

# ACHIEVING UNIVERSAL ELECTRIFICATION IN INDIA

A roadmap for rural solar mini-grids

April, 2016

© 2016. Institute for Transformative Technologies (ITT). All Rights Reserved.

### **Rights and Permissions**

This work may be reproduced, in whole or in part, without permission, with attribution.

### **Attribution**

Please cite this work as follows: "Institute for Transformative Technologies (ITT), April 2016. Achieving Universal Electrification in India: A roadmap for rural solar mini-grids"

### **For more information**

[info@transformativetechnologies.org](mailto:info@transformativetechnologies.org) | [www.transformativetechnologies.org](http://www.transformativetechnologies.org)

**The Institute for Transformative Technologies (ITT)** is dedicated to using the power of advanced technology to address the world's most pressing problems. To accomplish its mission, ITT partners with the world's leading R&D institutions (such as the Lawrence Berkeley National Lab, the University of California, the Indian Institute[s] of Technology, and the Massachusetts Institute of Technology), established companies in developing countries with a proven commitment to addressing social problems, government and inter-governmental agencies, and NGOs. Access to Electricity is one of ITT's core areas, and India is a primary country of focus.

This report is part of a broader collaboration between ITT and Tata Power Delhi Distribution Limited (TPDDL), a joint venture between Tata Power and the Government of the National Capital Territory (NCT) of Delhi. TPDDL, a leading electricity distribution company of India, serves a populace of 7 million in the North and North West parts of Delhi and has turned around the electricity distribution business from a loss-making venture to a successful business entity.

#### **Authors**

Dr Shashi Buluswar | Dr Hasna Khan | Tia Hansen | Zach Friedman

#### **Editor**

Urvashi J Kumar



## FOREWORD



Access to electricity has been an essential force in India's recent growth and progress. If India is to become a true leader on the global stage, such progress needs to continue, particularly for low-income rural communities. Unlike in decades past, however, India can no longer provide electricity to its citizens purely from conventional sources like coal, gas and large hydroelectric dams. It is time to turn the page, and to embrace the new generation of clean technologies.

The sheer number of Indian citizens without reliable electricity underscores the magnitude of the challenge. At the same time, the scale of the Indian market presents a tremendous opportunity for innovative solutions.

Solar power has made inroads into the Indian market, and can soon become cost-competitive with conventional sources. However, a number of technological and business innovations are needed to make it affordable, especially for India's rural poor.

This report analyses the underlying challenges in making solar power a reality in rural India, and identifies what actions can be taken to overcome them. In doing so, it lays a strong foundation for helping India achieve universal electrification. It also introduces a roadmap for helping India become a true global leader in clean energy, not just for itself, but also for the rest of the developing world.



**Jamshyd N Godrej**

Chair, Advisory Board, Smart Power India  
Chairman & Managing Director, Godrej & Boyce Mfg. Co. Ltd

## CONTENTS

Executive summary	01
<hr/>	
India's dual electrification imperative: Improving access and going clean	05
<hr/>	
The case for solar has now been established	09
<hr/>	
Within the spectrum of solar solutions, mini-grids offer the ideal choice for much of rural India; however, they are also the most nascent	13
<hr/>	
A number of significant hurdles are keeping solar mini-grids from becoming a large-scale reality	18
<hr/>	
The roadmap to achieving the dual electricity imperative: A combination of technology, business and policy innovations	33

## Executive Summary

---

India, as one of the world's largest and most rapidly emerging economies, sits at the intersection of two major challenges when it comes to electricity: how to provide reliable electricity to approximately 235 million people in rural communities who currently lack access; and how to control the environmental impact of powering such a large population and expanding economy. The Government of India has made it a priority to increase access to electricity for rural communities, emphasising renewable and decentralised sources. It has done so by mandating construction of electricity infrastructure across thousands of villages, setting ambitious renewable energy targets, and committing sizeable budgets.

There is now a groundswell of opinion that solar is the ideal renewable energy technology for most of India. There is also strong evidence to suggest that decentralised mini-grids offer the best modality for implementing solar power systems in rural areas of India. Unfortunately, there are a number of hurdles that are preventing solar mini-grids from becoming a large-scale reality in rural India: (i) Solar power, despite having dropped significantly in cost, is still considerably more expensive than conventional sources like coal; this can make it difficult for the government to choose solar over coal. (ii) The cost of solar mini-grids is also too high relative to what low-income rural consumers in India can afford in electricity bills. Also, the absence of affordable appliances for low-income households and enterprises (e.g., refrigerators, irrigation pumps) severely restricts demand for electricity, which in turn exacerbates an already difficult economic equation for utilities hoping to invest in solar mini-grids. (iii) The capital costs of mini-grids are distributed over a large number of components, making it very difficult to achieve major cost reductions. (iv) Lead-acid batteries—the default technology for energy storage in mini-grids in developing countries—have significant technical challenges that limit their usability; there is currently no other affordable, reliable battery technology on the market (although some are emerging). (v) “Smart” meters for electronically monitoring and managing usage are too expensive, largely due to the small size of the current market. (vi) Mini-grid installations currently do not function as a well-integrated system; instead, they operate as a sub-optimal, loose assembly of disparate components, resulting in losses across the system. (vii) “Anchor” users to ensure adequate, predictable consumption, can be hard to find and manage. (viii) There is a significant lack of financing for solar mini-grids, largely because they are still considered risky. Regulations governing off-grid electrification in India are still emerging. While there has been considerable momentum on this front in recent months, any lack of clarity on such policies can increase investors' perception of risk.

These challenges may force the Indian government—as with governments around the world—to choose between affordably providing electricity to its people, and controlling its environmental footprint. In the worst case scenario, India will meet its rural electrification targets through conventional sources like coal, and renewables will be restricted to financially lucrative urban and peri-urban markets. We believe that these challenges can be overcome, and solar mini-grids can fulfill their promise of providing clean electricity to millions of rural households in India. We recommend an ambitious three-pronged approach, combining technology innovations, investment from large-scale private sector actors, and targeted policy changes.

