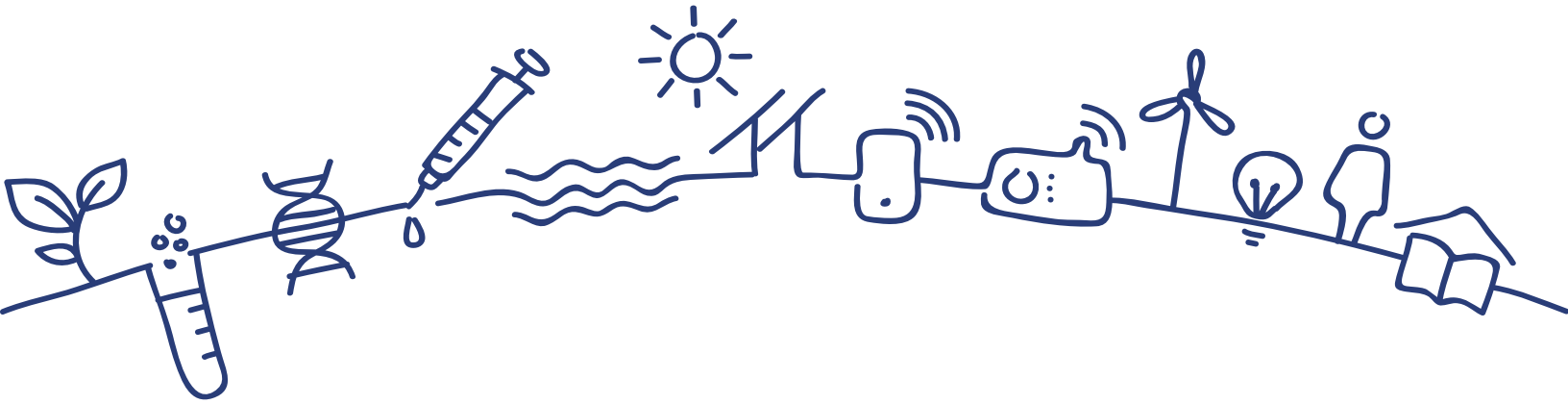
50 BREAKTHROUGHS

Critical scientific and technological advances needed for sustainable global development



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NOTES ON METHODOLOGY AND LAYOUT

Traditionally studies focused on future-facing topics have relied on surveys of experts, using approaches like the Delphi Method[1], a structured iterative process of interviews and reviews. Early in our study, we discovered two challenges with such a process. First, the absence of a broad, credible evidence base about what works has led to entrenched opinions. Second, such an approach would likely have led to a laundry list of 50 *technologies* or *devices*, rather than to a robust problem analysis which logically leads to the *breakthroughs* required—agnostic to specific technologies.

Hence, this study employs a six-part approach to reach its conclusions:

1. Describe and analyze the 5-10 most important contextual facts about the specific problem.
2. Identify the key challenges, which have kept effective solutions from becoming a reality.
3. Identify, based on input from recognized topic-specific experts, the most promising interventions to overcome those hurdles.
4. Determine the dependence of each of these interventions on: policy reforms, infrastructure development, education and human capital development, behavior change, access to user finance, an innovative business model, and finally, a new breakthrough technology.
5. We focus on interventions with a significant dependence on a breakthrough technology, and identify the important parameters the technology needs to fulfill. Based on the underlying technical challenges, we then estimate the time-to-market by when these breakthroughs may become deployable products.
6. Finally, we identify the most important hurdles to sustainable, large-scale deployment, based on many of the factors listed above (e.g., policy reforms, etc.), and score the difficulty of deployment on a 5-point scale: simple, feasible, complex, challenging, and extremely challenging. The purpose of this final analysis is to encourage technologists and funders to understand these challenges before making major investments in their work.

Each chapter is divided into three parts: Core Facts and Analysis, Key Challenges, and Scientific and Technological Breakthroughs. The 5-point scale and the complexity we ascribe to each of the factors and constraints relevant to the deployment of a particular technology are illustrated in **Table A**. The lowest score (feasible) is reserved for cases when the particular constraint is not relevant to deployment; the constraint is given the highest score (extremely challenging) if it can be a serious bottleneck to deployment. The aggregate score reflects the overall degree of difficulty, considering the collective weight of the individual constraints. The methodology is clearly subjective. **Exhibit A** is a sample of how we have illustrated the difficulty of deployment for each breakthrough across the study. This particular sample highlights a CHALLENGING breakthrough.

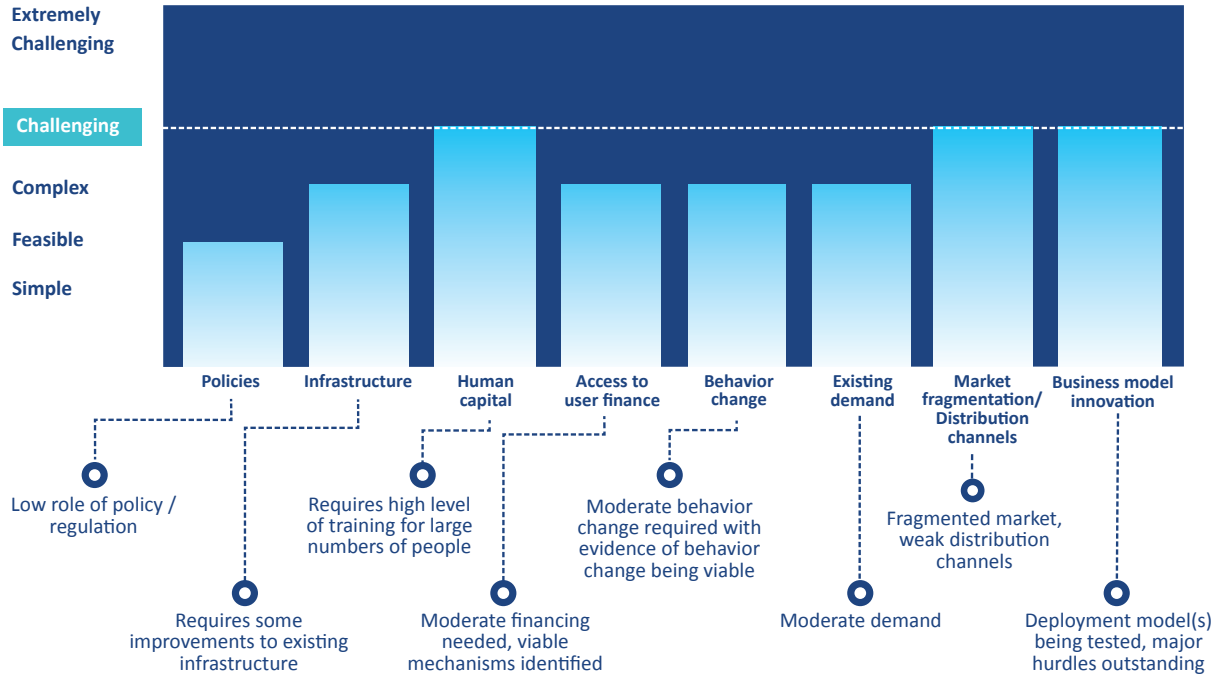
[1] A structured communication technique, originally developed as a systematic, interactive forecasting method which relies on a panel of experts who anonymously reply to questionnaires and subsequently receive feedback in the form of a statistical representation of the 'group response', after which the process repeats itself. The Delphi method is based on the assumption that group judgments are more valid than individual judgments. It was originally developed by the RAND Corporation in the 1950's to forecast the impact of technology on warfare.

Table A

	Simple	Feasible	Complex	Challenging	Extremely Challenging
Policies	Minimal role of policy/regulation	Low role of policy/regulation	Regulated market with supportive policies	Highly regulated market with policy changes required	Highly regulated and controversial changes required
Infrastructure	Minimal need for infrastructure	Dependent on existing infrastructure	Requires some improvements to existing infrastructure	Requires moderate improvements to infrastructure	Requires major improvements to infrastructure
Human capital	Minimal need for human capital development	Low-moderate need for human capital development	Moderate need to train a limited number of people	Requires high level of training for large numbers of people	Requires national scale training programs
Access to user finance	Financing not required	Limited financing required	Moderate financing needed, viable mechanisms available	Significant financing required, limited mechanisms available	Significant financing required, no identified mechanism
Behavior change	No behavior change required	Minimal behavior change required	Moderate behavior change required with evidence of behavior change being viable	Major behavior change required, potentially on daily basis	Significant behavior change needed on daily basis, changes contrary to cultural norms
Existing demand	Strong existing demand	Existing demand	Moderate demand	Low demand, needs to be built	Extremely low demand or not a perceived need
Market fragmentation/ Distribution channels	Highly concentrated market or well defined channels	Fairly concentrated market and/or well defined channels	Moderate fragmentation of customers, under-developed channels	Fragmented market, weak distribution channels	Highly fragmented, challenging to reach customers
Business model innovation	Clear deployment models existing at scale	Deployment model in process of scaling	Deployment model(s) being tested	Deployment model(s) being tested, major hurdles outstanding	No identified deployment model, major hurdles identified

Exhibit A

Breakthrough – Difficulty of deployment



ACCESS TO ELECTRICITY [1, 2]

USAID

Access to electricity is fundamental to every aspect of human development. More than 1 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. Even as efforts to improve electrification continue, it is important to recognize that it is not electricity itself that changes lives, but rather, what people are able to do with electricity. Recent years have seen an increase in proliferation of 'pre-electrification' appliances like solar-powered lights and mobile phone chargers. While this has some benefits, low income households need a number of other appliances such as refrigerators, televisions (or other ICT devices), fans, and tools for improving workplace productivity to improve their overall quality of life. In that context, there are 2 major problems: appliances currently on the market are too expensive for low income populations, and even if they were affordable, the electricity they consume costs much more than the 'energy budget' of these users.

While much of South Asia will have electricity through connection to the existing power grids, it is likely that large parts of rural Africa and some parts of rural South Asia will need decentralized mini-grids to have access to electricity. The most cost-effective (and environmentally sustainable) energy sources for rural mini-grids will be renewables like solar, wind and micro-hydro. Of these, solar power

[1] While this section focuses on electricity, we recognize that other forms of energy (e.g., for cooking, transport, operation of motors) are also important to development.

[2] Please note that this section focuses on household and small industry. The electricity needs of heavy industry may not be met by the solutions suggested in this analysis.

is the most widely available renewable energy resource. Currently, solar photovoltaic (PV) mini-grids are difficult and expensive to install and operate (relative to the resources available in low income rural populations). Combined with weak market economics and misaligned policies, these challenges have made mini-grids commercially unsustainable. While supportive policies and financing mechanisms will need to be a core part of any solution, 5 technological breakthroughs can improve the lives of low income rural people across South Asia and sub-Saharan Africa.

- Suite of solar photovoltaic mini-grid components, to significantly reduce upfront costs
- Appliances for household use (e.g., TV, refrigerator) and income generation (e.g., irrigation pump), which are significantly more affordable and energy efficient than those on the market today
- New bulk storage technologies for decentralized mini-grids, which provide improved performance at a significantly lower cost
- Affordable and easy-to-use grid management solutions for decentralized renewable energy rural mini-grids
- A ‘utility-in-a-box’ for making it simpler, cheaper and faster to set up and operate renewable energy mini-grids

Electricity is the most versatile and efficient way of consuming energy. It can be easily converted to multiple forms of energy for a variety of needs—heat, light, mechanical energy. It is relatively non-polluting and loss free at the point of use, and its use can be calibrated easily, i.e. with the flick of a switch. It can be generated centrally, and distributed conveniently and efficiently across long distances, making it extremely economical (Theraja & Theraja, 2013) (IEC, 2014). This makes it ideal for powering appliances for activities and services that are central to human wellbeing, comfort and productivity.

CORE FACTS AND ANALYSIS

Electricity is vital for human development, but low income countries and populations do not have enough access to it. The lack of access to electricity forms a vicious cycle with development. On one hand, low income countries are not able to invest in the infrastructure to generate and distribute electricity to its citizens (especially in remote areas); on the other, lack of access to electricity is a fundamental barrier to human development. These barriers exist in every fundamental aspect of development.

Health

Without power health facilities cannot operate medical devices, refrigerate temperature-sensitive pharmaceuticals, or even have lighting to provide care at night. An estimated 1 billion people use health facilities which are not electrified (Practical Action, 2014).

Education

Children in low income families cannot get a proper education because their schools cannot operate computers, access the Internet, or operate laboratories for them to learn in (even if they had the computers and other equipment). Worse yet, many students do not have access to appropriate lighting at home to be able to study after sunset.

Food security, agriculture and economic development

Smallholder farmers and agribusinesses cannot operate powered equipment, to grow, preserve and process adequate food for their families, communities and countries. Similarly, businesses in other sectors cannot operate even the equipment needed for offices and factories.

Gender equity

Women are disproportionately affected by the lack of electricity. The lack of appliances leads to significantly more manual work for women. In the absence of electricity for indoor lighting (combined with other forms of clean energy for cooking), women suffer more from indoor air pollution. When outside their homes, they are also exposed to a greater risk of violence due to the absence of outdoor lighting. Similarly, they are at a greater disadvantage compared with men when it comes to operating manual equipment.

Exhibit 1 shows the effect of electrification on development by mapping the UN human development index (HDI) against the rates of electrification (defined by the International Energy Agency as the annual consumption of at least 250 kilowatt-hours (kWh)[3] of electricity in rural areas and 500 kWh in urban areas, for a household of 5), for a representative sample of countries (IEA, 2013) (UNDP, 2014).

