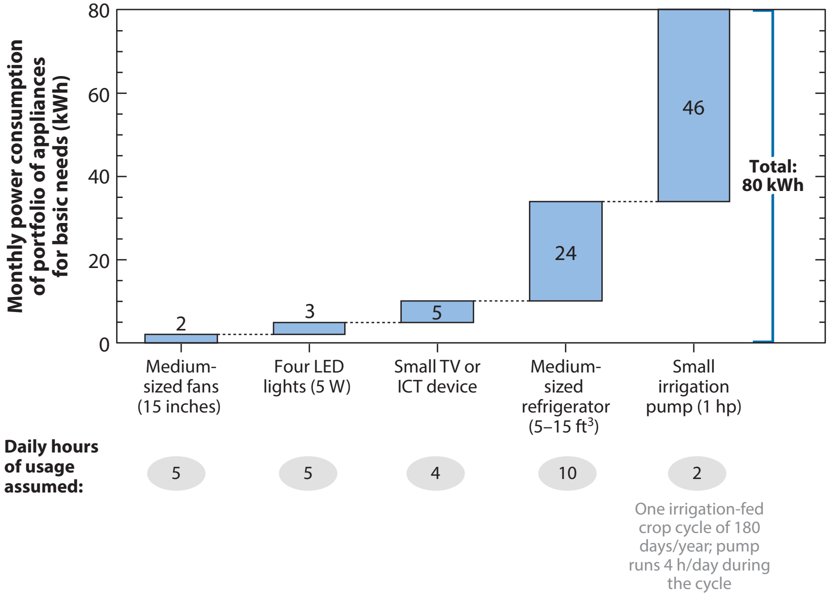

Figure 3

Power consumption for services to meet the basic needs of low-income rural households based on the power draw of efficient appliances (4). This is a conservative scenario for the basic needs of a smallholding farm household and includes income generation. The irrigation pump electricity usage, i.e., for a 1-hp pump, is conservative; we assume the pump runs 4 h daily during one irrigation-fed crop cycle that lasts 180 days. However, pumps typically have a higher rating, i.e., 3–5 hp, and may be shared by farmers or used in farms that employ multiple sharecroppers (4, 5). Actual usage of pumps and other appliances may also vary by other factors, e.g., the quality of electricity, subsidies, and pricing schemes for appliances and electricity. We assume that marginal variations in household size would not change the number of energy-intensive appliances and services needed, e.g., refrigerator, irrigation pump, etc. Actual observation of usage is limited by lack of access and affordability of both electricity and appliances for low-income rural populations. Abbreviation: ICT, information and communication technology; LED, light-emitting diode.

lines carry electricity over long distances; transmission is expensive owing to (among other reasons) the cost of infrastructure and comprises roughly 40% of the total electricity bill of a power system (7). In many cases (depending on population density and income levels), it is cost-effective to extend the grid within a specific range by extending the transmission or distribution lines. This range, known as the grid perimeter, usually includes urban and peri-urban areas, where even low-income populations often have access to a power grid. However, rural populations in developing countries are often beyond the grid perimeter. Two-thirds of the world's poor live in villages that are too costly to reach via grid extension (especially relative to the sparse, small, and low-income markets they represent). This is particularly true in sub-Saharan Africa, where a majority of the population is expected to be in rural areas for the foreseeable future (**Figure 5**). In such cases, decentralized RE minigrids—smaller independent grids that are (at least initially) not connected to the main grid—offer more practical alternatives for a variety of technical and financial reasons (8, 9). Currently, only 4% of the world's electricity is generated using renewable sources, such as solar and wind. Coal and natural gas are the main sources of electricity worldwide, and more so in South Asia and sub-Saharan Africa. Renewable sources, such as wind, solar, hydropower, and biomass, are abundant in nature, even though their availability varies by geography. For

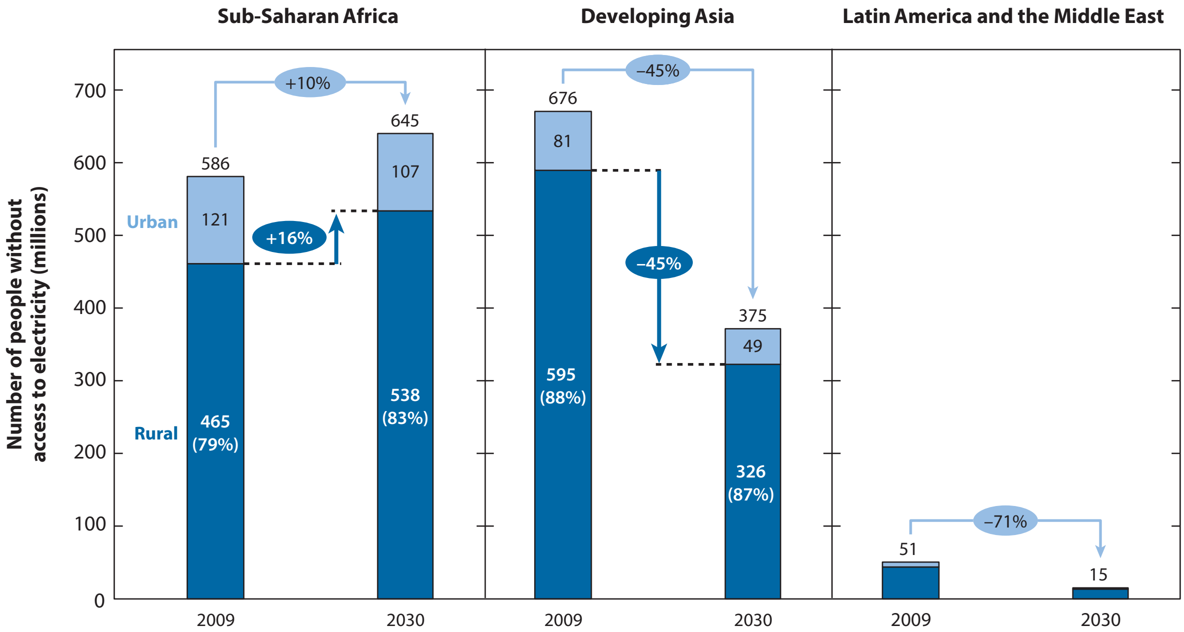

Figure 4

Expected change in the number of people without electricity access from 2009–2030 (in millions). The problem of lack of access to electricity in sub-Saharan Africa is expected to get worse by 2030, even in the International Energy Agency's optimistic scenario in which countries fulfill their current commitments (6).

small-scale applications like minigrids, they are more economical than conventional power plants; they do not suffer losses in economies of scale; and fuel costs are zero (except for biomass). According to recent estimates by the International Finance Corporation (IFC), the average capital cost for providing a new connection to a household with a minigrid starts at $50, whereas providing a new connection by extending the main grid to a household that is sufficiently close to it can start at $500 (10). With zero emissions (except biomass), they have a significantly lower environmental footprint and pose no risk of catastrophic environmental damage (as do nuclear power plants). According to the IEA, RE is the least-cost path to supply roughly 55% of the additional power generation that is needed for universal access by 2030 (**Figure 6**).