## 1 TECHNOLOGY INNOVATIONS

**Improved batteries.** Three alternatives to existing lead-acid chemistry should be evaluated. First, “advanced” lead-acid, which make proprietary enhancements to existing lead-acid chemistry. Second, sodium-ion, a new chemistry developed for mini-grids, which potentially lends itself to low-cost, large-scale manufacturing in a country like India. Third, a hybrid system comprised of an electronic charge control mechanism to combine lithium-ion and conventional lead-acid batteries.

**An integrated “utility-in-a-box”.** A suite of components needs to be developed, with standardised components, metering, automated billing and collection, and inverter and charge control electronics. These must be optimised for the specific battery technology and usage. The system should also lead to a 10-20% cost reduction.

**Affordable, energy-efficient refrigeration,** in order to increase demand for electricity.

**Brushless DC motors for fans and irrigation pumps,** as an alternative to the existing AC motors which are energy-intensive. This can also be a critical lever for increasing affordable consumption.

## 2 A PIVOTAL INVESTMENT FROM A LARGE-SCALE INCUMBENT IN THE VALUE CHAIN

For each of these innovations, the best technology may not automatically win in the marketplace. Key considerations include market demand, capital investments required for manufacturing, strength of the supply chain and availability of the necessary materials and workforce. Hence, in addition to evaluating and developing the above technologies, it will be critical to conduct a thorough operational analysis to determine the feasibility of large-scale manufacturing (ideally in India). An established private sector player will need to make a pivotal investment, to catalyse investments from others along the value chain.

## 3 TARGETED POLICY CHANGES TO BUILD ON THE GOVERNMENT’S STATED COMMITMENTS

**Public-private partnerships (PPPs) between the government and private utility companies,** much like those used to provide electricity to India’s largest cities. This model has proven itself in urban centers, and can work in rural areas as well.

**Allowing access to existing public infrastructure** in areas where there is a government grid but an unreliable or inadequate supply of electricity. This can significantly reduce the capital cost of setting up mini-grids. This also lays the foundation for thousands of such distributed solar power stations to—over time—be integrated into the national grid.

**Incentives for community electrification,** modeled after the *Swachh Bharat* initiative (which promotes construction and use of toilets), to encourage household and community-level electrification. (e.g., subsidies for households to have their homes connected, with additional community-level incentives for payment of bills, etc.).

Over the next two to three years, ITT will work to find solutions in the first two areas: promising technologies to improve the cost and performance of solar mini-grids, and innovative business models for key private sector actors.

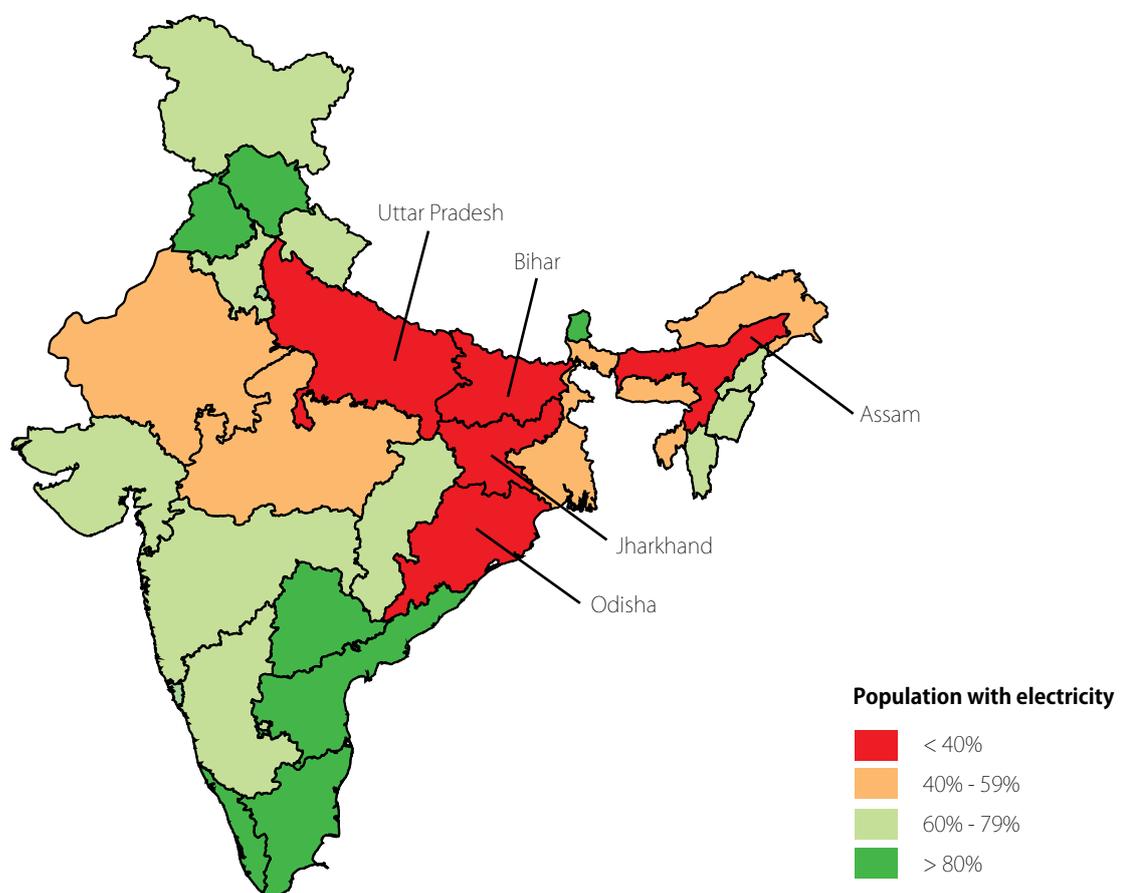


235 million  
Indian citizens  
**mostly in rural areas**  
do not have electricity



## India's dual electrification imperative: Improving access and going clean

As India continues to emerge on the global stage as an economic and geopolitical power, it still needs to overcome a number of major challenges related to poverty alleviation and development. Among the most important of these is access to electricity. Today, approximately 235 million Indian citizens—mostly in rural areas—do not have electricity,<sup>1</sup> making India the country with the largest population of people living without electricity. These people are either entirely off the main grid, or their communities have only token access to a grid through which very little electricity actually flows to their homes and workplaces. This problem is particularly acute in states with large concentrations of rural poverty, such as Bihar, Odisha, Uttar Pradesh and Jharkhand (Exhibit 1).<sup>2</sup> In addition to the official number of people without electricity, many millions have only nominal, highly unreliable connections.