The Human Development Index of countries vs. percent of population with electricity

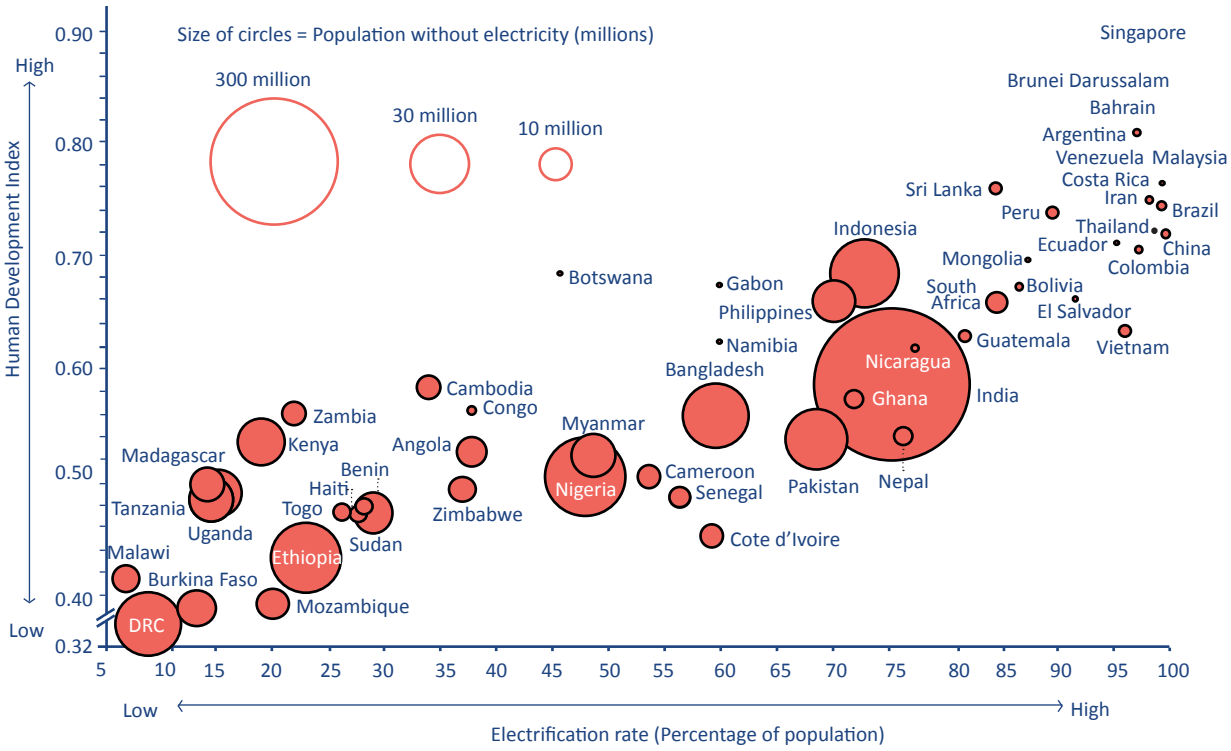


Exhibit 1: The lack of access to electricity forms a vicious cycle with underdevelopment: less developed countries do not have the means to invest in electrification, and the low levels of electrification limits development. This chart shows the electrification rate as the number of connections. The International Energy Agency (IEA) 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 5. Please note that some countries (concentrated in the top right corner of the graph) have negligible populations without access to electricity.

1 Low income populations pay significantly more for energy than their wealthier counterparts, on a per-output-unit basis

One unfortunate irony is that people who do not have access to electricity actually have to pay a much higher price per unit of energy—compared with wealthier segments of the population—when they use alternatives to electricity such as kerosene. As **Exhibit 2** shows, for a given amount of light, the cost of kerosene is 325 times that of an incandescent bulb, and 1,625 times that of a compact fluorescent lamp. Rural households in developing countries spend as much as $10 per month on lighting using candles, kerosene and dry-cell batteries. For households with electricity access in industrialized countries that amount of money can provide 24 bright light sources (Mills, 2002) (UNDP, 2005).

[3] As a frame of reference, 250 kWh can power a floor fan, a mobile telephone and two compact fluorescent light bulbs for about 5 hours per day, over the course of a year (IEA, 2013).

Cost of energy for a given amount of light: kerosene vs. incandescent bulb vs. compact fluorescent light

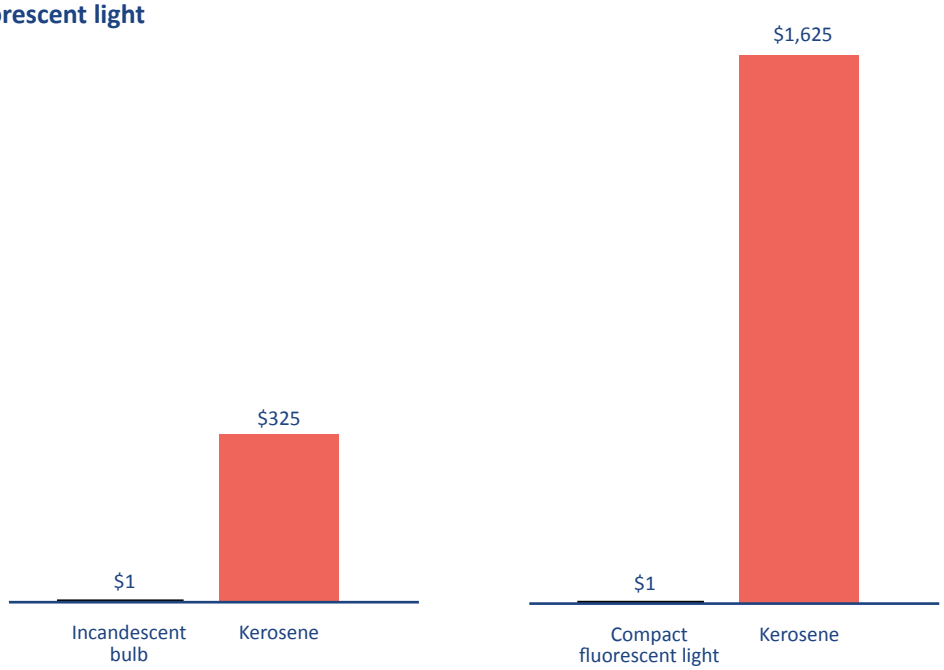


Exhibit 2: Energy sources available to low income populations often cost much more—on a per-output-unit basis—than those available to higher income populations. For example, to get a given amount of light output, kerosene costs 325 times the cost of lighting an incandescent bulb with electricity, and 1,625 times that for a compact fluorescent light.

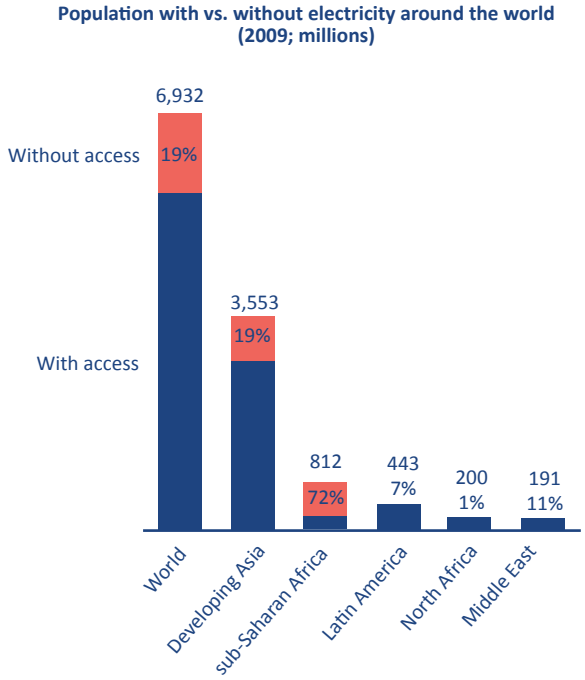
2 More than 1 billion people lack electricity, mostly in rural South Asia and sub-Saharan Africa; the problem will persist in the foreseeable future, and will likely worsen in sub-Saharan Africa

Developing regions suffer from an endemic lack of electricity. Currently, 1.3 billion people, mostly in rural sub-Saharan Africa and South Asia, lack access (based on the IEA definition of electrification). This represents one-fifth of the world's population (IEA, 2011). As **Exhibit 3** shows, Developing Asia has the largest number of people without electrification (675 million out of a regional population of 3.6 billion), while 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. Among the countries in Developing Asia,[4] India has the largest share (42%) of people without electricity.

Despite progress in other aspects of development, the population without access to electricity in sub-Saharan Africa is expected to increase from an estimated 586 million in 2009, to a projected 645 million by 2030. Note that this projection is under the IEA's 'optimistic scenario', in which all countries fulfill their current commitments to policy and investments for expanding electricity infrastructure. In this scenario, the population with electricity in Developing Asia is expected to decrease from 676 million in 2009 to 375 million in 2030. In aggregate, the IEA's optimistic scenario projects that there will still be 1 billion people without access to electricity in 2030 (**Exhibit 4**) (IEA, 2014). Most of those without access will still be in rural areas.

[4] 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 countries from Southeast Asia), while others isolate the data for South Asia. Hence, some exhibits show the data for Developing Asia, while others show it for South Asia.

Distribution of the population with access to electricity



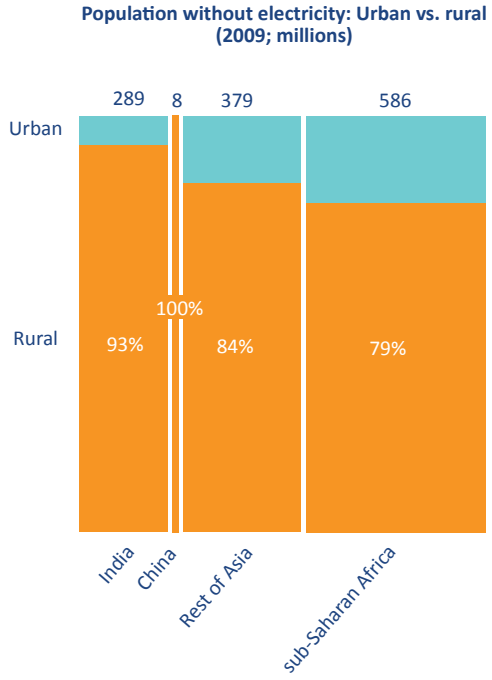


Exhibit 3: Currently, the largest populations without access to electricity are in Developing Asia and sub-Saharan Africa, and are concentrated in rural areas.

Expected change in the number of people without access under the IEA's optimistic scenario

(2009-2030; millions)

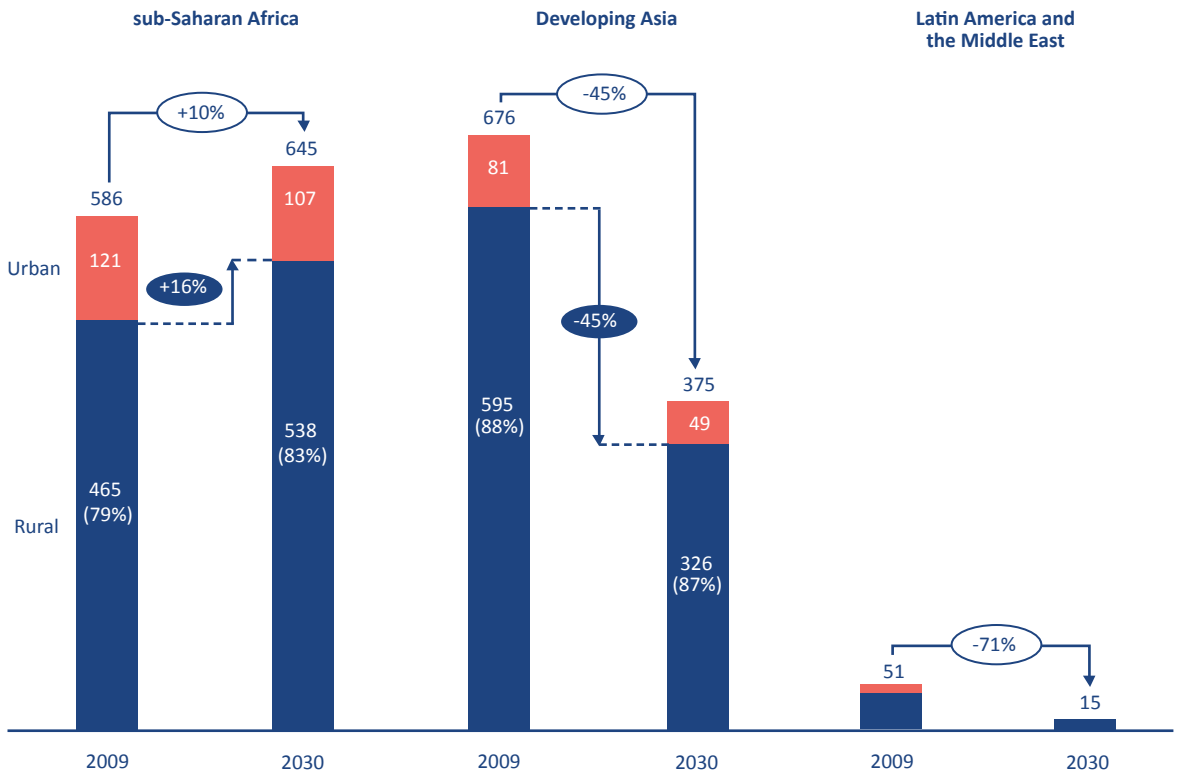


Exhibit 4: The problem of lack of access to electricity in sub-Saharan Africa is expected to get worse by 2030, even in the IEA's optimistic scenario in which countries fulfill their current commitments.

3 Electricity does not, by itself, change lives; it is what people do with it that matters. Hence, beyond access to electricity, low cost, energy efficient appliances are needed

'Access' to electricity has been defined differently in different contexts. In some it has meant having an electricity connection, while in others it has meant reliable supply and being able to consume a minimum quantity of electricity. However to be meaningful for human development, access to electricity must be measured by the quality and range of usage of electricity via appliances to improve quality of life and workplace productivity. In other words, merely having an electrical connection is not helpful if the consumer does not have the necessary appliances, and if those appliances cannot be powered by the electricity available. In addition, having access to just enough electricity to power light bulbs, a fan and a mobile phone is unlikely to lead to substantive improvements in quality of life or economic opportunity. As discussed later, an appropriate suite of energy efficient appliances should also include a refrigerator (to preserve high-nutrition perishable food), an ICT device (TV and/or computer), and an appliance to improve economic productivity (e.g., an irrigation pump). There is increasing

recognition that electricity access should be defined in terms of the level of amenities and services it enables (Sustainable Energy for All, 2013).