Stand-alone RE home systems (dedicated to a household) are easier to deploy than minigrids and have scaled up successfully with support from donors and governments with appropriate financing models. But they support limited services, and it is hard for them to simultaneously support multiple appliances, especially ones with a high-power draw, such as refrigerators (11). In comparison, minigrids can support larger loads and higher load variance, as well as have economies of scale that lower unit costs. If operated successfully, they can scale up and become attractive for interconnection with the main grid as the local economy grows (10). Hence, although stand-alone systems are valuable, minigrids are ideal for full-fledged electrification and long-term development.

There is no standard definition of a minigrid. On the basis of general usage in the available literature and the capacity needed to sustain services in rural communities, we concur with a typical assumption that a minigrid has a capacity from 10 kW to a few megawatts (10, 11). There are no specific threshold criteria that can be uniformly applied for selecting minigrids over grid extension. In the past, minigrids have been installed in places where the population density was greater than

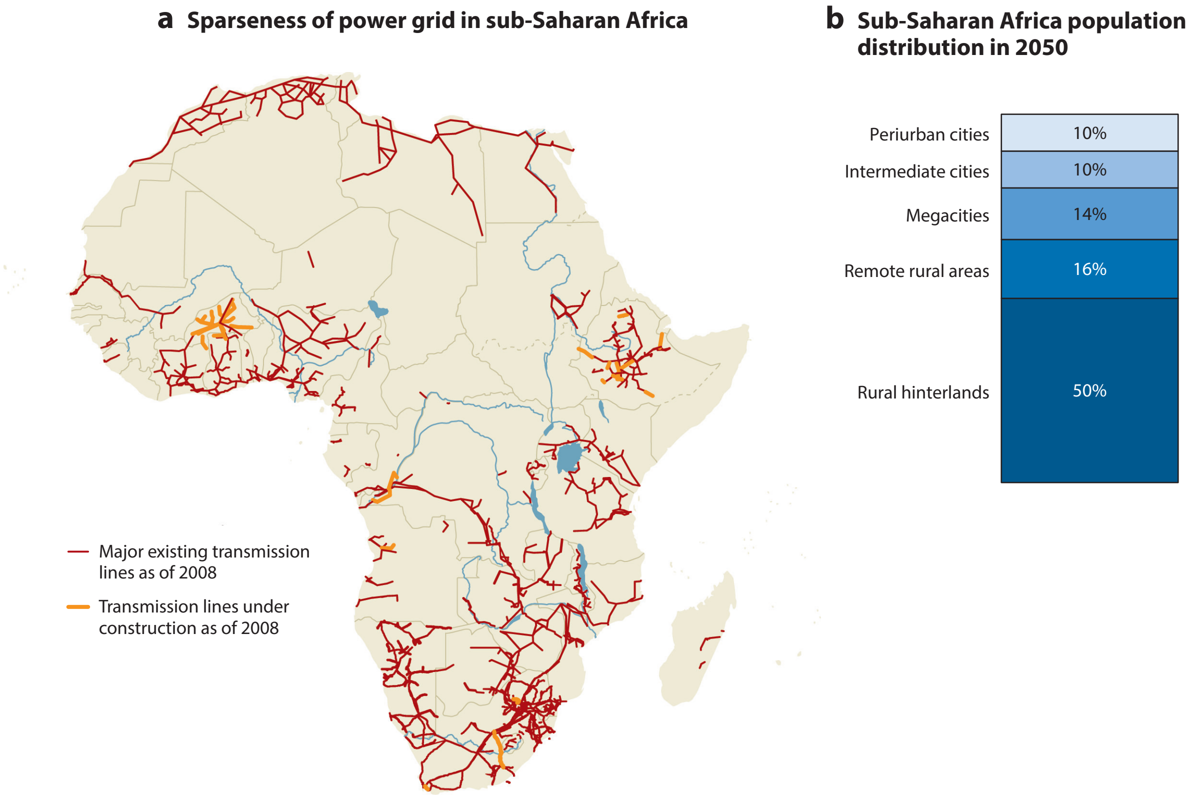

Figure 5

The importance of off-grid solutions in sub-Saharan Africa. (*a*) Only a very small portion of sub-Saharan Africa is currently connected to power grids. (*b*) With a majority of the population expected to remain rural even as far into the future as 2050, off-grid solutions hold the key to solving the electrification puzzle (8, 9).

250–300 inhabitants per square kilometer, the distance from the grid has been more than 5 km, and the expected demand was about 150 kWh per person per year (11). These considerations are highly contextual (11, 12).

4. SOLAR PHOTOVOLTAIC AND RECHARGEABLE BATTERIES: KEY TO DELIVERING THE PROMISE OF RENEWABLE ENERGY MINIGRIDS

The various sources of RE—wind, sunlight, biomass, geothermal, and hydropower—are present at varying intensities in different parts of the world. The optimal RE resource for each location largely depends on the quality and intensity of the available resource at the specific site, the cost of building and operating the system relative to local demand, and the availability of human capital. Several attributes of solar PV technologies make them well suited for adoption in developing rural regions. Solar PV is the most widely applicable technology because of its extremely flexible site location. Compared to other RE sources, solar PV systems are relatively easy to set up, operate, and maintain. They are also highly modular and configurable, and solar PV technologies have significant room for cost reductions. For more details, refer to Appendix A.