Source: Government of India, 2011 Census.

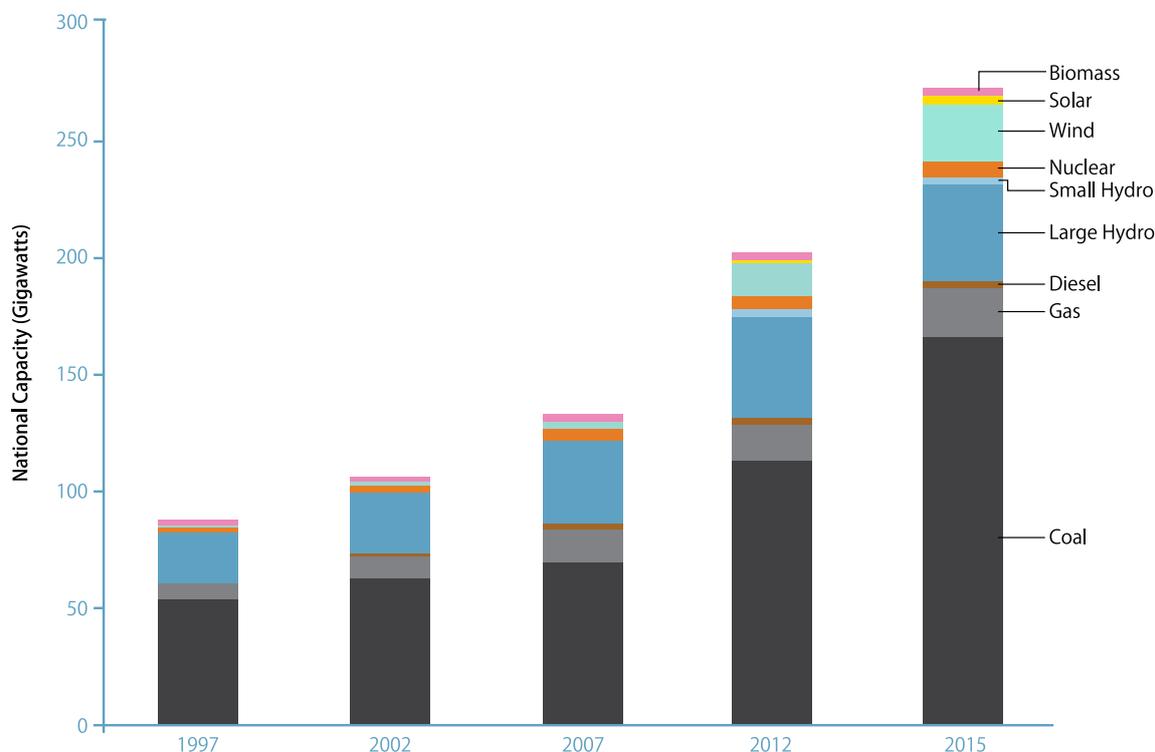
### Exhibit 1.

A large portion of India lacks access to electricity, particularly in states with large concentrations of rural poverty, such as Bihar, UP, Jharkhand and Odisha.

<sup>1</sup> World Bank Development Indicators, 2015; International Energy Agency, 2015.

<sup>2</sup> Government of India, 2011 Census.

Still, over the past two decades, India has made tremendous strides in both economic development and electrification. Electrification rates have jumped from 50% to almost 80% between 1990 and today. The government's *Deendayal Upadhyaya Gram Jyoti Yojana* initiative promises to further accelerate electricity access to thousands of villages across the country.<sup>3</sup>



Source: India Central Electricity Authority, March 2015.

#### Exhibit 2.

India's power generating capacity has been dominated by coal, gas and large hydro. However, renewables grew from a mere 1% of the overall generating capacity in 1997 to 13% in 2015.

Historically, the increase in electrification has been through coal, gas and large-scale hydropower, which have consistently accounted for the lion's share of India's power sources (Exhibit 2).<sup>4</sup> As a result, India's environmental footprint has dramatically worsened, and it has become one of the world's leading emitters of greenhouse gases. With the world's largest population without electricity, and the world's third largest mass of greenhouse gas emissions, no other country in the world today faces such a monumental concurrency of these two challenges (Exhibit 3). In addition, pollution from coal-fired power plants is reported to cause the premature deaths of more than 100,000 Indian citizens each year, costing the Indian economy US\$4.6 billion annually.<sup>5</sup>

Naturally, India's large population is the single biggest driver of the scale of these issues. (On a per-capita basis, India's emissions remain considerably smaller than industrialised countries. India's per capita CO<sub>2</sub> emissions are approximately one-tenth that of the USA.) Similarly, on a percentage basis, India's electrification rate (79%) is only a few percentage points lower than the world average of 85%.<sup>6,7</sup>

<sup>3</sup> Government of India, *Deendayal Upadhyaya Gram Jyoti Yojana* (<http://www.ddugjy.gov.in/mis/portal/index.html#>).