4 Mini-grids offer considerable economic advantages compared with both grid extension and standalone systems, for serving remote rural populations

Electricity is typically delivered using a very large centralized system called the power grid. It is 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 delivered (almost instantly) to users across large geographical areas. Transmission lines carry electricity over long distances using high-voltage current to reduce transmission losses. When the transmission lines reach clusters of users, the voltage is stepped down and distribution lines carry electricity to end users. Transmission of this nature is expensive due to (among other reasons) the cost of infrastructure, and comprises roughly 40% of the total electricity bill of a power system (IEA, 2010). In many cases (depending on population density and income levels, for instance) it is cost-effective to extend the grid within a 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 grid power. However, the poorer, sparser and smaller a community is, the smaller the grid perimeter. Such a community must then be close to the grid, to make grid extension economically feasible without subsidies. This is usually the dynamic at play with low income rural populations in developing countries. Two-thirds of the world's poor live in villages which are typically too far from the grid to be feasibly reached via grid extension; 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 (**Exhibit 5**). In such cases, decentralized mini-grids—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 (Schnitzer, et al., 2014) (Practical Action, 2012). According to recent estimates by the IFC, the average per-connection capital cost for mini-grids starts at $50, whereas extending the grid to a sufficiently adjacent community can start at $500 (IFC, 2012).

Mini-grids are also more advantageous than standalone small (e.g., home-based) systems, due to economies of scale. Standalone small systems are easier to deploy especially where population density is low. They have been promoted by donors and governments, and have scaled up successfully when supported by appropriate financing models (Grameen Shakti, 2014). However standalone systems support limited service levels, and it is hard for them to support multiple appliances simultaneously, especially ones with high power draw such as refrigerators. As such they are more appropriate in the form of limited service, rechargeable, pre-electrification systems supporting individual appliances (IED, 2013). In comparison, mini-grids can support larger loads and higher load variance. They also have lower unit costs compared to home systems, by virtue of economies of scale. They can scale up as local economic activity, and as an outcome local demand, grows. If operated successfully, they can scale up and become attractive for interconnection with the main grid (IFC, 2012). Hence, while continued investment towards improving standalone systems will be valuable in the next few years, mini-grids are ideal for full-fledged electrification and long-term development.

A number of studies underscore the significant development benefits of mini-grids. These studies, including UNDP surveys of a large number of households across many parts of South Asia, demonstrated increases of more than 50% in household income, significant reductions in maternal and childhood mortality rates, as well as improved educational outcomes (Schnitzer, et al., 2014).

Interestingly, however, there is no standard definition of a mini-grid, beyond general characterizations that they are much smaller than main power grids with respect to capacity and size. Based on general usage in available literature, and the capacity needed to sustain household and productive services in small to moderate communities, we assume that a mini-grid has a capacity from 10kW to a few megawatts (IFC, 2012) (IED, 2013). There are no clear threshold criteria for selecting mini-grids over grid extension either. In the past, mini-grids have been installed in places where the population density is greater than 250-300 inhabitants per square km, the distance from the grid has been more than 5 km, and the expected demand was about 150 kWh per person per year (IED, 2013). It should be noted, however, that such considerations are highly contextual (IRENA, 2013) (IED, 2013).

The importance of off-grid solutions in sub-Saharan Africa

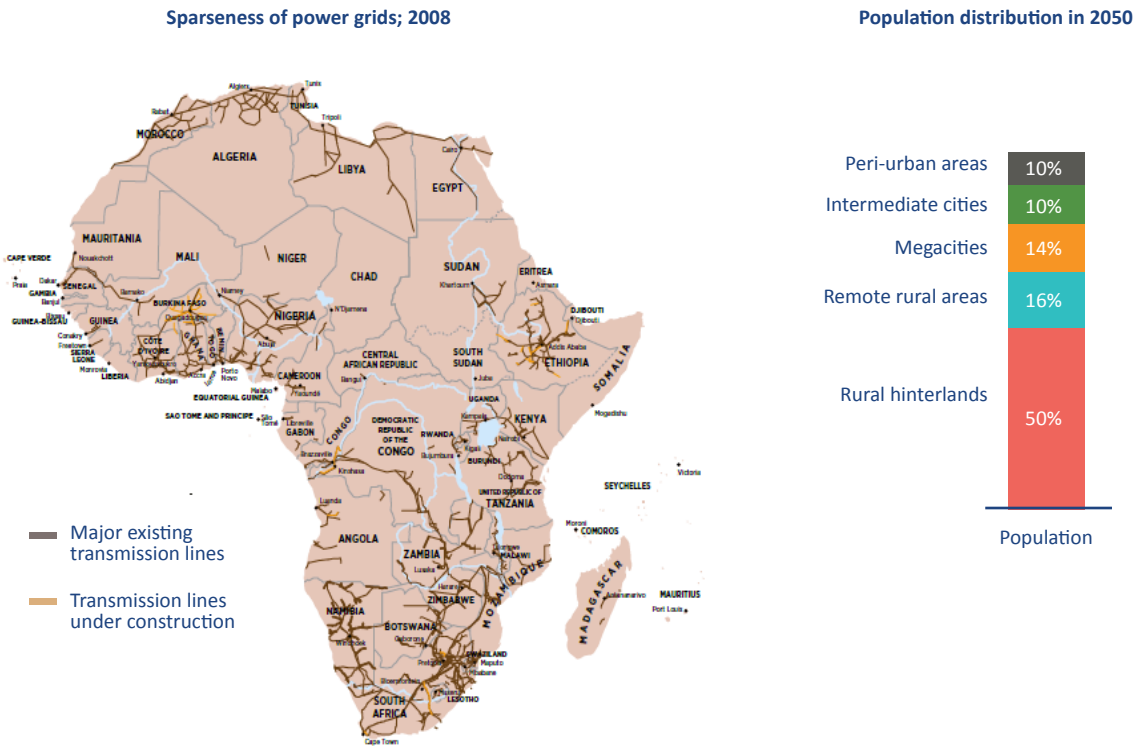


Exhibit 5: Only a very small portion of sub-Saharan Africa is currently connected to power grids. With a majority of the population expected to remain rural even as far into the future as 2050, off-grid solutions hold the key to solving the electrification puzzle.

5 Renewable energy systems are ideal for mini-grids

Currently, only 4% of the world's electricity is generated using renewable sources like solar and wind (**Exhibit 6**). Coal and natural gas are the main sources of electricity globally, and more so in South Asia and sub-Saharan Africa. Hydropower—often counted as a renewable source—is the third major source. Renewable sources such as wind, solar, hydropower and biomass are abundant in nature, even

if their availability can vary by geography. They are more economical than conventional sources of electricity production like coal and natural gas, with considerably lower capital investments and low fuel costs. These sources are also environmentally sustainable, with zero emissions (except for biomass) and significantly lower environmental footprints at the source, and pose no risk of catastrophic environmental damage (like nuclear power plants).[5] These sources—whose supply is fixed by natural constraints, and cannot be adjusted up or down to meet user demand—are also better utilized in contexts that support multiple users and diverse activities, as opposed to a single user or activity that may not utilize them to the fullest when there is supply (IEA, 2011). According to the IEA, renewable energy is the least-cost path to supply roughly 55% of the additional power generation that is needed for universal access by 2030 (**Exhibit 7**).

Sources of electricity generation

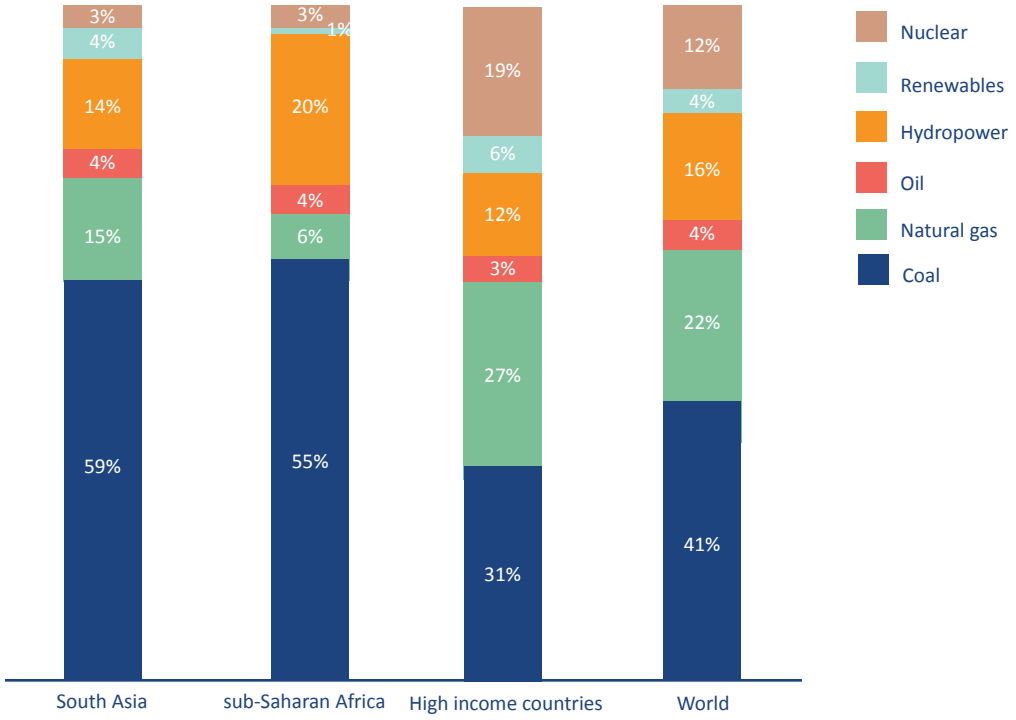


Exhibit 6: Coal, natural gas and hydropower are the predominant sources of electricity generation across the world. Only 4% of the world's electricity, and about 1% of all electricity generated in sub-Saharan Africa, comes from renewable resources.

[5] Large-scale hydropower dams are very expensive and can have significant environmental impact. On the other hand, smaller-scale micro-hydropower facilities can be economical, with a limited environmental footprint.

IEA estimates of the mechanisms and energy sources required for universal electricity access by 2030

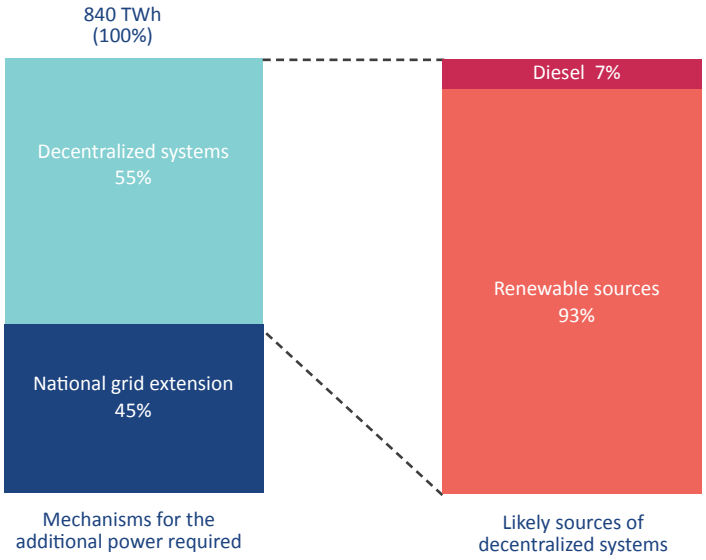


Exhibit 7: To achieve universal electrification by 2030, the IEA estimates that 55% of the power will need to be provided by decentralized systems, with almost all of it from renewal energy sources.

6 Solar photovoltaics is the most widely suited technology for decentralized renewable energy mini-grids

The various sources of renewable energy—wind, sunlight, biomass, geothermal and hydropower—are present at different intensities in different parts of the world. The optimal renewable energy 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. Of the various renewable energy sources, solar power has the largest scale of application since it is the most widely available resource, and can be produced from many distributed sites (rather than isolated resource-dependent locations). Solar power can be generated in most of Asia and Africa (with a few exceptions due to extreme rains and cloudiness) (IED, 2013). By comparison, hydroelectric power needs to be close to a perennial water current with sufficient strength, and 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 (IED, 2013) (IRENA, 2013). 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. For instance, sugarcane bagasse—among the most widely produced feedstock in sub-Saharan Africa suitable for gasifiers—cannot be stored for long periods, and is not available for several months a year (DFID & IED, 2013). Biomass power generators are also best suited for locations with 'anchor clients' such as small mills and agri-businesses, which have sizable but fixed and predictable power needs (IED, 2013). Since wind and hydro systems are site-specific, their distribution costs are highly variable, depending on population distribution rather than any factor intrinsic to the technology. Solar power, on the other hand, can be located very close to or even in the midst of settlements, significantly reducing

distribution costs.

Solar photovoltaics (PV) are electronic devices 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 US, and research has continued since then to improve their efficiency and performance. Since their invention, there have been 3 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 which use a fraction of the material (compared to the first generation) by depositing solar cells on thin substrates like 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. They do, however, have strong potential for further cost reductions. Due to cost vs. efficiency tradeoffs, first generation PV is better for dedicated home systems while thin-films are suited for mini-grids and utility scale systems.

There are also some emerging third generation PV technologies. Concentrated PV (CPV) uses optical devices to concentrate sunlight on solar cells, and a tracking system. Since 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 multi-junction solar cells. This nascent technology appears to have significant potential for gains from the learning curve.[6] Dye-sensitized solar cells (DSSC), another third generation technology, use photo-electrochemical solar cells which harvest photons from sunlight mimicking photosynthesis. DSCC current has low efficiency, and needs new dyes that can absorb broader spectral ranges. Another issue that needs to be addressed is performance degradation due to UV light. Lastly, Organic PV (OPV) has solar cells composed of organic or polymer materials. OPV uses inexpensive, abundant and non-toxic materials but needs to become much more efficient and stable (IRENA, 2012).