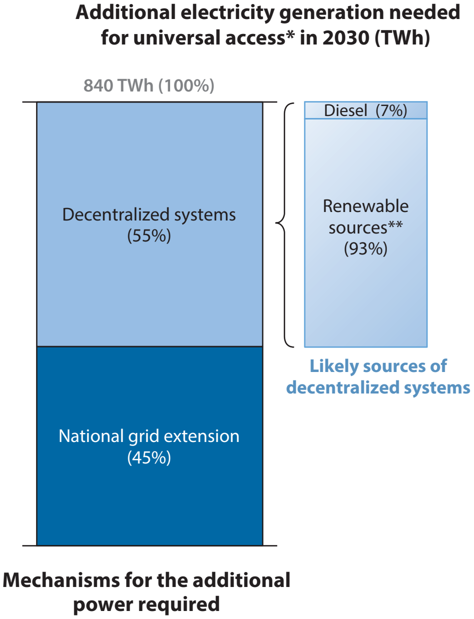

Figure 6

International Energy Agency (IEA) estimates of additional electricity generation required for universal electricity access by 2030. To achieve universal electrification by 2030, the IEA estimates that 55% of the additional power will need to be provided by decentralized systems, with almost all of it from renewable energy sources, with solar having the largest share (6). *IEA's scenario of universal access by 2030 is for a minimum annual consumption of 250 kWh of electricity in rural areas and 500 kWh in urban areas. **Renewable resources are solar, wind, and biomass with solar having the largest share. Abbreviation: TWh, terawatt hours.

To date, the relative simplicity of solar PV technology, combined with supportive policy incentives, such as feed-in tariffs and tax breaks, have made it one of the fastest growing RE technologies. Its global installed capacity, since 2000, has multiplied by a factor of 37, growing at an average of 44% per year, from 1.8 gigawatts in 2000 to 67.4 gigawatts at the end of 2011 (14). Although solar PV may not be the optimal choice in every context, it is generally useful for many reasons and is extensively applicable across the globe. **Table 1** summarizes the pros and cons of various RE technologies in the context of rural electrification in developing countries (11, 13, 14).

Rechargeable batteries are necessary to maintain a reliable supply of power in decentralized renewable minigrids. A reliable supply of electricity is important to support an adequate range of services for households and income-generating activities. Unlike fuel-based power, nonfuel RE resources are intermittent and unpredictable. Ensuring uninterrupted electricity—even as demand fluctuates—is a key challenge for power grids. In conventional power grids, pumped water is an inexpensive and efficient mechanism for bulk storage and accounts for 95% of global storage capacity (15). This is only practical for large-scale systems (100 MW or more). For RE minigrids, however, the power required from storage systems is in the range of 100 kilowatts to a few megawatts for up to 10 hours at a time. **Figure 7** shows the power output and discharge times for various storage technologies, highlighting the range that is most applicable for minigrids. This range includes flow batteries, sodium-sulfur batteries, lithium-ion batteries, and lead-acid batteries, which are all rechargeable.

Table 1 Suitability of renewable energy technologies for rural electrification in decentralized minigrids of developing countries[a]

RE technology	Diffuse (versus site specific)	Low volatility	Low O&M	Modular	Low up-front cost	Low levelized cost	Potential for improvement	Remarks
Solar PV	●	◕	●	●	◑	◔	◕	• Widely abundant • Intermittent but predictable • Negligible O&M cost and complexity • Highly modular • Relatively high up-front and replacement costs • Highest learning rate (20%) and deployment growth with room for significant improvements
Wind	◔	◑	◑	◔	◑	◔	◔	• Highly site specific • Relatively unpredictable; more complex forecasting and demand-side management needs • High O&M cost and complexity for turbines • Not modular; high economies of scale with significant losses of economy as scale reduces • Relatively high up-front cost • Moderate learning rate and room for improvements; turbine O&M costs likely to increase and limit cost reductions
Biomass	◑	◑	○	◑	◕	◕	◔	• Highly site specific with high transportation costs • Reliable supply of electricity with simple storage needs—but vulnerable to feedstock supply and price volatility • High O&M—feedstock collection, storage and pre-processing; thousands of moving parts (gasifiers); high need for labor and technical expertise; maintenance and environmental concerns (water and by-product disposal) • Ideal for fixed power generation with predictable demand
Hydro	◔	◑	◕	◔	◑	◔	○	• Low up-front costs • Mature technology with modest cost reduction potential • Highly site specific • Seasonal volatility due to fluctuation of river levels • Low O&M costs but needs technical expertise • Needs high utilization; advisable with grid connection • Moderate up-front costs but complex and long installation if built from scratch • Mature technology with modest cost reduction potential

● Most favorable ○ Least favorable

Among these, deep-cycle lead-acid batteries are the only commercially available technology, which can still add as much as 50% to the cost of a solar PV system, and have performance and maintenance issues to boot (11). Other technologies need further development to reach commercial viability for minigrids. Lithium-ion batteries widely used for mobile phones and laptop computers are still too expensive at a large scale. Sodium-sulfur and vanadium-redox flow batteries have been used effectively in midsize renewable systems but are still much more expensive than deep-cycle lead-acid batteries.

5. SIGNIFICANT AFFORDABILITY GAP FOR BASIC SERVICES IN DECENTRALIZED SOLAR MINIGRIDS

Even if electricity is made available through decentralized solar PV minigrids, which are promising because of their cost-effectiveness and scalability in rural developing regions, and even if appliances become affordable, the affordability gap between what poor people can afford to pay and the