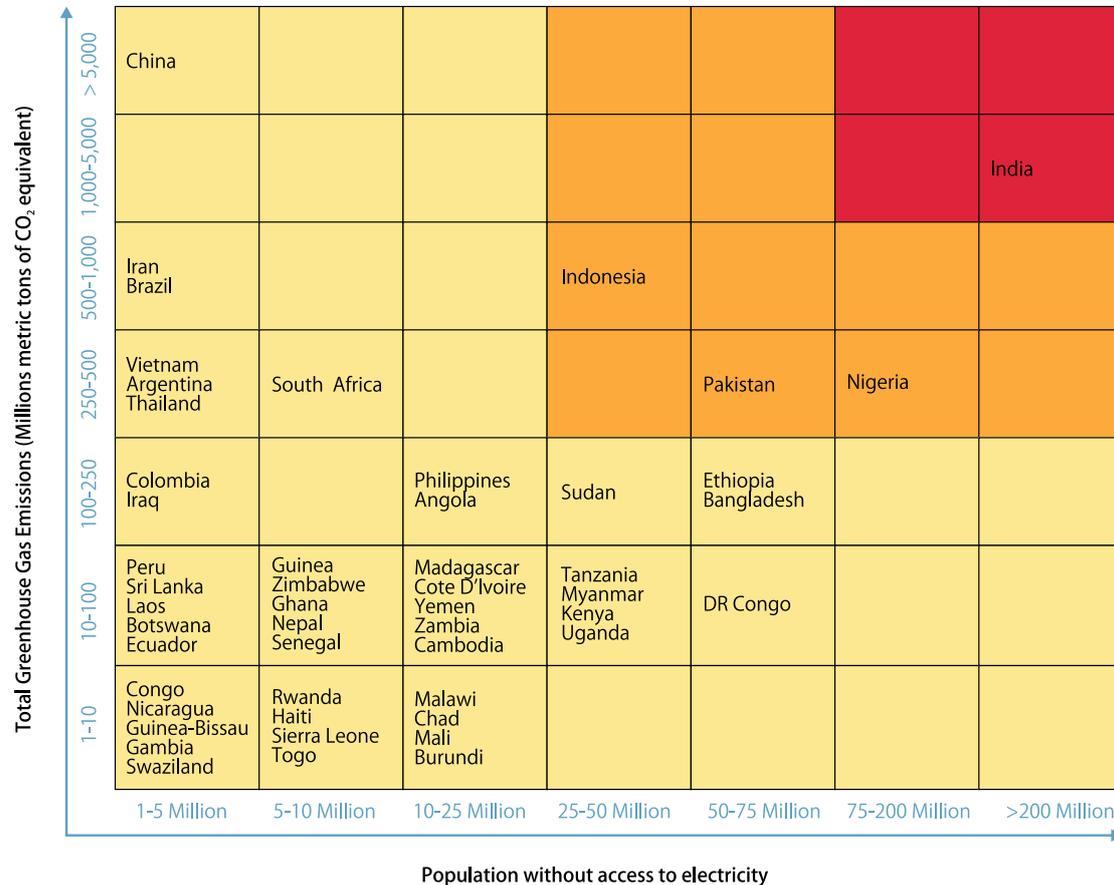
<sup>4</sup> India Central Electricity Authority, March 2015.

<sup>5</sup> L. Friedman, *Scientific American*, "Coal power in India may cause more than 100,000 premature deaths annually", 11 March 2013.

<sup>6</sup> IPCC, 5<sup>th</sup> Assessment Report, 2014; World Resources Institute, *Climate Data Explorer*, 2015.

<sup>7</sup> World Bank Development Indicators, 2015.

Still, the sheer magnitude of the numbers underscores the challenge the Indian government faces with respect to both the level of investment required, and complexity of implementing major nationwide initiatives.



Sources: World Bank Development Indicators, 2015; Intergovernmental Panel on Climate Change, 5<sup>th</sup> Assessment Report, 2014.

**Exhibit 3.**

More than any other country in the world, India faces a monumental challenge at the intersection of electricity access and greenhouse gas emissions. This reflects India’s vast population, its economic output, the state of its infrastructure, as well as endemic poverty.

As India undertakes this dual challenge, a number of scenarios are possible. In the best case scenario, a single set of synergistic solutions will address both problems simultaneously. Indeed, renewables such as solar, biomass, small hydro, and wind, which are suited to serve off-grid rural communities, have collectively grown from a negligible 1% of production in 1997, to more than 13% in 2015 (Exhibit 2).

Over the past year the Government of India—towards its stated commitment of combating climate change—has announced plans to add 175 gigawatts (GW) of clean energy by 2022,<sup>8</sup> and to having 40% of its electricity come from renewable and other low-carbon sources by 2030.<sup>9</sup> Beyond combating climate change, achieving these ambitious objectives could also go a long way towards improving access to electricity across the country.

<sup>8</sup> NDTV, “PM Modi Stresses India’s Commitment for 175 GigaWatts Clean Energy Goal”, 28 September 2015 (<http://www.ndtv.com/india-news/pm-modi-stresses-indias-commitment-for-175-gigawatts-clean-energy-goal-1223706>).  
<sup>9</sup> The Guardian, “India unveils climate change plan”, 2 October 2015 (<http://www.theguardian.com/world/2015/oct/02/india-pledges-40-percent-electricity-renewables-2030>).

In the worst case, however, new supplies of electricity will barely keep up with the ever-growing demand and India will have to rely heavily on non-clean sources, many of which are currently more cost-effective than sustainable sources. Consequently, rural electrification will be achieved in name only, with villages having poles and cables but no meaningful access to electricity,<sup>10</sup> and the pace of rural electrification will slow down because the remaining un-electrified communities will be increasingly remote and hard to reach. Even though clean energy investments are likely to keep growing, they will focus on financially attractive urban and peri-urban markets, and less lucrative rural areas will be left out of the conversation on sustainable development. This, in turn, will exacerbate the gap between India's less developed regions, and the ones that are better integrated into the modern national and global economies.

Unless the economics of rural electrification improve markedly, nationwide access to electricity is unlikely to become a reality, and access to electricity in rural areas will be limited to small home systems and nano/micro-grids.