To date, the comparative simplicity of PV technologies have increased the advantage of solar power over other sources of renewable energy

Compared to other sources solar PV systems are relatively easy to set up, operate and maintain

Lead times for construction can be high for micro-hydropower. Transportation can drive up the cost of installing equipment for wind (turbines) and hydroelectric, and of feedstock for biomass. Operations and maintenance (O&M) of wind systems need significant technical expertise. Biomass also demands high O&M due to lack of uniformity of feedstock (particularly for digesters) and complex operation with thousands of mechanical parts requiring significant labor and technical expertise (for gasifiers). Solar PV, on the other hand, is comparatively easier to set up, operate and maintain, with less need for monitoring or technical expertise. This practical consideration is of essence 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 (**Exhibit 8**).

[6] 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.

Electricity generation costs in mini-grids ($/kWh)

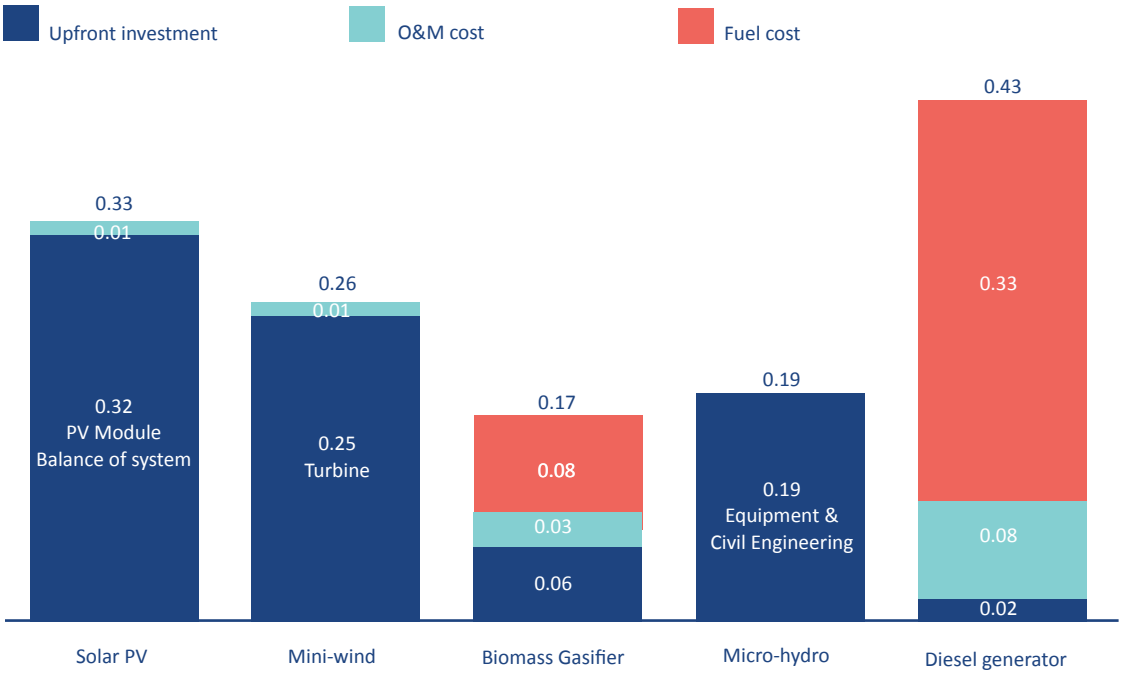


Exhibit 8: The upfront capital expense (CapEx) of solar PV is higher than other renewable energy technologies for mini-grids, but cost and complexity of operations and maintenance (O&M) is low. This a key consideration for resource-constrained settings. Note that these numbers are mini-grid scale systems in emerging market economies, and costs are much lower for large (utility) scale systems. Costs can also vary highly by location. Distribution costs for wind and micro-hydro are highly variable, since generation facilities are highly site-specific. Finally for renewable energy technologies that are not fully mature i.e., wind and solar PV, costs change quite quickly. For instance, PV module and the balance-of-system (BOS) costs—the key drivers of CapEx—have fallen significantly in recent times. The average price for utility-scale PV project has dropped from $0.21/kWh in 2011 to $0.11/kWh in 2014 (IFC, 2012) (IRENA, 2012) (US Department of Energy, SunShot, 2014).

Solar PV systems are highly modular and configurable

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, on the other hand 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 (IRENA, 2013).

Solar PV has significant headroom for cost reductions

Both micro-hydropower and biomass technologies are fairly mature with low potential for further 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 renewable energy technologies. Wind, by comparison, has a learning rate of 7% (IRENA, 2012). This, matched with the global growth of solar PV, resulted in massive cost reductions which are expected to continue, 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 kWh by 2020.

The relative simplicity of solar PV technology, combined with supportive policy incentives like feed-in tariffs and tax breaks, have made it one of the fastest growing renewable energy 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 (IRENA, 2012). While Solar PV is not the optimal choice in every context, it is generally well suited for many reasons and is applicable extensively across the globe. **Table 1** summarizes the pros and cons of various renewable energy technologies, in the context of rural electrification in developing countries (IED, 2013) (IRENA, 2012).

Suitability of renewable energy technologies for rural electrification in developing countries

● Very favorable ○ Highly unfavorable

Technology	Diffuse (vs. site specific)	Volatility	O&M costs	Modularity	Upfront cost	Levelized cost	Potential for improvement	Remarks
Solar PV	●	◕	●	●	◑	◔	◕	- Widely abundant - Intermittent but generally predictable - Low operations & maintenance (O&M) cost and complexity - Highly modular - Relatively high upfront and replacement costs - High learning rate (20%) and deployment growth with room for significant improvements.
Wind	◔	◑	◑	◔	◑	◔	◔	- Highly site-specific - Relatively unpredictable, and requires complex forecasting and demand-side management - High O&M cost and complexity (for turbines) - Not modular: high economies of scale with significant losses of economy, as scale reduces - Relatively high upfront cost - Moderate learning rate and some room for improvements; turbine O&M costs likely to increase
Biomass	◑	◑	○	◑	◕	◕	◔	- Moderately 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 costs: feedstock collection, storage and pre-processing; many moving parts (gasifiers), high need for technical expertise and maintenance - Environmental concerns: water and byproducts disposal - Ideal for fixed power generation with predictable demand - Low upfront costs - Mature technology with modest cost reduction potential

Hydro	◔	◑	◕	◔	◑	◔	○	- Highly site-specific - Seasonal volatility due to fluctuations in water flow - Low O&M costs, but need technical expertise - Needs high utilization, advisable with grid connection - Moderate upfront costs but complex and long installation if built from scratch - Mature technology with modest cost reduction potential

Table 1: Pros and cons of different renewable energy technologies in the context of decentralized mini-grids in rural developing regions. Note that one important criterion for comparing the various technologies is levelized cost of electricity (LCOE), which is the ratio of the present value of lifetime system costs (discounted using the rate of cost of capital), to lifetime electricity generation. The drivers of LCOE are capital expenses (cost of infrastructure and installation), cost of capital, operations and maintenance (O&M), the quality and output of the energy resource, the life of the system, and utilization of the system's capacity.

7 Storage is critical component of decentralized renewable energy systems, to ensure a reliable supply of electricity; rechargeable batteries are well suited for this purpose

A reliable supply of electricity is important to support an adequate range of services for households and income-generating activities. Unlike fuel-based power, non-fuel renewable energy resources are intermittent and unpredictable. Sunlight has varying intensity through the day, and is not available at night, and wind can start and stop anytime. Ensuring uninterrupted electricity—even as demand fluctuates—is a key challenge for power grids. To avoid blackouts conventional power plants are built bigger than they need to be, and operated at peak-load capacity longer just to generate excess electricity in anticipation of peak demand. Storage technologies convert electricity into other forms of energy when surplus electricity is generated, and then convert this back to electricity as needed. Storage is thus used to balance fluctuations in demand, reduce costly peak-load capacity of power plants and help them operate more efficiently.

In conventional power grids water is used for storage; surplus overnight electricity from coal, gas and nuclear plants is used to pump water from a lower to an upper reservoir, and this is used to produce hydropower during high-demand periods as needed. This inexpensive and efficient mechanism accounts for 95% of global storage capacity (IRENA, 2012). Such a mechanism, however, is only practical for large scale systems (100 megawatts or more), because of the volume of water needed to generate enough power.

For renewable energy mini-grids, 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. **Exhibit 9** shows the power output and discharge times for various storage technologies, highlighting the range that is most applicable for mini-grids. The most commonly used storage system for solar PV mini-grids is deep cycle lead-acid batteries. These are a relatively mature and widely available technology but require some maintenance and can

add as much as 50% to the cost of a solar PV system (IED, 2013). There are a number of other storage technologies, but most need further development to reach commercial viability for mini-grids. Of these, lithium-ion (Li-ion) batteries are widely used for mobile phones and laptops, but large Li-ion are still too expensive. Sodium sulphur (NaS) and Vanadium Redox flow batteries have been used effectively in small to mid size renewable power systems, but these too are currently much more expensive than deep cycle lead acid.[7] Note that storage is not required for biomass systems, or for hybrid fuel-renewable systems.

Power output and discharge time of various storage technologies

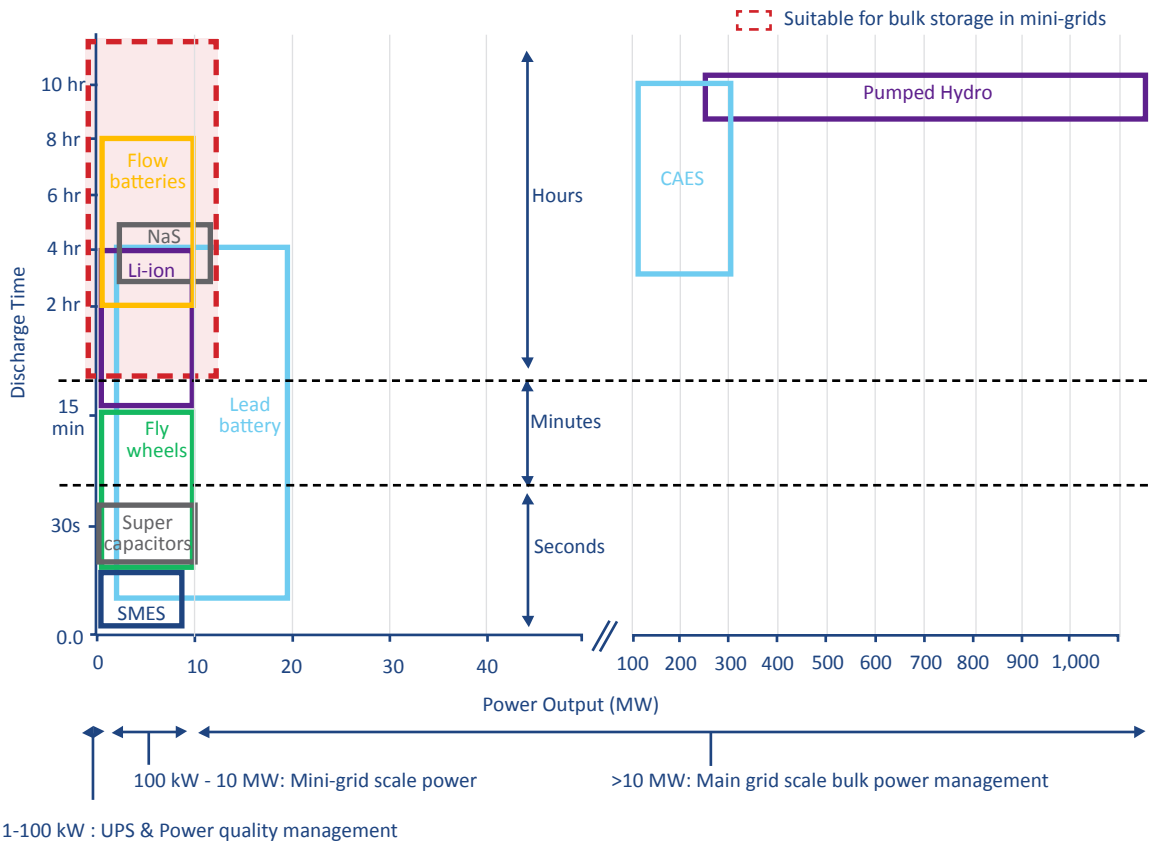


Exhibit 9: Performance of different storage technologies with regards to power output and discharge time. Technologies in the 100 kW-10 MW power output range and discharge time in the range of hours, are suitable for bulk storage in decentralized renewable energy mini-grids (IRENA, 2012).

8 Active grid management is crucial for ensuring effective performance and reducing losses

Grid management involves monitoring, supervision and (as necessary) repair of the various parts of the grid, from generation, to distribution and consumption. Poor grid management increases operational costs as well as losses from unrealized revenues due to a number of reasons—manual (and hence inaccurate) metering and collection, tampering, payment defaults, under or over utilized capacity

[7] Of the various storage technologies shown in **Exhibit 9**, 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 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) uses superconducting technology to store electricity in magnetic fields. Technologies like fly wheels and supercapacitors do not have sufficiently long discharge times. Others like compressed air and pumped hydro can only work with very high capacities (IRENA, 2012).

and wasted power, and sub-optimal pricing. Effective grid management in mini-grids can significantly improve their profitability, service quality and risk profile. This, in turn, can reduce the cost of capital, which is one of the biggest cost drivers. Grid management, even in well functioning systems, currently requires significant effort. It is even more challenging for decentralized renewable energy grids in rural areas. The functions grid management systems can perform are outlined below

During generation

Monitoring and troubleshooting operations in realtime, collecting and analyzing system data, optimizing and synchronizing multiple power sources in hybrid systems, managing storage to smooth intermittence of renewable energy supply, and regulating voltage, frequency and load levels (i.e., matching demand with supply).