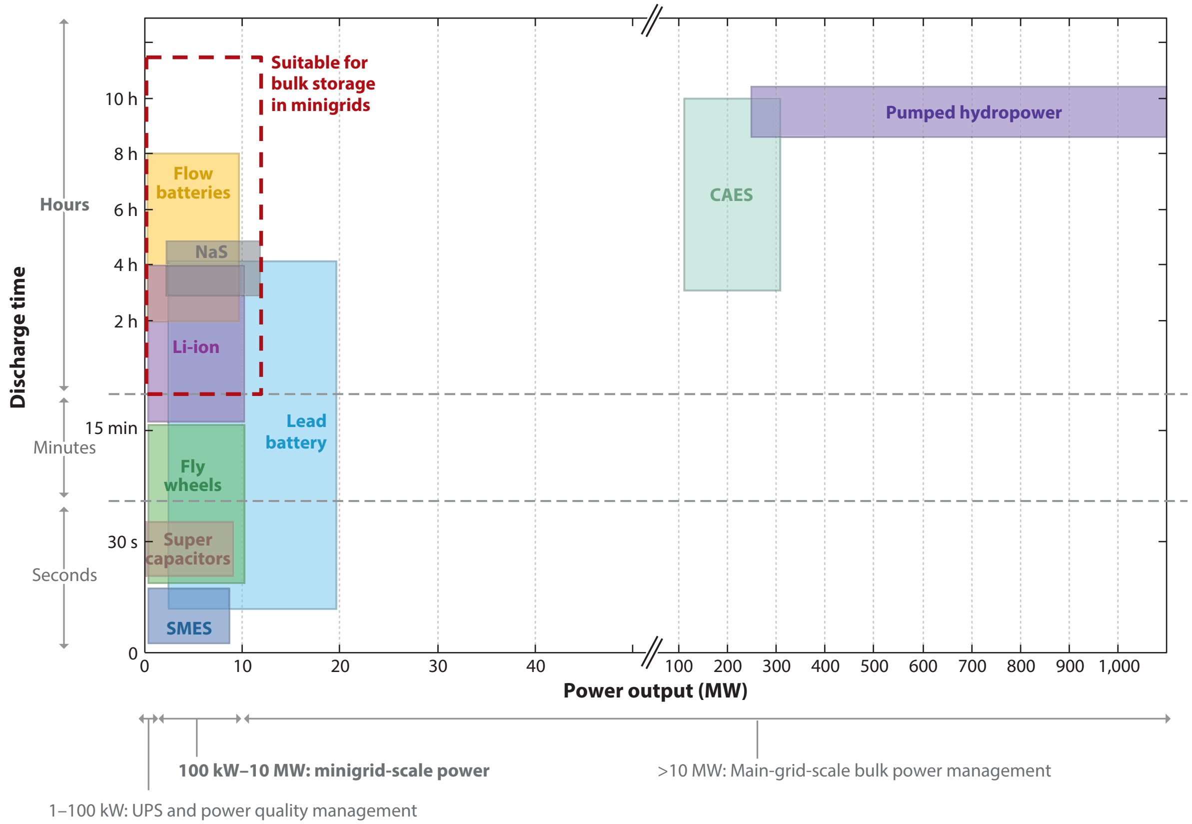

Figure 7

Performance of different storage technologies with regard to power output and discharge time. Technologies in the 100 kW–10 MW power output range and discharge time in the range of hours are suitable for bulk storage in decentralized renewable energy minigrids (15, 16). Of the various storage technologies shown here, compressed air energy storage (CAES) stores energy by compressing and storing air in large, low-cost natural buffers (e.g., caverns); fly wheels store electricity as mechanical energy, which is then converted back to electricity; and thermal energy storage, which is under demonstration for concentrating solar power (CSP) plants, stores excess solar heat and generates electricity at sunset. Supercapacitors store electricity as electrostatic energy. Superconducting magnetic electrical storage (SMES) stores electricity in magnetic fields. Some technologies, e.g., fly wheels and supercapacitors, do not have sufficiently long discharge times. Others, such as compressed air and pumped hydropower, can only work with very high capacities. Abbreviations: Li-ion, lithium-ion batteries; NaS, sodium-sulfur batteries; UPS, uninterruptible power supply.

cost of these services is too high in decentralized RE minigrids and seems intractable without deep subsidies. As explained in Section 2, with currently available appliances, a rural household would need to consume 80 kWh of electricity on average each month to meet its basic needs for electricity-powered services. But what can poor households afford?

Although there is variation by country and region, the poorest four billion people at the base of the pyramid who make less than $5 a day can be grouped into three segments based on their relative poverty: low income (earning $3–$5/day), subsistence ($1–$3/day), and extremely poor (less than $1/day). These households typically spend 10% of their income on energy of which roughly half is spent on cooking. This translates to monthly electricity budgets of $7.50, $4.50, and $1.50, respectively, for each of the three segments described above. Currently, the cost of

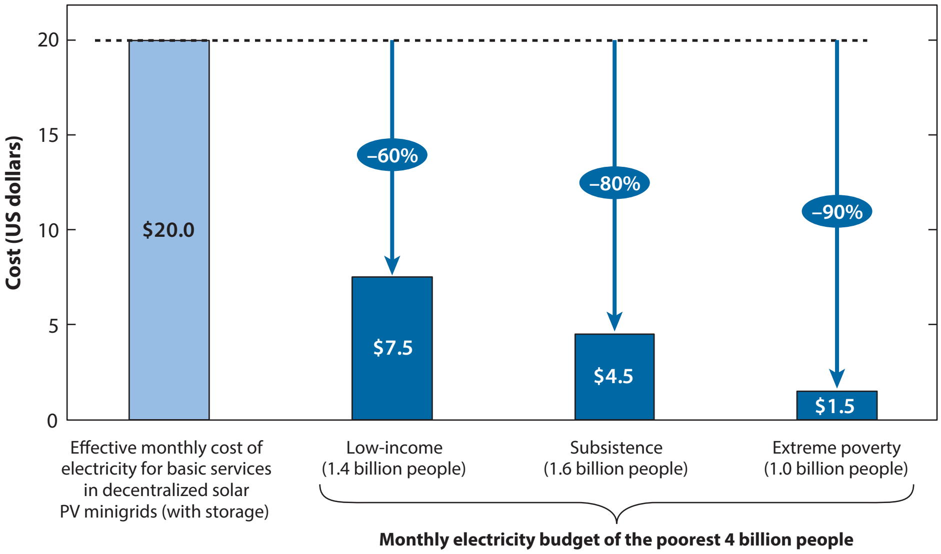

Figure 8

Effective cost of electricity for a basic portfolio of appliances versus what each lowest-income population segment can afford. The effective cost of basic services, which is driven by the cost of electricity and the efficiency of appliances, in decentralized solar photovoltaic minigrids with storage needs will have to fall sharply to match the electricity budgets of populations earning less than $5 per day (10, 17).

electricity in decentralized solar PV minigrids (with storage) is estimated at $0.24/kWh at this level; if a household needs to consume 80 kWh each month, the effective cost of basic services is $20 per month without subsidies (**Figure 8**). Therefore, it appears that the effective cost of electricity for a basic portfolio of appliances—$20 per month—is almost three times what populations living in the $3–$5/day income range can afford and significantly more than what populations living at subsistence and extreme levels of poverty can afford (10, 17).

For electricity to be affordable for the practical needs of human development, it must become less expensive, and appliances must become more efficient. In effect, the relationship between the required decrease in the cost of electricity and the increase in appliance efficiency represents an isoquant, which is shown in **Figure 1**. According to this analysis, the affordability gap is 60% for those making $3–5/day. This means that to close the affordability gap for those making $3–5/day, the cost of electricity needs to drop by 60%, or the efficiency of the corresponding portfolio of appliances needs to improve by 60%, or both need to happen for a similar combined effect. Improvements have to be much greater to bridge the affordability gap for those with lower incomes.