---

<sup>10</sup> The Hindu, "Electrified, but without electricity", 7 October 2014  
(<http://www.thehindu.com/opinion/op-ed/electrified-but-without-electricity/article6475940.ece>).

## The case for solar has now been established

Solar, still at less than 4% of national production, has grown dramatically over the past few years.<sup>11</sup> The growth of solar power in India reflects a larger global trend, driven by the rapidly decreasing cost of solar photovoltaic (PV) technology (Exhibit 4).<sup>12</sup> Apart from the favourable trend in the prices of solar photovoltaic technology, several other factors make solar power the most attractive mechanism to electrify rural India.

- Sunlight is an abundant resource through most of India, with almost 60% of the country receiving annual average global insolation of 5kWh/m<sup>2</sup>/day, which is more than adequate for decentralised solar power (Exhibit 5).<sup>13,14</sup>
- Solar power systems are modular, and lend themselves to distributed installation. This dramatically reduces the need for large initial capital investments, and the systems can gradually scale up as demand increases. This is in stark contrast with conventional coal-fired and gas-fired plants, which require significant investment for centralised generation, with limited scope for gradual ramp-up or distributed generation. Solar installations require limited maintenance, especially from high-skilled technicians. Furthermore, there are no ongoing costs such as fuel. That said, the levelized cost of solar is currently considerably higher than coal and other sources.<sup>15</sup>



© The Rockefeller Foundation

<sup>11</sup> India Central Electricity Authority, March 2015.

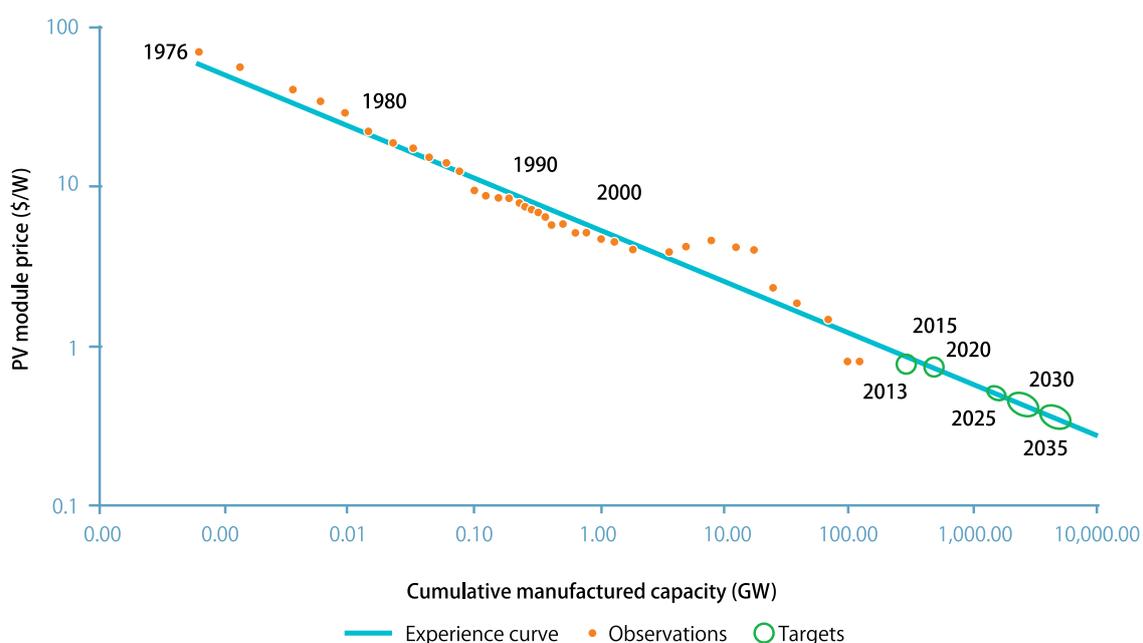
<sup>12</sup> International Energy Agency, "IEA Technology Roadmap: Solar Photovoltaic Energy", 2014.

<sup>13</sup> T. V. Ramachandra, R. Jain and G. Krishnadas, "Hotspots of solar potential in India", *Renewable and Sustainable Energy Reviews*, 15 (3178–3186), 2011.

<sup>14</sup> Solar Energy Centre, Ministry of New and Renewable Energy, 2010 ([http://mnre.gov.in/sec/GHI\\_Annual.jpg](http://mnre.gov.in/sec/GHI_Annual.jpg)).

<sup>15</sup> International Energy Agency, "Projected costs of generating electricity", 2015. Note: The levelized cost of electricity (LCOE) is the ratio of the present value of lifetime system costs (discounted at the rate of cost of capital), to lifetime electricity generation.

- A number of technical hurdles that have historically prevented distributed solar power from proliferating are finally beginning to be overcome with the help of innovative technologies accompanying the burgeoning solar market. (A number of these innovations are discussed later in this report.)
- India has a number of homegrown manufacturers capable of producing many of the necessary components of solar power systems, at scale. As this market matures, setting up and maintaining solar power systems will not be hindered by unavailability of quality components, or by the absence of a service and maintenance ecosystem.
- The policy and investment environment for solar in India has been encouraging. The government has committed to a target of “100% electrification by May 1, 2018” with a 2016 budget of more than \$1.25 billion (INR 87,765 crores).<sup>16</sup> The government’s Decentralised Distributed Generation (DDG) scheme also creates strong incentives for renewables like solar.<sup>17</sup>
- India has several utilities, both public and private, through public-private partnerships, with the capacity to rapidly install solar mini-grids and begin providing electricity to rural communities.



Source: International Energy Agency, “IEA Technology Roadmap – Solar Photovoltaic Energy”, 2014.