During distribution

Minimizing technical and non-technical losses from theft and measurement errors, which can exceed 30% in some African countries (IED, 2013).

During consumption

Synchronizing demand and supply (e.g., current limiters, power management administrators, and smart meters), billing and fee collection systems (e.g., prepayment devices, mobile banking systems) and fraud prevention systems (IED, 2013).

9 Funding for decentralized renewable energy mini-grids is facing significant shortfalls

According to the IEA (and as shown in **Exhibit 7**), renewable energy mini-grids are expected to be the least-cost path to supply more than half of the additional power generation that is needed for universal access by 2030. It is generally assumed that investment in this infrastructure cannot be fully recovered, because of the weak purchasing power of low income users. Hence, it is expected that significant public or donor funds will be required. According to the IEA, the least-cost path for achieving universal access by 2030 (based on the lowest-cost regional cost per MWh, taking into account relevant regional parameters) will require $44 billion of infrastructure expansion annually—$18 billion for extension to national grids, and $26 billion for decentralized systems (**Exhibit 10**). Out of this $26 billion, the IEA expects that only $6 billion of funding will materialize, leaving a 77% shortfall, even in the optimistic scenario based on current commitments. Shortfalls related to both grid extension and decentralized systems are expected to be highest in sub-Saharan Africa (**Exhibit 11**), with decentralized systems facing disproportionately higher share of the funding gap (IEA, 2011). This, combined with Africa's huge untapped potential for renewable energy resources, presents a compelling case for technological breakthroughs to reduce barriers to expansion of decentralized renewable energy systems (IRENA, 2011).

Investment required to expand electricity infrastructure for universal access by 2030, along with projected funding shortfalls

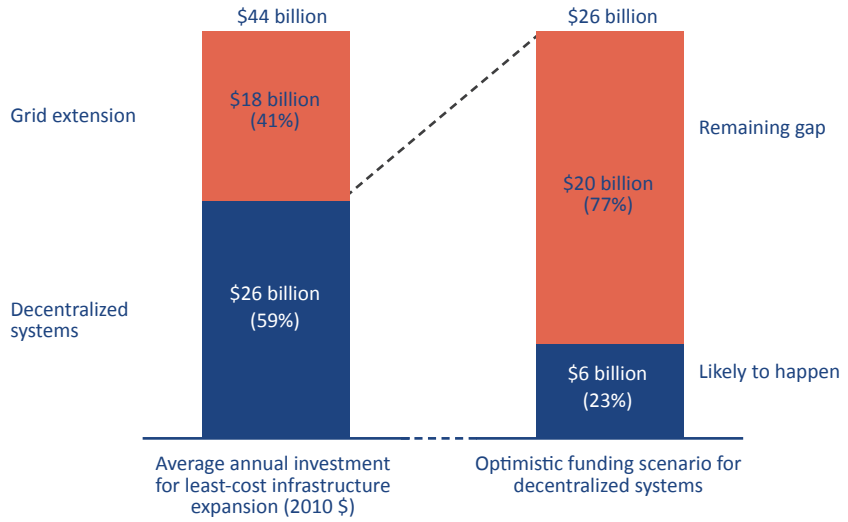


Exhibit 10: To achieve universal access by 2030, according to the IEA, $44 billion of annual investment is needed for expanding electricity infrastructure. Even in the IEA's optimistic scenario per current commitments, there are expected to be major shortfalls.

Funding shortfalls in electricity infrastructure expansion to achieve universal access by 2030, by region and type of system

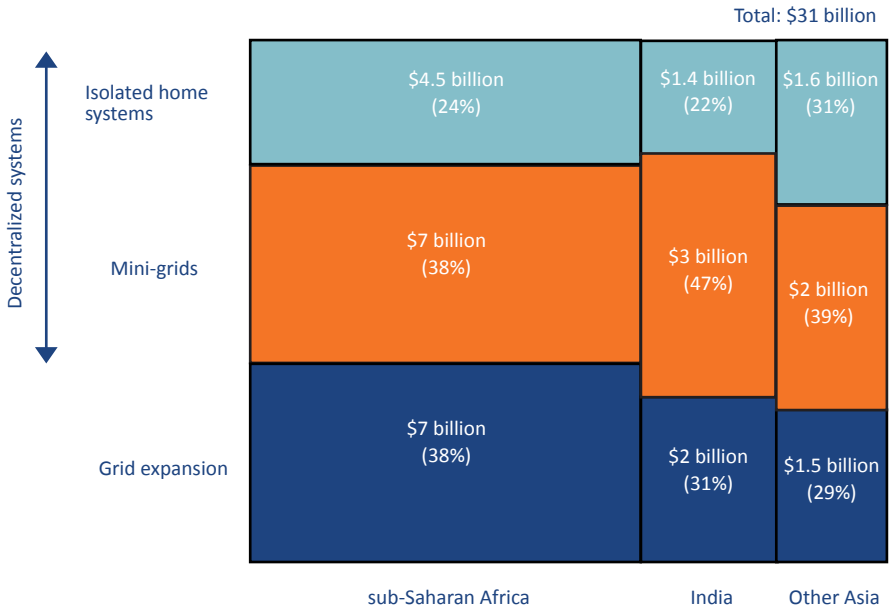


Exhibit 11: According to the IEA, most of the annual shortfall in infrastructure expansion needed for universal access by 2030 is concentrated in sub-Saharan Africa and in decentralized systems.

KEY CHALLENGES

There is considerable interest across the industrialized world in improving renewable energy technologies. However, most of those efforts appear to be geared towards reducing the environmental footprints of wealthier population segments, rather than improving access to electricity for low income populations in developing countries. While there will likely be some spillover benefits, a number of major challenges have to be overcome before anything close to universal access to electricity is possible.

1 The upfront cost of building renewable energy systems is too high to provide financially self-sustaining services for low income users

The key drivers of CapEx for Solar PV mini-grids are PV modules and the balance-of-system (BOS) which comprises both equipment (e.g., racking structures and inverters) and 'soft costs' such as labor, site preparation, licensing fees, etc. (IFC, 2012) (IRENA, 2012). BOS costs vary widely by geography, primarily because of soft costs. Residential PV systems in the US were twice as expensive as those in Germany in 2012 primarily because of soft costs (Seel, et al., 2014).

Efficiency gains can also reduce effective cost of Solar PV. First generation PV is a fairly mature technology but second-generation, i.e., thin-film PV which is ideal for mini-grids, is fairly recent and has the potential for further improvements (**Exhibit 12**). There are 3 levels of efficiency (of conversion of solar irradiance to electrical energy) demonstrated by any technology (**Exhibit 13**). Commercial efficiency relates to versions that are manufactured and available at commercial scale. Research efficiency is manifested in research conditions and is higher than commercial efficiency. Lastly, 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.

In the case of large scale on-shore wind systems, up to 85% of CapEx is for production, transportation and installation of wind turbines. Of this, the rotor blades, tower and gearbox comprise 60% of the cost. There is a tradeoff between efficiency and cost—system efficiency increases significantly with the height and span of turbines, but so does cost of production, transport and installation. The cost of operations and maintenance is also significant (20-25% of the LCOE) (IRENA, 2012). Wind is not suitable for small scale applications, because turbines with a smaller diameter are far less efficient than larger ones (IRENA, 2013). This makes wind difficult and costly to deploy in small markets with weak infrastructure. Finally the learning rate for wind is 7%, which means that cost reductions associated with growth in installed capacity are likely to be modest compared to solar PV which is 20-22% (IRENA, 2012).

As mentioned earlier both biomass and micro-hydro technologies are relatively mature, and do not offer much potential for further cost reductions.

[8] Note that this estimates applies to large scale on-shore wind systems; since wind power's efficiency reduces with scale, the proportion is likely to be higher for mini-grid scale systems.

Cost structure of solar PV installations for thin-film technologies

(2010 estimates)

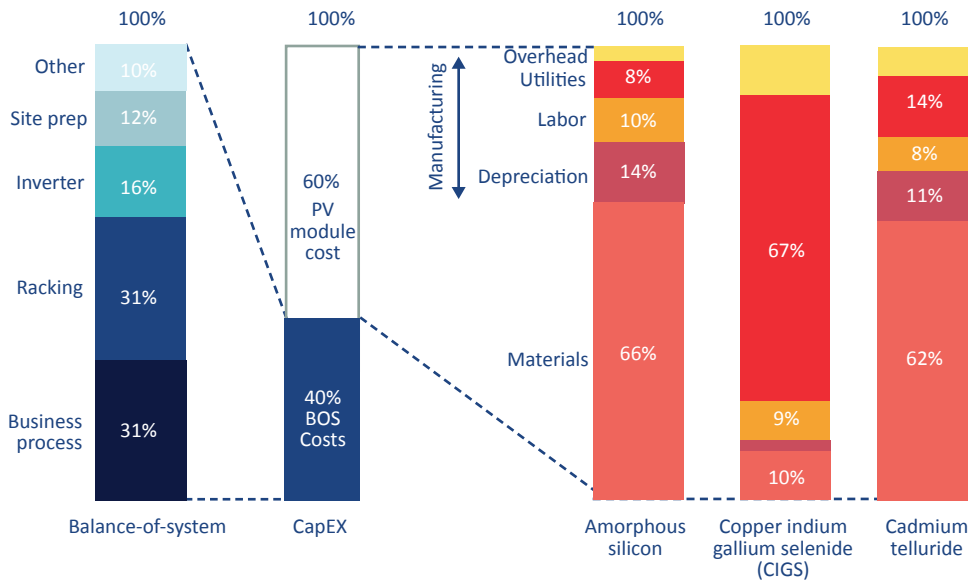


Exhibit 12: The cost structure of solar PV installations can vary widely by geography and by scale and configuration of systems. Manufacturing costs for thin-films (which are a relatively new technology), provide opportunities for cost reductions from growth in installed capacity and associated learnings (IRENA, 2012).

Efficiency of various solar PV technologies (%)

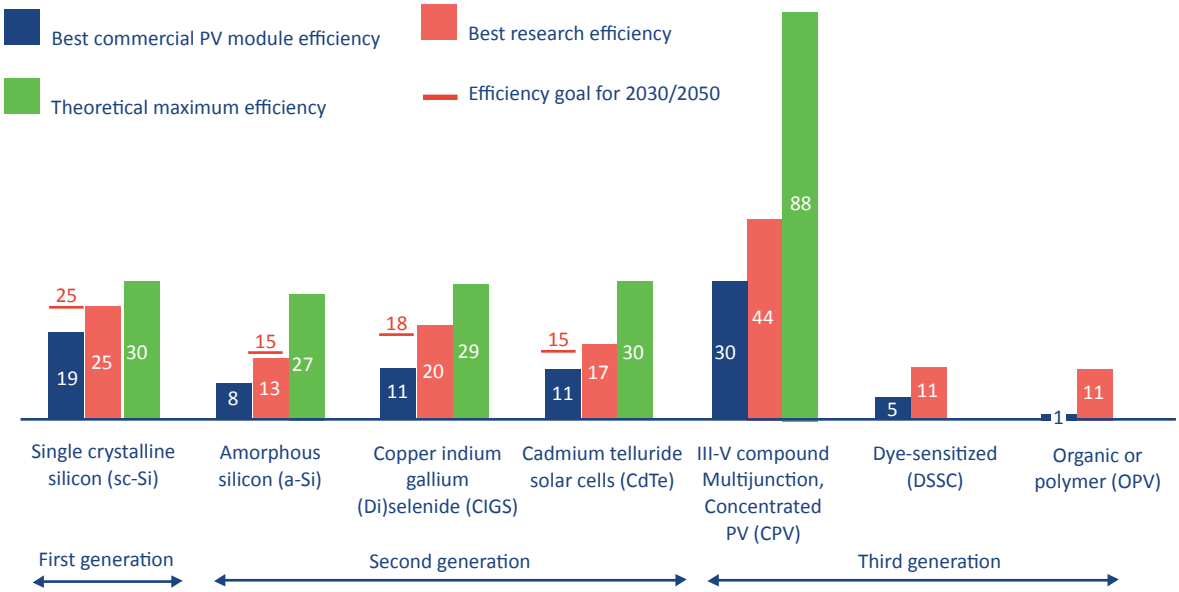


Exhibit 13: The commercial, research, and theoretical maximum efficiency of the various second generation solar PV technologies is generally in line with the first generation (single crystalline silicon). Some third generation technologies offer the possibility of higher efficiency (IRENA, 2012).

2 The high cost of capital, misaligned policies, and weak purchasing power of low income users, collectively make the business case for renewable energy mini-grids even more challenging

The electricity market for low income rural users in developing countries is still very nascent. Anchor clients—businesses which can guarantee demand—are few and far in between, especially in rural sub-Saharan Africa. Being predominantly agri-based economies, rural markets also have seasonal variation in demand.

Financing for building mini utilities is scarce and have a high cost of capital. As a result, many mini-grids are funded through grants. In-country financing prospects are not encouraging, as governments and utilities in developing countries lack a firm revenue base from taxes and high income consumers, to subsidize projects serving low income users. Utilities in such countries typically run on losses with high rates of non-payment, and appear unlikely to finance new projects. Rural renewable energy mini-grids typically need heavy subsidies to achieve a financial return on investments. For example, projects in Kenya have been observed to need subsidies in the range of 20% to 70% to achieve a 10% internal rate of return (IED, 2013) (IEA, 2011) (IRENA, 2013). Private investors appear to prefer grid extension projects for urban and peri-urban users as they represent more established and profitable business models.

Mini-grids are more complex to deploy than standalone household systems, which despite their limited potential for full-fledged electrification and higher unit cost of electricity, have relatively short payback periods (e.g., 1-5 years for a solar home system). With appropriate financing schemes, such standalone systems are proving to be much easier to deploy in a viable manner. Mini-grids on the other hand, are more complex systems with longer pay back periods. They need greater technical and project expertise, have higher up-front costs and need long term loans (>= 10 years) at low to moderate rates (IRENA, 2012). However, they face significant barriers to capital, since local banks often lack access to long term financing, and need guarantees that investors are not able to provide. For instance, average lending rates can be as high as 19% to 29% in Uganda, Mozambique, Malawi, and 67% in DR Congo. In some of these countries, the longest loan terms are 3-5 years. For larger banks, the transaction volume for such investments is too small to be of interest (IED, 2013) (IRENA, 2013).