6. TECHNOLOGY BREAKTHROUGHS TO BRIDGE THE AFFORDABILITY GAP

Although decentralized RE minigrids, especially solar PV minigrids, have the potential to play a crucial role in providing universal access to electricity, a major setback is the affordability gap between the cost of electricity in these systems and what the typical user in poor rural markets can afford. This makes it hard to sustain them without deep subsidies and significantly undermines their business case. Not surprisingly, even though RE minigrids are expected to be the least-cost path to supply more than half of the additional power generation that is needed for universal

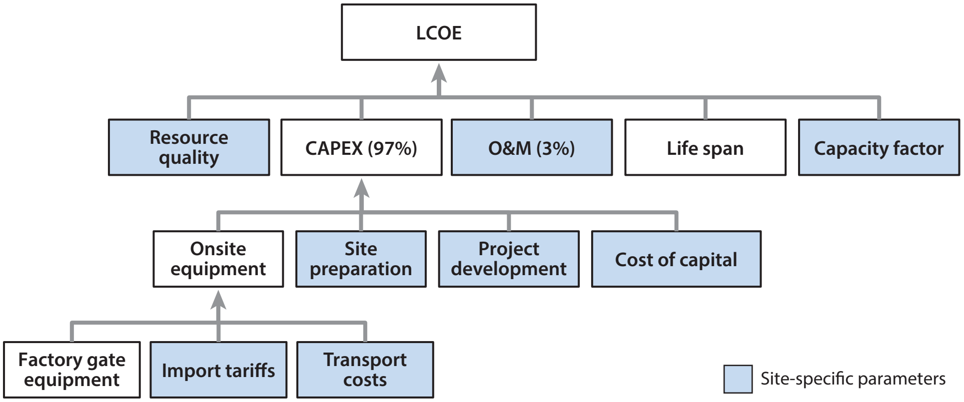

Figure 9

Factors affecting the levelized cost of electricity (LCOE) generation. LCOE generation for renewable technologies depends on numerous factors, many of which are site specific. Capital expenditure (CAPEX) (the up-front cost of procuring and setting up the equipment) is the key driver of LCOE for renewable energy minigrids. It includes soft costs, such as planning and labor. Numbers for CAPEX and operations and maintenance (O&M) in this figure are from International Finance Corporation benchmarks for electricity generation in solar photovoltaic minigrids with a 10% weighted average cost of capital (10).

access by 2030[2] (**Figure 6**), they are expected to face a 77% shortfall in funding (relative to the need for universal access through infrastructure expansion), even in an optimistic scenario based on current commitments (6). Shortfalls are expected to be highest in sub-Saharan Africa (6). Currently most rural minigrids are funded through grants and need heavy subsidies to achieve a return on investments. For example, projects in Kenya have been observed to need subsidies in the range of 20–70% to achieve a 10% internal rate of return (6, 11, 20). In-country financing prospects are not encouraging, as utilities in developing countries typically run on losses with high rates of nonpayment and are not well positioned to finance new projects. Governments lack a firm revenue base from taxes to subsidize projects serving low-income users, and private investors prefer grid extension projects for urban and peri-urban users owing to higher and less risky returns on investment.

Policy reforms and better market institutions are important for RE minigrids to succeed.[3] So financing mechanisms to improve access to affordable long-term capital, stronger regulations to ensure transparency in tariffs and reduce risk for private sector actors, and leveling the playing field for independent power providers (e.g., through feed-in-tariffs, power purchase agreements, and comparable subsidies for RE systems as are currently provided for fossil fuels) are crucial. At the same time, however, technology levers that can improve the economics of RE minigrids, or make appliances cheaper and much more efficient, can help bridge the affordability gap. This can make services affordable and attractive for end users, help RE minigrids be more self-sustaining and expand faster, and also improve quality by reducing the burden on minigrids (23).

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[2] According to the IEA, this was based on the lowest regional cost per MWh, taking into account relevant regional parameters.

[3] Minigrids face a range of barriers in terms of policies and gaps in market institutions. There are significant barriers to obtaining capital for private service providers. Average lending rates can be as high as 19% to 29% in Uganda, Mozambique, and Malawi, and 67% in the Democratic Republic of the Congo (11, 20). Domestic energy policies can also stack the odds against RE minigrids, making them less viable. Market distortions such as fossil-fuel subsidies make alternatives to RE minigrids, such as diesel generator sets, artificially less expensive. In 2010, African countries imported $18 billion worth of oil (more than the entire amount they received in foreign aid), with $50 billion of oil subsidies every year (21, 22).

The levelized cost of electricity (LCOE) in a system, the standard metric for the cost of generating electricity, is the ratio of the present value of lifetime system costs (discounted using the rate of cost of capital) to lifetime electricity generation. Drivers of LCOE are highly site specific (refer to **Figure 9**), but the key cost drivers are up-front costs, i.e., capital expenditures (CAPEX). Ongoing operations and maintenance (O&M) costs tend to be relatively low and fuel costs zero (except for biomass) (10, 19). The up-front costs include equipment for generation, storage, and grid management, as well as soft costs, such as site preparation and set up.

The following five breakthroughs can play a crucial role in improving the economics of RE minigrids and the efficiency of appliances. It is important to note that these breakthroughs are not specific technologies per se but rather the contours of the technology solutions that are needed.

6.1. Suite of Components That Significantly Reduce Up-Front Costs of Solar Photovoltaic Minigrids

The key drivers of CapEx for solar PV minigrids are PV modules and the balance-of-system costs, which include some equipment (e.g., racking structures and inverters) and soft costs, such as labor, site preparation, licensing fees, etc. (10, 14). Balance-of-system costs vary widely by geography, primarily because of soft costs; for example, residential PV systems in the United States were twice as expensive as those in Germany in 2012 (21).

The potential for cost reduction in solar PV is promising. First-generation PV technologies have a very high learning rate[4] of 20% (i.e., every time the global installed capacity doubles, prices fall by 20%). Second- and third-generation technologies are relatively new with scope for cost reductions over time. Specific opportunities include reduction in manufacturing costs (e.g., manufacturing copper indium gallium selenide, one of the leading thin-film technologies, accounts for a substantial proportion of the cost of the PV module), and discovery of new materials [emerging research and development (R&D) suggests the possibility of using magnesium chloride in the production of cadmium telluride solar cells, a lower-cost and environmentally safer alternative to cadmium chloride, which is both expensive and toxic] (24).