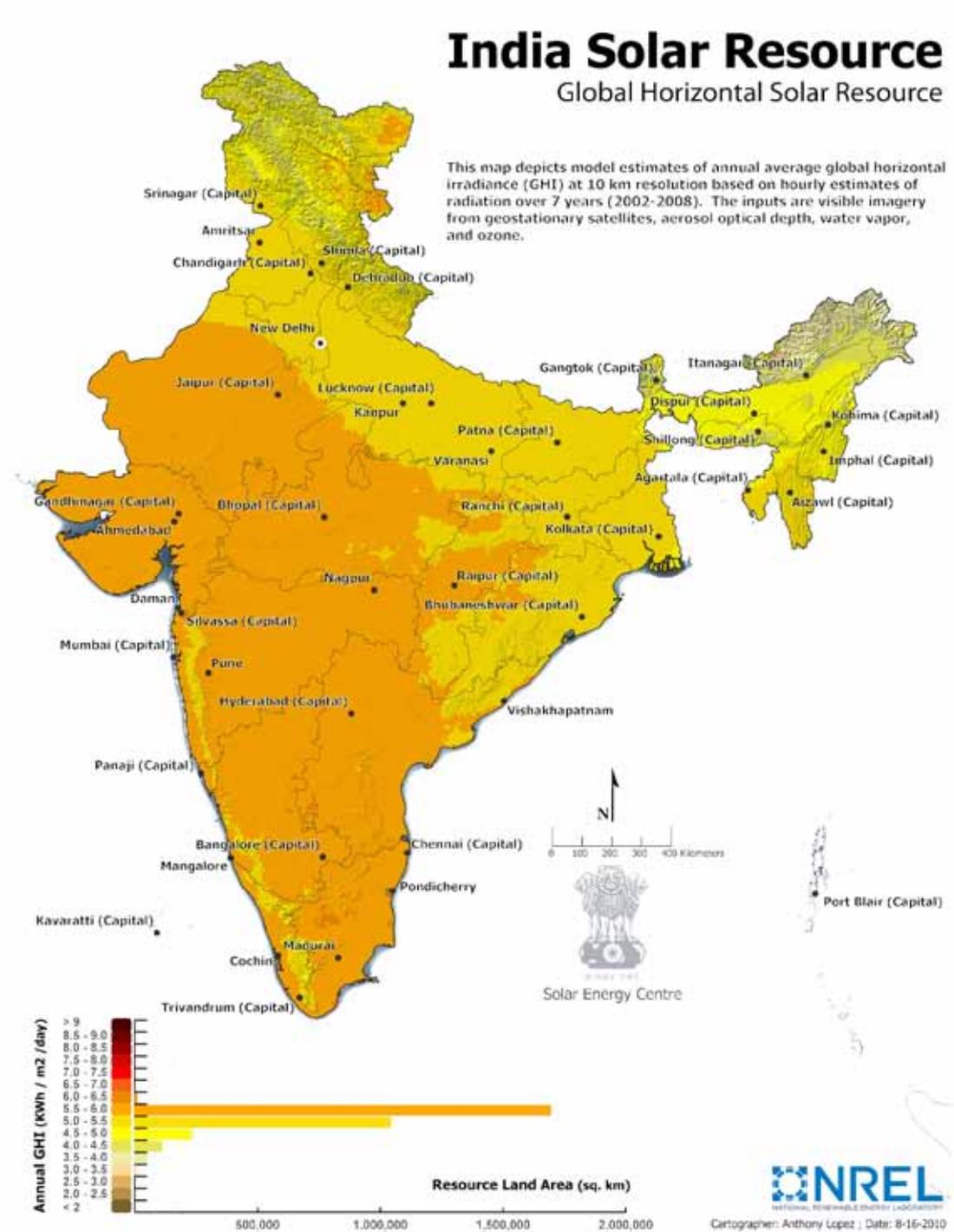
**Exhibit 4.**

Over the past several years, the cost of solar PV has been falling globally—a trend that is projected to continue.

<sup>16</sup> India Today, “Budget 2016: Power ministry gets Jaitley’s thumbs-up over rural electrification”, 29 February 2016 (<http://indiatoday.intoday.in/story/budget-2016-power-ministry-gets-jaitley-thumbs-up-over-rural-electrification/1/608088.html>).

<sup>17</sup> Government of India, Ministry of Power (<http://powermin.nic.in/d-d-g>).

Notwithstanding the many advantages of solar, it is important to note that there are a number of localities and contexts where other renewables may be more appropriate.



Source: NREL, 2010.

**Exhibit 5.**

India has adequate solar resources through much of the country.



## Within the spectrum of solar solutions, mini-grids offer the ideal choice for much of rural India; however, they are also the most nascent

There are five modalities in which solar power systems are being deployed in India: Grid-connected urban/peri-urban installations, which can eventually enable extension of the grid to rural communities; decentralised (AC) mini-grids of various sizes (5kW, all the way up to 100kW); decentralised (DC) micro/nano-grids; small islanded solar home systems; very small systems to power lights and mobile phones.

The following discussion makes the case that decentralised AC mini-grids are the ideal option for providing a meaningful amount of electricity to most rural communities.

### Grid-connected urban and peri-urban installations are likely to reach only those rural areas which are already close to an existing grid, rather than remote communities

On one end of the spectrum of solar installations are urban and peri-urban installations such as solar farms and rooftop panels, connected to the main grid. As the number of such installations grows, they can collectively generate enough electricity to help the grid extend and reach hitherto un-electrified rural communities. There are, however, three key risks with relying on grid extension as the exclusive (or primary) means of reaching rural areas. To begin with, the more distant a community is to the existing grid, the more it will cost to build the infrastructure (cables, poles, sub-stations) required to reach it. As a result, remote communities may have to wait a very long time before they get access to electricity. The second risk is that remote parts of the grid will be vulnerable to breakages or failures anywhere along the long chain of distribution lines. The third risk is that the mere construction of cables-and-poles infrastructure can be mistaken for true access to electricity. Indeed, India has no shortage of villages that are nominally connected to the grid, but rarely have electricity.<sup>18</sup> Hence, it is reasonable to conclude that grid extension is a more logical choice for rural communities located relatively close to a functioning, reliable part of the existing grid.