Finally, domestic energy policies can stack the odds against renewable energy mini-grids, making them less viable than they could otherwise be. Market distortions such as fossil fuel subsidies make alternatives to renewable energy mini-grids 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 (IRENA, 2013).

3 The cost of powering basic household appliances—even if they were affordable—is currently too high for low income rural users on decentralized solar PV mini-grids

Access to electricity is more than charging a cell phone or lighting a few bulbs. 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. Unfortunately, poor people have very constrained energy budgets and cannot afford these services without deep subsidies in decentralized renewable energy mini-grids. This presents a bleak prospect for access considering the large gaps in expanding infrastructure.

The ‘effective’ cost of services is a function of two factors—the efficiency of appliances (which determines how much electricity an appliance consumes), and the cost of electricity. In the following analysis, we assume that a portfolio of appliances to meet the basic household needs for a low income rural family 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 (Craine, et al., 2014) (Greentech Media, 2013), the household will consume roughly 80 kWh each month (**Exhibit 14**).

Relative power consumption of appliances useful to low income rural households

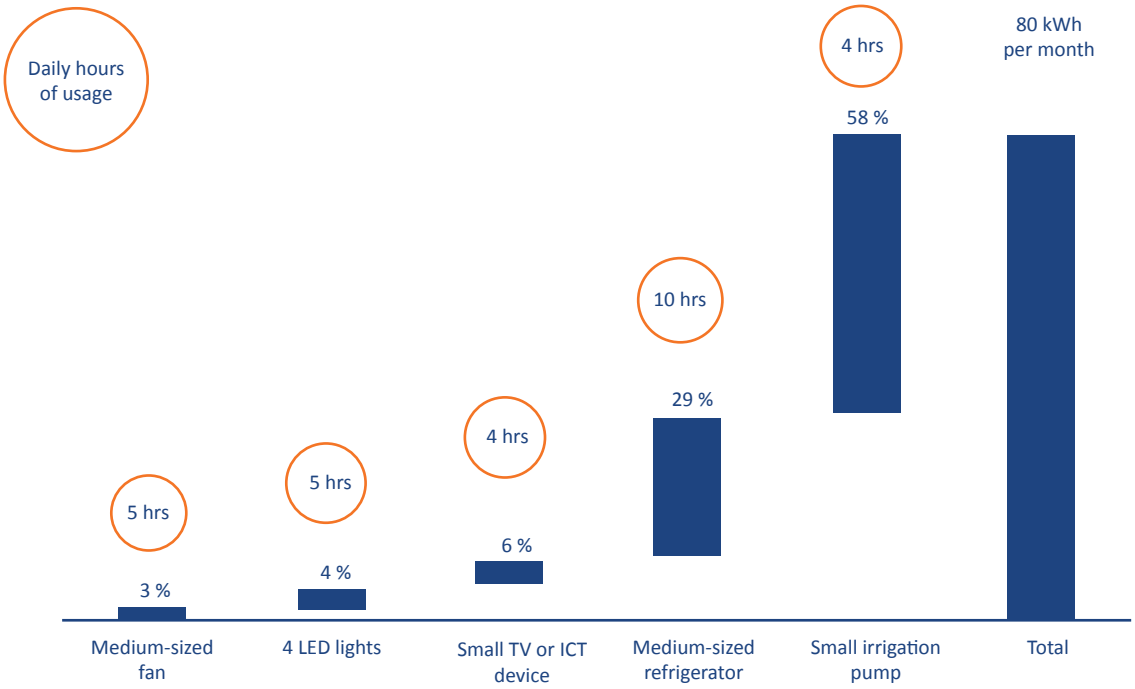


Exhibit 14: A conservative estimate suggests that a small rural farming household, using an essential set of appliances at current energy efficiency levels, is 80 kWh per month (Craine, et al., 2014) (Greentech Media, 2013).

Currently, the cost of electricity in solar PV mini-grids is estimated at $0.24/kWh.[9] At this level, the effective cost of basic services is $20 per month (assuming no subsidies). The question then becomes: how does this compare to what low income households can afford for monthly electricity bills? While there is variation by country and region, the poorest 4 billion people at the base of the pyramid (BoP) who make less than $5 a day can be grouped into 3 segments based on their relative poverty—'low income' (earning $3-$5/day), 'subsistence' ($1-$3/day), and 'extremely poor' (less than $1/day) (**Exhibit 15**). 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 3 segments described above. Therefore, it appears that the effective cost of electricity for a basic portfolio of appliances—$20 per month—is almost 3 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 (IFC, 2012) (Rangan, et al., 2011).

For electricity to be affordable for the practical needs of human development it needs to become less expensive, and appliances need to become more efficient. In effect, this relationship between the required decrease in the cost of electricity and the increase in appliance efficiency represents an 'isoquant', which is shown in **Exhibit 16**. It is important to note that this is an illustrative analysis using benchmarks, and does not represent actual observed data (which may be influenced by a range of

[9] This estimate assumes solar PV costs as per the 2nd round of bidding for National Solar Mission in India (Abhyankar, et al., 2013). Balance-of-systems costs are based on a standard breakdown of costs in solar PV systems (IRENA, 2012). In addition, we assume storage adds 50% to system costs for solar PV mini-grids (IED, 2013).

factors). For instance, consumption will be influenced by quality of electricity, subsidies and pricing schemes for appliances and electricity. The cost of electricity will vary widely by installation, availability of resources, cost of capital, and subsidies. The purpose of our analysis then is not to pinpoint precise numbers, but rather to illustrate the wide gap between effective cost of electricity for basic needs, and what low income populations can afford.

Effective cost of electricity for a basic portfolio of appliances, vs. what each BoP population segment can afford

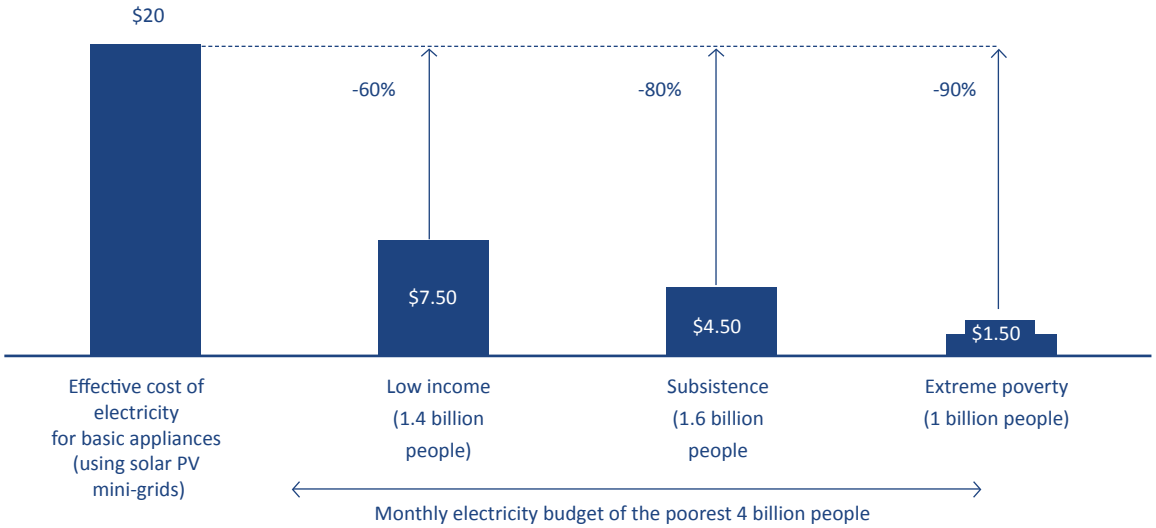
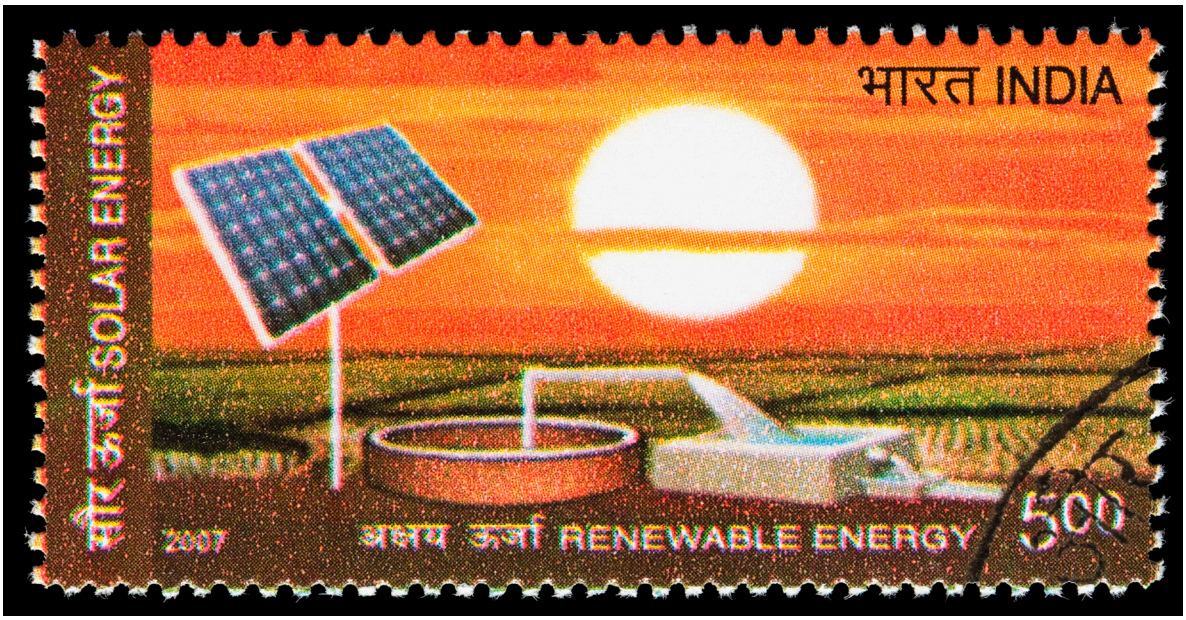


Exhibit 15: The effective cost of basic services in decentralized solar PV mini-grids with storage needs will have to fall sharply to match the electricity budgets of populations earning less than $5 a day. The effective cost of services is driven by the cost of electricity, and the efficiency of appliances.



'Isoquant' curve representing combinations of reductions in cost of electricity vs. electricity consumed by appliances to fit the monthly 'energy budget' of populations earning $3-$5 per day

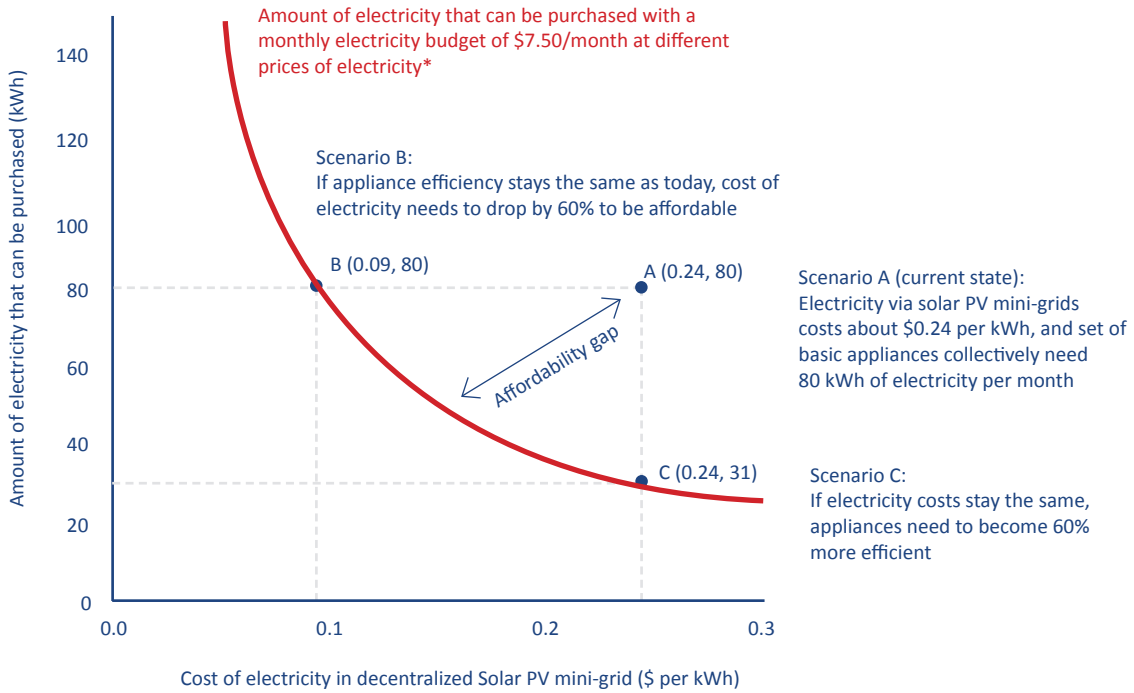


Exhibit 16: The effective cost of electricity can be reduced for low income populations if the cost of electricity reduces and/or if the efficiency of appliances improves. Currently, electricity via solar PV mini-grids costs $0.24 per kWh (including storage), and the illustrative portfolio of basic appliances consumes 80 kWh per month. Based on this, there is a 60% affordability gap (as shown in **Exhibit 15)**. Hence, either the cost of electricity needs to be reduced by 60%, or the combined energy efficiency of the basic portfolio of appliances needs to improve by 60%. This is an illustrative analysis, not based on actual observation, because low income populations cannot afford the appliances. One assumption is that the cost of the appliances themselves will decrease, at which point their energy efficiency will become a significant barrier to adoption. Note that this analysis applies only to the 1.4 billion people living on $3-$5 per day. The gap for the 2.6 billion people living on less than $3 per day is much higher.