Efficiency gains in converting solar irradiance to electrical energy can also reduce effective costs. There are three levels of efficiency demonstrated by any technology. Commercial efficiency relates to versions that are manufactured and available at a commercial scale. Research efficiency is manifested in research conditions and is higher than commercial efficiency. Finally, theoretical efficiency as per the laws of science is even higher but likely not feasible in practical conditions. As a technology matures, the learning curve pushes commercial efficiency closer to research efficiency, and further R&D pushes research efficiency closer to theoretical limits. First-generation PV is a fairly mature technology, and its commercial efficiency is close to theoretical efficiency. But second-generation thin-film PV, which is ideal for minigrids, is fairly recent and has room for significant gains. The third-generation concentrated PV (CPV) technology also offers possibilities, with realized and theoretical efficiencies of 30% and 88%, respectively. Its installed capacity is expected to increase annually by double digits, growing by 750% between 2013 and 2020. It can also withstand the hot and dry climates typical to sub-Saharan Africa (25). Cost of materials, robustness, and lifetime of technologies also have a bearing on the effective cost per unit of electricity. So although CPV is highly efficient, its components are heavy and fragile, making transportation and

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[4] The learning curve or learning rate is defined as the reduction in unit costs each time the total installed capacity doubles. Hence, a learning rate of 20% for a particular technology means that unit costs have declined by 20% over time as installed capacity has doubled.

installation a challenge. Similarly third-generation technologies like dye-sensitized solar cells and organic PV have low efficiency and high volatility but very low materials cost.

Even though the economic outlook for PV components is hard to predict (because of the fluctuating cost of materials and the variability in market and policy environments), solar PV generation is expected to reach parity with conventional grid sources by 2020 in many markets (14, 26, 27). However, reaching parity will take much longer for decentralized rural minigrids because PV system cost reductions are not enough; these minigrids have to also contend with the very high cost of storage.

6.2. Significantly More Affordable and Energy Efficient Appliances for Households and Livelihoods

Improving the overall affordability of electric services entails improving the efficiency of relevant appliances. This will increase demand for electricity and also reduce the load on minigrids, improving the quality of supply and reducing the likelihood of power failures (28).

Some appliances, such as light bulbs, fans and TVs have achieved significant gains in efficiency. Although energy-efficient versions of these appliances are appearing in industrialized markets, they tend to cost more than the energy-intensive versions (even though in many cases the electricity savings eventually compensate for the higher prices) (29). Improving the efficiency of low-cost versions of appliances is critical to ensuring that electrification realizes its potential impact. There has been less progress on improving the efficiency of work-related appliances, e.g., irrigation pumps. Most of the pumps currently being used are very inefficient and end up costing farmers a lot of money over time (30, 31). In countries like India, diesel subsidies intended to ease the financial burden on farmers are leading to millions of tons of carbon emissions. Emerging alternatives, such as stand-alone solar pumps, are still too expensive (5, 31).

Owing to high opportunity costs, businesses have been reluctant to invest in the development of ultralow-cost appliances for low-income rural populations as well as for energy-efficient versions of these appliances. In emerging markets, urban middle- and lower middle-income users represent a profitable segment where profits are yet to be fully tapped out, and these also have better risk-reward profiles than rural low-income markets. To serve the latter with the right kind of energy-efficient appliances, businesses need to invest in R&D, build new manufacturing lines (for the new appliances), and create new distribution channels. These are all expensive and risky propositions with long payback periods.

Specific technical challenges and opportunities vary by type of appliance. For instance, fans with brushless direct-current motors can be twice as efficient as ones with conventional induction motors. More efficient blades lead to a twofold to fourfold increase in efficiency compared to the US Environmental Protection Agency's Energy Star requirements (32). Refrigerators can achieve high-efficiency gains simply with better insulation, and advances in new refrigerants can improve the efficiency of cooling engines (33). Superefficient TVs that draw a fraction of the power that currently available efficient TVs consume are also beginning to become commercially available (34). As mentioned above, these innovations are now focused on the environmental concerns of industrialized markets and are not being designed for the constraints of rural markets in Asia and sub-Saharan Africa.

The key deployment challenge is distribution, as is typical for rural markets, especially for products that require postsale technical support. The up-front cost of appliances is also a barrier but could potentially be addressed using financing schemes. User support services are crucial as most target customers are first-time users, and these products are significant investments for them.

6.3. Minigrid Scale Bulk Storage with Significantly Better Cost and Performance

Improved battery technologies are required to achieve a step change in the economics of rural electrification. Hybrid minigrids, i.e., which are supplemented by fuel-based systems, such as generator sets, may be able to do without storage (the generator set provides storage) but are complex, need more technical expertise, and are dirty. To sustain adequate use of appliances in decentralized RE minigrids, where sources are intermittent, and backup power from main grids is not an option, rechargeable batteries are essential for bulk storage. However, neither the cost nor the performance of existing technologies is adequate. Even lead-acid batteries, the least expensive commercially available option, can add more than 50% to a PV system cost and double the cost of electricity (11). Assessing the exact cost for storage is difficult because of variability in usage patterns and geographic parameters combined with the nascent nature of these technologies and the limited number of installations.

Rechargeable batteries need to perform along a range of parameters to be effective in decentralized systems: high depth of discharge (the ability to come as close to being fully discharged without adverse effects on battery life); memory effect (reduction in the battery's maximum capacity when it is repeatedly recharged without being fully discharged); round-trip efficiency (the ratio of energy recovered from a storage device to the amount of energy put into the device); modularity, which allows batteries to be scaled down without loss in performance; configurability of power output and capacity; operating needs, such as pumping, cooling, threshold operating temperatures, manual monitoring; and level of technical expertise required for installation and maintenance. Each family of rechargeable batteries has its unique advantages and challenges (**Table 2**). For more details, see Appendix B.

Beyond low cost (low enough to support usage by populations living on less than $5 a day), such a technology also needs to be robust, durable, compact, easy to transport, and easy to install. Operation and maintenance should require minimal technical expertise and limited additional infrastructure.

The rapid pace of innovation in storage technologies continues but mostly for portable batteries. The storage market is expected to increase 20-fold between 2010 and 2020, driven by the electric vehicle industry and more recently by large-scale deployment of RE farms in industrialized countries. This will likely benefit lithium-ion technology, which has a very high learning rate of 30% (12). Optimistic industry projections suggest a reduction of 50–75% in electric vehicle battery prices in 5–10 years and gains in energy density by 30–50% from alternative materials and solutions for both automotive and power applications (35). Because most of the emerging rechargeable battery technologies are still precommercial, it will likely take at least five years for the first wave of these to materialize.