### Micro/nano-grids and small home systems do not generate enough electricity to power an adequate suite of appliances

At the smaller end of the solar spectrum are home systems and small micro/nano-grids. Solar home systems are increasingly becoming affordable, and have gained considerable market traction in recent years.<sup>19</sup> Currently, such installations generate just enough electricity to enable a narrow range of uses such as lighting and charging of mobile phones. For very poor and/or remote communities, this is often the only option for any access to electricity, at least in the near term. Over the next few years, the continued proliferation of solar home systems—combined with the introduction of affordable, energy-efficient appliances—is likely to make considerable headway in providing affordable electricity to low-income rural households, without the need for investments in infrastructure. However, as we argue later in this report, true long-term development will require households to have a broader range of life-enhancing appliances such as refrigerators, fans, TVs and/or other information and communication (ICT) devices, etc. Similarly, appliances to improve workplace productivity (e.g., irrigation pumps and a range of other motorized implements) are also required, to truly benefit from access to electricity.

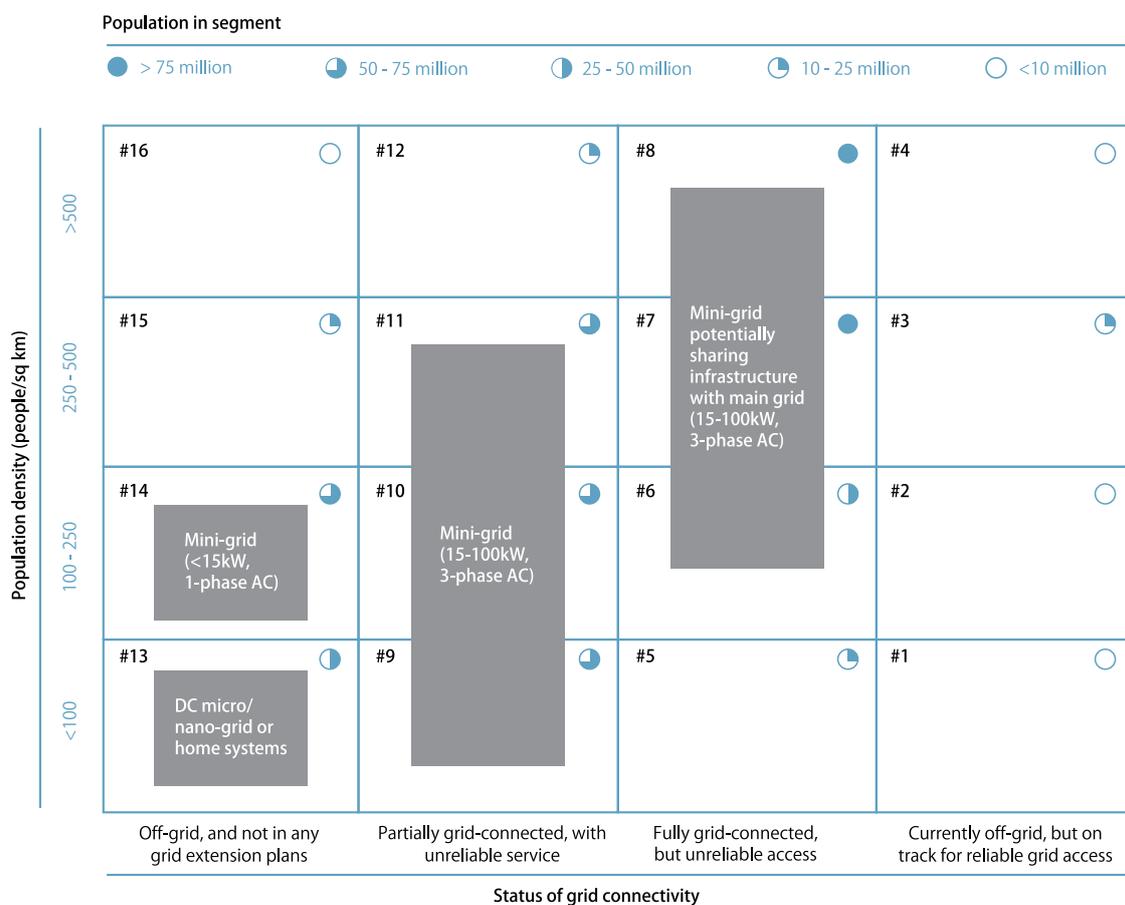
<sup>18</sup> The Hindu, "Electrified, but without electricity", 7 October 2014 (<http://www.thehindu.com/opinion/op-ed/electrified-but-without-electricity/article6475940.ece>).

<sup>19</sup> IFC, "Solar lighting for the base of the pyramid: overview of an emerging market", 2010.

Without dramatic improvements in energy-efficiency, small solar home systems will not generate enough electricity to power such a broader range of appliances.<sup>20</sup>

## Mini-grids are the ideal option for rural India

In the middle of the spectrum of solar power systems, are two types of decentralised installations that can serve the needs of users who are either far from the grid, or are nominally grid-connected but with unreliable supply. These include dedicated systems (usually in the 5-15kW scale) to serve failure-averse users such as telecom towers and hospitals, and mini-grids in the 5-50kW (or larger) range which serve individual villages and surrounding higher-demand loads such as telecom towers, small enterprises, factories or institutions.



Source: ITT analysis.

### Exhibit 6.

The majority of India's rural communities live in areas which lend themselves to mini-grids of various sizes and configurations. Please note that this segmentation applies to India's less populated rural regions.

<sup>20</sup> Please note that we do not consider larger rooftop installations (1kW or more) to be relevant to rural India, because few homes there are built with structures solid enough to support an array of solar panels.

Exhibit 6 shows our estimate of the size of various segments (numbered 1-16) of the Indian rural population with respect to reliable current/projected grid access and population density, and our assessment of the electrification modality most appropriate for that segment.