4 Rechargeable batteries are currently too expensive, and have challenges providing a continuous supply of quality electricity in renewable energy mini-grids

Rechargeable batteries are essential for providing continuous and reliable supply of electricity in solar PV and wind renewable energy mini-grids, in an environmentally sustainable manner. However, neither the cost nor the performance of existing technologies is adequate. Assessing the exact cost for storage is difficult, because of the unpredictability of capacity needed (which can vary significantly from one location to another based on geographic parameters and usage patterns), as well as battery life (which depends on the frequency and depth of discharge, for current technologies like lead-acid batteries). This lack of knowledge is partly due to the limited number of installations, and is particularly true of nascent storage technologies like flow batteries. Even lead-acid batteries, the least expensive commercially available

option, can add more than 50% to the cost of a PV system, and double the cost of electricity (IED, 2013).

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 allows batteries to be scaled down without loss in performance; configurability of power output and capacity; and 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**):

- Lead-acid batteries are the least expensive commercially available rechargeable batteries, but 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 to address these challenges are still emerging. Disposal of lead-acid batteries have environmental and health risks that require careful handling and regulation.
- Li-ion batteries has very high power density, modularity, no memory effect, and high depth of discharge. However, they are expensive, and have limited capacity and safety concerns (about abnormal heating from overcharging and short circuits). Currently, they are best suited for small scale applications, and require significant improvements to achieve reduced cost, higher safety and more capacity.
- NaS 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 mini-grids. 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. They are well suited for storage in megawatt-size, utility-scale mini-grids (village-scale or larger), and are typically available in multiples of 1 megawatt (with installations in the 2-10 megawatt 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.
- Flow batteries are highly configurable, with very high depth of discharge and 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 Batteries (VRB) flow batteries can last longer than 100 years according to some estimates, although cell stacks need to be replaced every 8-10 years. VRBs are still pre-commercial, and are currently being used in projects ranging from a few kilowatts to a few megawatts (IRENA, 2012) (Sandia, 2013).

Advantages, challenges and future outlook of each type of battery technology

	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 - 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 (power, electric cars) - Likely best suited for modular, small scale applications
NaS	- Least cost in pre-commercial phase - Operational in wide range of projects - Very cheap, abundant materials - Can sustain MW size applications	- Very high operating temperature (300°C) - Heavy and bulky	- High cost reduction potential - Smaller batteries are emerging - Likely choice for village- or larger-scale mini grids 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 cooling system to absorb heat for charging and discharging	- High cost reduction potential - Likely Choice for village- or larger-scale mini-grinds i.e., full-fledged electrification

Table 2: Comparative assessment of different rechargeable battery technologies that are suitable for bulk storage services in mini-grids (IED, 2013) (IRENA, 2012).

5 Appliances for basic household amenities (e.g., fans, refrigerators) are still too expensive and too energy-intensive

In recent years, there has been a proliferation of appliances such as solar lanterns and charging kits for mobile phones (IFC, 2012). It is important to note that these appliances should be considered pre-electrification—valuable tools to improve quality of life, but not a substitute for true access to electricity. The type of appliances required to make fundamental improvements in quality of life—fans, refrigerators, small mechanized tools to improve workplace productivity—are currently unaffordable to the poor. Even if these appliances were somehow procured, their electricity demands would far exceed the 'energy

budgets' of low income populations (**Exhibit 14**, **Exhibit 15** and **Exhibit 16**). Improving the efficiency of these appliances will not only increase their affordability for the end user, but also directly improve overall grid economics by reducing the burden on the grid and the possibility of power interruptions (Abhyankar & Phadke, 2012).

Some appliances such as light bulbs, fans and TVs have achieved significant gains in efficiency. However, these are still too expensive, sometimes even for middle income consumers. Even if they are not affordable the poor, the energy savings achieved by a number of new, energy efficient appliances can offset their higher cost for consumers who can afford them (Letschert, et al., 2013) (**Exhibit 18**).

There has been less progress on improving the efficiency of work-related appliances like irrigation pumps. Most of the pumps currently being used are very inefficient, and end up costing farmers a lot of money over time (Phadke, et al., 2005) (Polak, 2013). In countries like India, diesel subsidies intended to ease the financial burden on farmers have led to millions of tons of carbon emissions. Emerging alternatives such as standalone solar pumps are still too expensive (Polak, 2013).

6 There are few effective solutions or tools for grid management of rural mini-grids

Effective grid management is crucial for operating grids reliably, efficiently and profitably. 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 quality of services (Schnitzer, et al., 2014). There is currently very little in the way of a technology solution for effective grid management of rural mini-grids. 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 mini-grids. Similarly, inexpensive prepayment meters—which make it significantly easier to manage fraud and fee collection—are being deployed in targeted markets, with the market for them becoming increasingly competitive (e.g., there are more than 20 manufacturers in India). In addition to these technologies, 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 mini-grid projects (IED, 2013).

However several improvements are needed before grid management technologies become affordable and simple enough to be deployed at scale in rural areas. Grid management remains a multifaceted problem requiring several devices to be installed at the point of generation, at the various points of consumption, as well as at points in between. This involves complex integration across the grid's control system, forecasting tools, sensors, and payment technologies.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Some of the most impactful levers for facilitating universal access to electricity may very well be policy reforms and support for market-based solutions. These solutions include 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 renewable energy systems as are currently provided for fossil fuels). Technological breakthroughs that can reduce the cost and complexity of installation and maintenance of mini-grids, and increase efficiencies for production and consumption, will facilitate the creation of self-sustaining markets that can scale up quickly. We believe 5 breakthroughs can accomplish this.

Suite of solar photovoltaic mini-grid components, to significantly reduce upfront costs.

Solar PV is well suited for rural renewable energy mini-grids in much of sub-Saharan Africa and South Asia, in places where grid extension is unlikely in the foreseeable future. However, the upfront cost of a renewable energy mini-grid system (its CapEx) is a significant driver of cost of electricity for the end user. Reducing the CapEx significantly will have a big impact in improving the economics of renewable energy mini-grids.

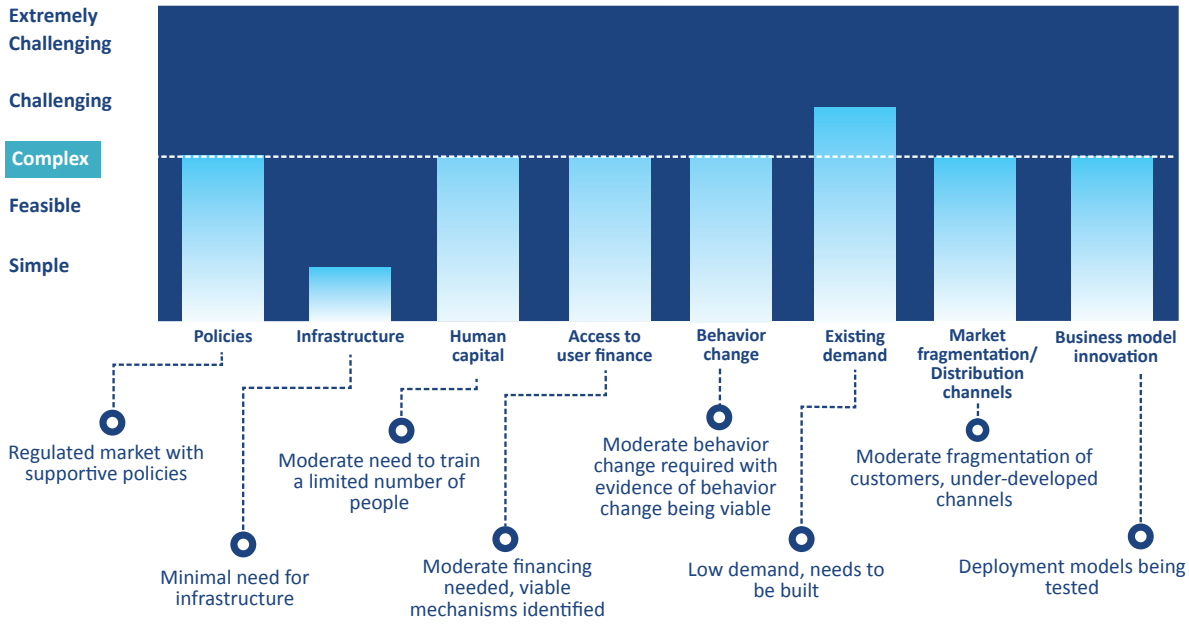
The potential for cost reduction in solar PV is promising. First generation PV technologies have a very high learning rate of 20% (i.e., every time the global installed capacity doubles, prices fall by 20%). Second and third generation technologies are relatively new, with scope for cost reductions over time. Specific opportunities include reduction in manufacturing costs (e.g., manufacturing copper indium gallium (di)selenide or CIGS, 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 R&D suggests the possibility of using magnesium chloride in the production of cadmium telluride solar cells, which is a lower cost and environmentally safer alternative to cadmium chloride, which is both expensive and toxic) (Semiconductor Today, 2014). There may also be opportunities in improving the efficiency of energy conversion. Although the commercial efficiency of first generation crystalline silicon is close to theoretical efficiency, thin-film solar cells have room for gains (**Exhibit 13**). 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 by double-digits annually, growing by 750% between 2013 and 2020 . It can also withstand the hot and dry climates typical to sub-Saharan Africa (PV Magazine, 2013). However, CPV components are heavy and fragile, making transportation and installation a challenge.

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 (IEA, 2010) (IRENA, 2012) (Greentech Media, 2013). However, reaching parity will take much longer for decentralized rural mini-grids, because PV system cost reductions are not enough; these mini-grids have to also contend with the (very high) cost of storage, as well as the low purchasing power of low income rural users. Overall, this breakthrough is likely to take over 10 years to materialize.

In terms of deployment, project financing is likely to be a major hurdle. Compared to other renewable energy technologies, PV is relatively simple to set up and operate, however the lack of

technical and business expertise required to run a utility may still be a bottleneck in very resource constrained settings. The nascent nature of markets comprising low income users with small variable usage patterns will make it harder to serve them profitably, especially in the absence of appropriate and affordable appliances. While these circumstances may change by the time the technology becomes a reality, commercially sustainable deployment will be COMPLEX.

Breakthrough 1 – Difficulty of deployment



Breakthrough 2

Appliances for household use (e.g., TV, refrigerator) and income generation (e.g., irrigation pump), which are significantly more affordable and energy efficient than those on the market today

For electricity to have an impact on development and quality of life, users need a range of amenities and services. This requires electrical appliances for reducing manual workloads, physical discomfort and health hazards, increasing the productivity of income generating activities, and enabling digital inclusion. These include lighting, a fan (or other cooling mechanism for the home), a refrigerator (for preserving perishable foods), an ICT device (e.g., a TV or a computer), and in the case of farmers, an irrigation pump. As things stand, 'pre-electrification' appliances like solar lights and systems for charging mobile phones are beginning to appear on the market, but are still far from being widely available and adopted. Appliances like TVs and refrigerators are currently not an option for low income rural populations because they are too expensive (by a factor of 3 or more), and require reliable electricity. There is increasing evidence that there will be strong demand for appliances like these. This, in turn, will keep pushing down market prices.

However, even if these appliances became affordable, the amount of electricity currently available appliances consume is more than the 'energy budget' of the 4 billion people living on $3-$5 per day or less. While energy efficient versions of some 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). Improving the efficiency of low cost versions of these appliances is critical to ensuring that electrification realizes its potential impact. Improving the overall

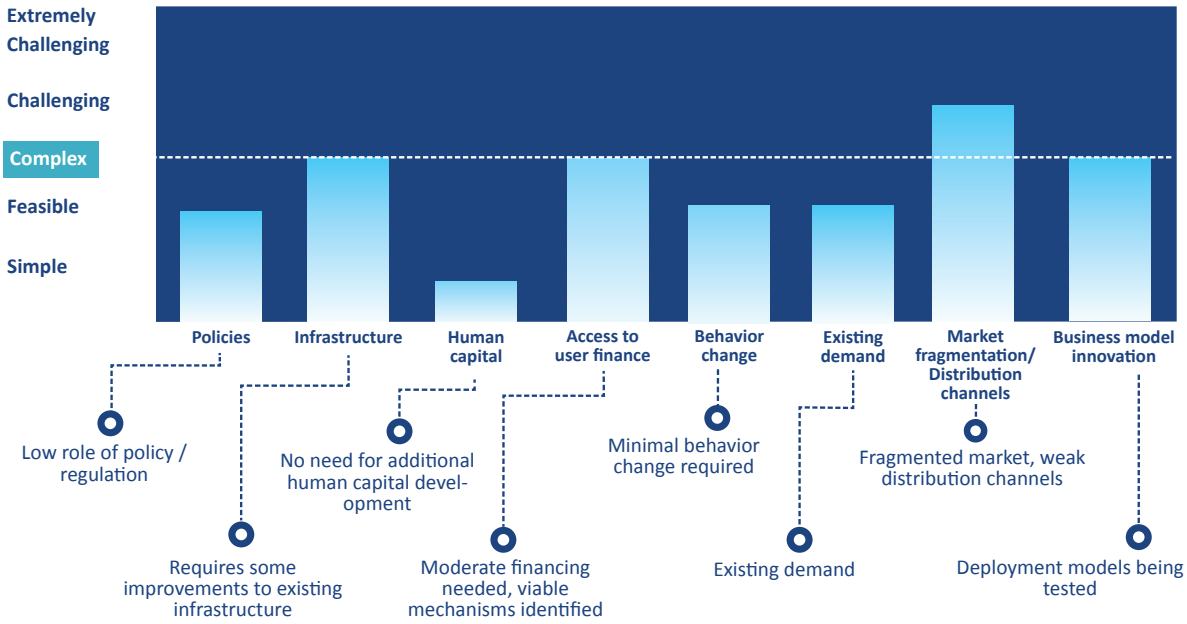
affordability of appliances will also lead to an increase in demand for electricity (Batchelor, et al., 1999). Increasing efficiency will reduce the load on mini-grids, in turn reducing the likelihood of power failures and load shedding.