6.4. Affordable and Easy-to-Use Grid Management Solutions for Decentralized Renewable Energy Minigrids

Effective grid management is crucial for operating grids reliably, efficiently, and profitably. Poor grid management reduces reliability and performance and also increases operational costs and losses from unrealized revenues for a variety of reasons, e.g., frequent breakdown in supply and quality of electricity due to poor coordination with storage, the high cost of manual metering and collection, tampering, payment defaults, under- or overutilized capacity, wasted power, and suboptimal pricing to name a few. Conversely, effective grid management can significantly improve the profitability, service quality, and risk profile of decentralized minigrids. This, in turn, can reduce the cost of capital, which is one of the biggest cost drivers.

Table 2 Advantages, challenges, and future outlook for each type of battery storage technology[a]

Battery type	Advantages	Challenges	Outlook
Lead acid	Least-cost commercial storage Reasonable performance Advanced deep-cycle versions optimized for solar cycles	Low energy density Low depth of discharge (ideally 50%) and never below 20% short life	Mature technology with limited potential for further improvements Most attractive in the near term due to acceptable performance at lowest cost
Li-ion	Better performance than lead acid Best performance for power and energy density, cycle efficiency, durability, and temperature range High discharge variability with no memory effect	Needs significant optimization for cost and capacity Needs significant optimization for safety and reliability	High potential for improvements driven by learning rates in other industries (e.g., power, electric cars) Likely best suited for modular, small-scale applications
Sodium-sulfur	Least cost in precommercial phase Scales up well; can sustain MW-size applications Very cheap, abundant materials	Need operating temperature of 300°C Bulky and therefore relatively harder to set up in resource-constrained settings	High potential for cost reduction Smaller batteries are emerging Likely choice for village- or larger-scale minigrids, i.e., full-fledged rural electrification
Flow	Easily configurable with dynamic power output and capacity High discharge variability with no memory effect Very long life with low maintenance	Low energy density Electrolytes need to be pumped to storage tanks Needs a cooling system to absorb heat for charging and discharging	High potential for cost reduction Likely choice for village- or larger-scale minigrids, i.e., full-fledged electrification

[a] Comparative assessment of different rechargeable battery technologies that are suitable for bulk storage services in minigrids (11, 15, 16).

An effective grid management system performs functions across generation, distribution, and consumption of electricity. For generation, it should enable monitoring and troubleshooting operations in real time; collecting and analyzing system data; optimizing and synchronizing multiple power sources in hybrid systems; managing storage to smooth intermittence of RE supply; and regulating voltage, frequency, and load levels (i.e., matching demand with supply). For distribution, it should minimize technical and nontechnical losses from theft and measurement errors, which can exceed 30% in some African countries (11). For consumption, it should synchronize demand and supply (e.g., current limiters, power management administrators, and smart meters), support billing and fee collection (e.g., prepayment devices, mobile banking systems), and prevent fraud (11). Weak grid management can lead to a vicious cycle of poor tariff collection and cost recovery, high O&M costs, customer overuse, and degradation in the quality of services (8).

Low-cost and energy-efficient smart meters are beginning to be commercialized in low-income markets, making it possible to measure consumption and demand for electricity in small, low-voltage rural minigrids. Similarly, inexpensive prepayment meters, which make it significantly easier to manage fraud and fee collection, are being deployed in targeted markets, with sales of them becoming increasingly competitive (e.g., there are more than 20 manufacturers in India). In addition, remote payment and monitoring technologies are also beginning to appear on the market with the expansion of mobile networks and mobile money systems. Pay-as-you-go systems are also increasingly being used for pre-electrification devices, such as solar lanterns, and in demonstration minigrid projects (11). However, further improvements are needed before they become affordable and simple enough to be deployed at scale in rural areas where skilled workers may not be available. Meters need to become significantly less expensive; grid management systems need to become simpler and easier to integrate with the rest of the grid, as well as to become more robust to deal with environmental factors, e.g., low voltage and voltage fluctuations. Forecasting systems, especially for wind, need to be improved for emerging markets. Grid management remains a multifaceted problem, requiring several devices to be installed at the point of generation, at the various points of consumption, and at points in between. This involves complex integration across the grid's control system, forecasting tools, sensors, and payment technologies. One encouraging trend is the rapid evolution of the Internet of Things (IoT). With this paradigm, a range of devices such as probes, sensors, actuators, transmitters, receivers, etc., can be attached to devices that are part of the minigrid, and generate and wirelessly transmit real-time operational data that can be used by grid management applications running remotely on laptops, cell phones and other devices (36).

6.5. A Utility in a Box to Make It Simpler, Cheaper, and Faster to Set Up and Operate Renewable Energy Minigrids

Making RE minigrids inexpensive and easy to install will significantly help to scale them up. Currently, it is a time-consuming, unpredictable, and challenging process, involving a highly fragmented supply chain. Many components need to be procured, transported, and integrated in hard-to-reach places without supporting infrastructure or adequate skilled labor. A utility in a box, which is easy for technicians (with some training) to install in a few days and also easy to maintain on an ongoing basis, would significantly improve the economics of rural minigrids. Specifically, this would reduce the balance-of-system costs, which constitute a major portion of minigrid installation CAPEX. It would also minimize the need for technical expertise for operations by standardizing and simplifying operations and maintenance (which is another major hurdle to the proliferation of minigrids).

Such a utility in a box should include all the key components of a decentralized RE minigrid for generation, storage, and grid management. Standardization and self-help tools for installation, O&M, and troubleshooting would be important. Similarly, modularity and configurability to meet the specific power demands of a particular installation would be crucial to ensure adequate capacity and maximum capacity utilization. In principle, an early version of such a technology can be developed relatively quickly because it involves design, integration, and standardization of existing tools much more than upstream R&D. An early version of such a system can be market ready in two to five years. Over time, more sophisticated components (e.g., for improved grid management) can be added.