However, businesses have so far been reluctant to invest in development of ultra-low-cost appliances for low income populations because of market uncertainties and high opportunity costs; they have been even more reluctant to invest in energy efficiency improvements for these markets. In emerging markets, urban middle and lower middle income users represent a profitable segment where profits are yet to be fully tapped out, and 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 will vary by type of appliance. For instance, fans with brushless direct current (BLDC) motors can be twice as efficient as ones with conventional induction motors. More efficient blades lead to a two-fold to four-fold increase in efficiency compared to the US EPA's Energy Star requirements (Sathaye, et al., 2013). Refrigerators can achieve high efficiency gains simply with better insulation, and advances in new refrigerants can improve the efficiency of cooling engines (Shah, et al., 2013). Super efficient TV's that draw a fraction of the power that currently available 'efficient' TV's consume are also beginning to become commercially available (Cnet.com, 2014). As mentioned earlier, these innovations are currently focused on the environmental concerns of industrialized markets, and are not being designed for the constraints of rural markets. Still, with rapidly growing markets like India, we believe some of these appliances will begin to appear within the next 3 years, while others will take 5 years or more.

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

Breakthrough 2 – Difficulty of deployment



New bulk storage technologies for decentralized mini-grids, which provide improved performance at a significantly lower cost

Consumers will use appliances at different times of the day, based on their specific household and livelihood needs, rather than the availability of power. In the case of distributed solar PV mini-grids, for example, users need lighting precisely when sunlight is not available. Similarly, refrigerators will need to run continuously through night and day. To enable such usage, a continuous and reliable supply of electricity will be required, without which the value for electricity will be limited, as will the willingness of users to pay for it. Some appliances (e.g., refrigerators) will not be very usable without continuous power. This makes bulk electrical energy storage services essential for renewable energy mini-grids, where sources are intermittent, and backup power from main grids is not an option.

Whereas large-scale storage solutions such as pumped water are practical for main grid, there are major gaps in current storage technologies usable for mini-grids. Lead-acid batteries—the only commercially available option—are too expensive, adding over 50% to the system costs for solar PV mini-grids and doubling the cost of electricity to the user. Other rechargeable battery technologies are not yet available at commercial scale, at the right level of cost and performance.

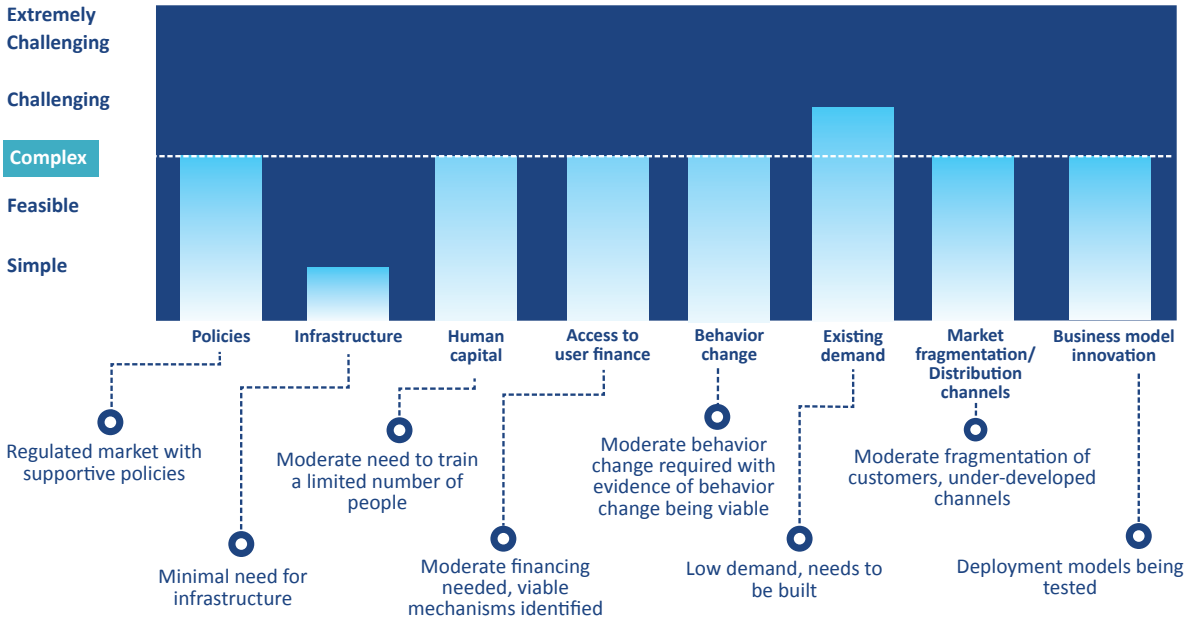
New battery technologies for bulk storage in decentralized renewable energy mini-grids are required to achieve a step change in the economics of rural electrification. Beyond low cost (low enough to support usage by populations living on less than $5 a day), such a technology will also need to be robust, durable, compact, easy to transport, and easy to install. It should also be modular and configurable, with the ability to scale up or down based on usage levels. Operation and maintenance should require minimal technical expertise, and limited additional infrastructure.

Each emerging technology faces its own set of challenges and opportunities. Lithium-ion batteries—currently in broad use for small devices such as mobile phones—will need to address barriers of cost, efficient scaling to mini-grid capacity, and safety hazards from overheating and fires. Flow batteries—relatively easy to configure and scale with limited technical expertise, and with a long life—have low energy densities, and need cooling mechanisms, along with safeguards for potentially toxic chemicals that are needed to make them. Sodium-sulphur batteries appear promising with respect to cost and performance, but are very bulky, operate at very high temperatures, and are corrosive.

The rapid pace of innovation in storage technologies will continue, 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 renewable energy farms in industrialized countries. This will likely benefit lithium-ion technology, which has a very high learning rate of 30% (IRENA, 2012). 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 in both automotive and power applications (Greentech Media, 2010). Since most of the emerging rechargeable battery technologies are still pre-commercial, it will likely take 5-10 years for the first wave of these to materialize.

Batteries are an essential component of decentralized rural mini-grids. Hence, the deployment challenges will be those associated with mini-grids writ large. These include limited demand, the very difficult market economics of a nascent market, and the dearth of technical skills required to install and maintain the systems. In addition, a number of safety issues will need to be addressed for technologies like lithium-ion and sodium-sulphur. While varying a little by the specific battery technology, deployment will be COMPLEX.

Breakthrough 3 – Difficulty of deployment



Breakthrough 4

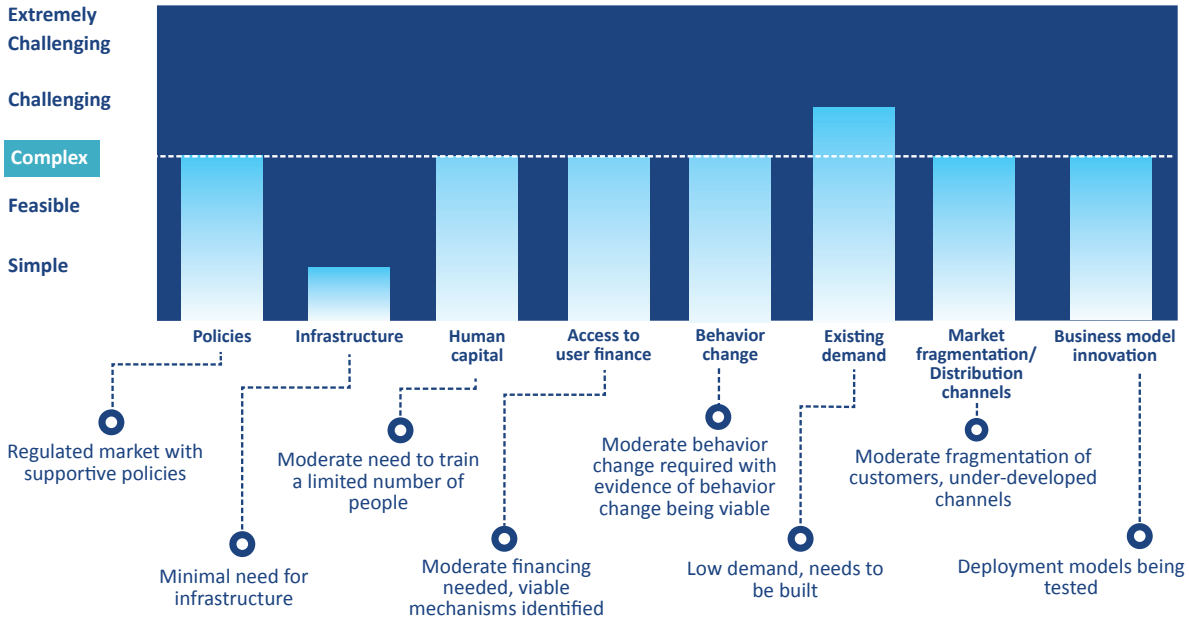
Affordable and easy-to-use grid management solutions for decentralized renewable energy rural mini-grids

Grid management involves forecasting, monitoring, regulating and troubleshooting at all stages of the grid: generation, distribution and consumption. It also involves prevention of losses and theft, as well as collection of revenues. Effective grid management can significantly improve quality of service and the overall economics of operating rural mini-grids, which are two of the main challenges currently facing aspiring mini utility providers. While solutions exist for large scale grids, they are not affordable or applicable at mini-grid scale, especially in low income rural settings where skilled workers may not be available.

A number of technical hurdles will need to be overcome: prepayment meters at the point of consumption (along with the hardware and software needed to use them) will need to become significantly less expensive; components for installing and integrating into the grid will need to be simplified and made more robust to deal with environmental factors, low voltage and voltage fluctuations; mobile payment applications will need to be integrated; and geography-specific forecasting systems for wind and solar will need to be developed. There is currently very limited market-driven pull for such systems. One encouraging trend, however, is the rapid evolution of a range of Internet of Things (IoT) systems (which are discussed in the section on Digital Inclusion) (Schneider Electric, 2014). A market ready solution will take about 10 years.

Grid management will be a key component of decentralized rural mini-grids. As such, the deployment challenges will be those associated with mini-grids writ large; limited current demand, challenging market economics, and a lack of skilled technicians to install and maintain the systems. As such, deployment will be COMPLEX.

Breakthrough 4 – Difficulty of deployment



Breakthrough 5

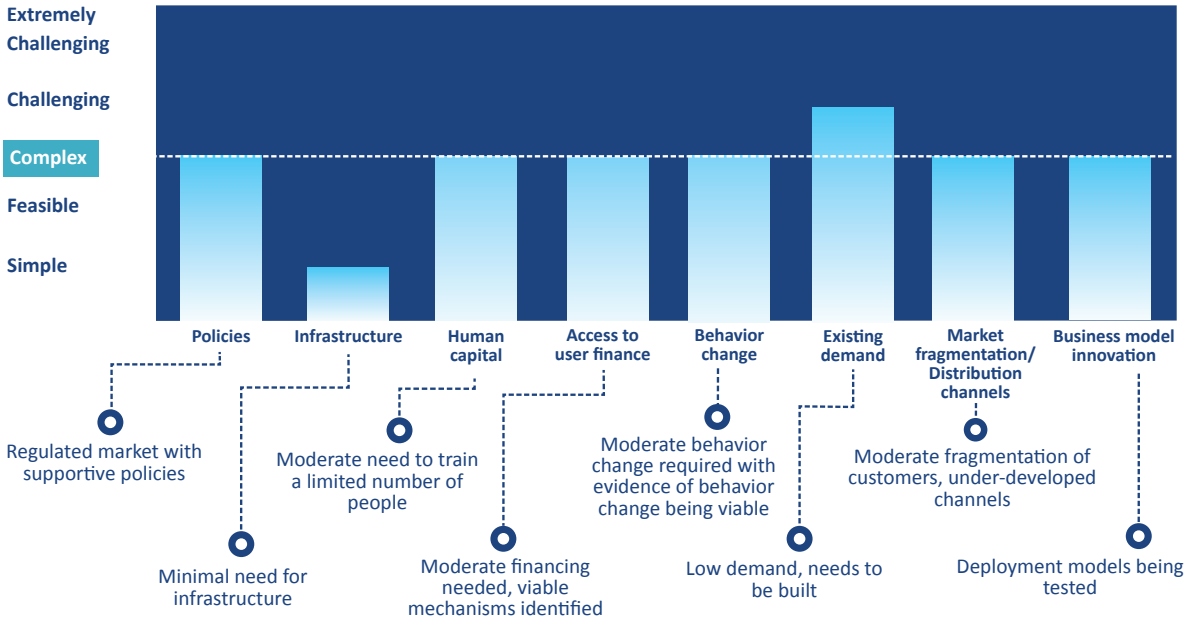
A 'utility-in-a-box' for making it simpler, cheaper and faster to set up and operate renewable energy mini-grids

Making renewable energy mini-grids 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, will significantly improve the economics of rural mini-grids. Specifically, this will reduce the balance-of-system costs which constitute a major portion of mini-grid installation CapEx. It will 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 mini-grids).

Such a utility-in-a-box should include all the key components of a decentralized renewable energy mini-grid, for generation, storage, and grid management. Standardization and self-help tools for installation, O&M and troubleshooting will be key. Similarly, modularity and configurability—to meet the specific power demands of a particular installation—will be crucial to ensure adequate capacity and maximum capacity utilization. In principle, an early version of such a technology can be developed relatively quickly, since 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 2-5 years. Over time, more sophisticated components (e.g., for improved grid management) can be added.

Deployment challenges will be the same as those impacting other breakthroughs related to mini-grids: limited current demand, challenging market economics, and a lack of skilled technicians to install and maintain the systems. As such, deployment will be COMPLEX.

Breakthrough 5 – Difficulty of deployment



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