APPENDIX A: SOLAR PHOTOVOLTAICS

Solar PV electronic devices are made with semiconducting materials (e.g., silicon, germanium) that generate electricity from sunlight, which provides the electrons with the energy needed to leave their bonds and cross the junction between the two materials. PV cells work with both direct and diffused light and hence generate electricity even during cloudy days. Electricity production is roughly proportional to the solar irradiance. The modern form of the solar cell was invented in 1954 at Bell Telephone Laboratories in the United States, and research has continued since then to improve their efficiency and performance. There have been three generations of solar PV technologies. The first generation (wafer-based crystalline silicon) is mature and commercially available. The second generation is made of thin-film modules that use a fraction of the material (compared to the first generation) by depositing solar cells on thin substrates, for example, glass, metal, and flexible polymers. Thin-film PV tends to have lower efficiency than crystalline silicon, but this is offset by low manufacturing and materials cost. Second-generation technologies are still relatively new and do not yet have significant installed capacity. However, they do have a strong potential for further cost reductions. Owing to cost versus efficiency trade-offs, first-generation PV is better for dedicated home systems, whereas thin films are suited for minigrids and utility-scale systems.

There are also some emerging third-generation PV technologies. CPV uses optical devices to concentrate sunlight on solar cells and uses a tracking system. Because the efficiency of silicon solar cells falls with higher temperatures, CPV uses semiconductors with very high conversion efficiencies (e.g., gallium arsenide). Tracking systems and optical components increase cost and complexity, as do cooling systems in some designs and multijunction solar cells. This nascent technology appears to have significant potential for gains from the learning curve. Dye-sensitized solar cells, another third-generation technology, use photoelectrochemical solar cells, which harvest photons from sunlight mimicking photosynthesis. Dye-sensitized solar cell current has low efficiency and needs new dyes that can absorb broader spectral ranges. Another issue that needs to be addressed is performance degradation caused by UV light. Lastly, organic PV has solar cells composed of organic or polymer materials. Organic PV uses inexpensive, abundant, and nontoxic materials but needs to become much more efficient and stable (14).

The following attributes of solar PV technologies make them well suited for adoption in developing rural regions:

- Solar PV is the most widely applicable technology with extremely flexible site location. Of the various RE sources, solar power is the most widely available resource. It can be generated in most of Asia and Africa (except in equatorial regions and the Guinea Gulf area owing to extreme rains and cloudiness) (11). By comparison, hydroelectric power needs to be close to a perennial water current with sufficient strength, and it is usually dependent on seasonal factors at smaller scales. Similarly, wind power sources need to be located near shores of water bodies or at higher altitudes where winds blow more consistently (11, 12). Biomass digesters and gasifiers need to be close to feedstock production to avoid volatility in price and supply and to minimize the cost of transporting the bulky raw material (11). Biomass power generators are also best suited for locations with anchor clients, which have sizeable but fixed and predictable power needs (11). Because wind and hydropower systems are site specific, their distribution costs are highly variable. Solar power, by contrast, can be located very close to or even in the midst of settlements, significantly reducing distribution costs.
- Compared to other sources, solar PV systems are relatively easy to set up, operate, and maintain with less need for monitoring or technical expertise. Lead times for construction can be high for microhydropower. Transportation can drive up the cost of installing equipment for wind turbines, hydroelectric power, and feedstock for biomass. O&M of wind systems need significant technical expertise. Biomass also demands high O&M because of lack of uniformity of feedstock (particularly for digesters) and complex operation with thousands of mechanical parts requiring significant labor and technical expertise (for gasifiers). These practical considerations are needed for technology to scale up in underdeveloped rural settings, where the lack of skilled workers and supporting infrastructure can limit adoption of technologies that otherwise work well in other environments.
- Solar PV systems are highly modular, and their configuration can be changed. Rural markets are typically small and vary significantly in size. Because these markets are nascent, demand is hard to estimate at the outset, and systems may need to be scaled up or down with time. This is relatively easy to do with solar PV without economic losses. Biomass, however, is best for limited and predictable demand. Wind is not very modular, with unit costs of smaller-scale applications significantly higher than large-scale ones (12).

- Solar PV has significant room for cost reductions. Both microhydropower and biomass technologies are fairly mature with less potential for additional cost reductions. For the latter, opportunities are limited to reducing fuel handling and preparation costs. The learning rate for solar PV is 20%, which is the highest learning among RE technologies. Wind, by comparison, has a learning rate of 7% (13). The global growth of solar PV and its learning rate resulted in massive cost reductions, which are expected to continue. This increase is propelled by concerted R&D efforts in industrialized markets, such as the US Department of Energy's SunShot Initiative, whose target is to reduce the total installed cost of solar energy systems to $.06 per kilowatt-hour by 2020 (37).

APPENDIX B: STORAGE TECHNOLOGIES

The key groups of bulk storage technologies suited for decentralized minigrids and their advantages and limitations are summarized below:

1. Lead-acid batteries are the least expensive commercially available rechargeable batteries, but these have low energy density and a short life for power applications. They also have low depth of discharge, which reduces their life. Advanced deep-cycle lead-acid batteries designed to address these challenges are still emerging. Disposal of lead-acid batteries has environmental and health risks that require careful handling and regulation.
2. Lithium-ion batteries have very high-power density, modularity, no memory effect, and high depth of discharge. However, they are expensive and have limited capacity, as well as safety concerns about abnormal heating from overcharging and short circuits. Currently, they are best suited for small-scale applications (e.g., mobile phones) and require significant improvements to achieve reduced cost, higher safety, and more capacity.
3. Sodium-sulfur batteries are made with low-cost, abundantly available materials and offer significant potential for further cost reduction. Hence, they are very well suited for large-scale applications in minigrids. However, they are very bulky (weighing several tons) and have high operating temperatures (300°C). Commercial versions are more expensive than deep-cycle lead-acid batteries. Sodium-sulfur batteries are well suited for storage in megawatt-size, utility-scale minigrids (village scale or larger), and they are typically available in multiples of 1 MW (with installations in the 2–10-MW range). As a relatively new technology with low production capacity, there is significant potential for cost reductions. Production of smaller batteries is in its early stages (16).
4. Flow batteries are highly configurable, with a very high depth of discharge and a long life, but need pumping and cooling. Configuring the battery is extremely simple; both the cell stack size and the electrolyte volume can be changed easily to modify power output. They can be fully discharged without any damage, thereby significantly improving operational range, increasing longevity, and minimizing the need for maintenance. Vanadium-redox-battery flow batteries can last longer than 100 years according to some estimates, although cell stacks need to be replaced every 8–10 years. Vanadium-redox batteries are still precommercial and are currently being used in projects ranging from a few kilowatts to a few megawatts (15, 38).

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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