**Segments #6-8** represent communities that have medium to high population density and have grid access (i.e. poles and cables connected to the main grid), but do not have reliable electricity. These communities are ideal for mini-grid systems, which can produce their own electricity, but potentially using the existing public grid for local distribution. The existing infrastructure is likely already set up for 3-phase AC to support heavier industrial usage. In most cases, policy changes by relevant governmental agencies will be required, to allow shared use of the existing infrastructure, while ensuring that the electricity produced at a mini-grid station serves the local community rather than being transmitted elsewhere. This may require cutting off the local grid from the main grid so that the locally produced electricity can remain local.

**Segments #9-11** represent communities that have low to medium population density. The grid typically reaches some part of these communities (e.g., along the main highway), but does not branch out beyond that, leaving most of the community off-grid. Such communities can ideally be served by decentralised mini-grids, with capacity between 15kW and 50kW depending on the area's population and industrial activity. If these systems use 3-phase AC infrastructure, they can also increase productive business activities, with the ability to integrate into the main grid, over time.

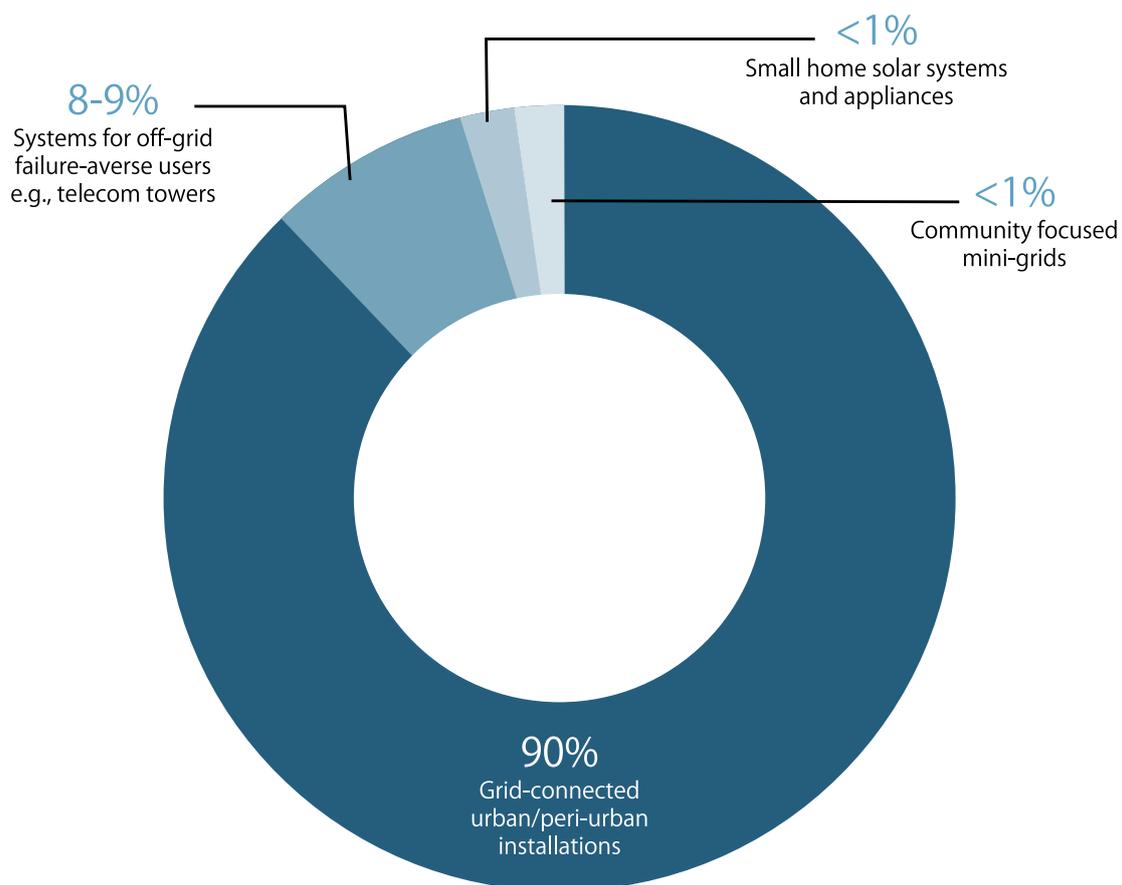
**Segment #14** represents populations of medium density that are fully off-grid, and are likely to be so even in the foreseeable future. They tend to have limited industrial activity, and hence single-phase AC mini-grids smaller than 15kW will perhaps suffice. Larger systems will likely not be economically feasible, because their capacity cannot be fully utilised yet.

**Segment #13** represents sparsely populated, off-grid communities, typically with limited economic means or industrial activity. Introducing DC nano-grids or solar home systems capable of powering LED lights, chargers for mobile phones, and similar light-load uses, can lay the platform for longer-term development. Arguably, this level of access can be considered "pre-electrification".

**Segments #1-4** represent rural communities of various population densities that are currently off-grid, but on track to being connected to the grid with reliable electricity. These account for a relatively small portion of the overall population. The same is true of segments #5, #12, #15 and #16. As such, this report does not focus on these segments.

Based on the above, our analysis concludes that mini-grids (of different sizes and configurations) are the ideal option for providing electricity for the vast majority of Indian rural communities currently without access. Over time, decentralised mini-grids can be absorbed into the main grid, as it extends to increasingly remote communities. When this happens, the mini-grids will begin contributing to the national electricity supply, rather than only serving the local communities where they are installed.

Currently, however, most of the solar-related activity in India (Exhibit 7) is either in grid-connected urban and peri-urban installations (constituting roughly 90% of installed solar capacity across the country), or in small home and appliance-based systems, which (by virtue of being very small) collectively constitute less than 1% of nationwide solar output. In addition, dedicated off-grid systems supporting telecom towers (and similar failure-averse users) account for 8-9% of national installed capacity.<sup>21</sup> As of early 2016, there are very few organisations in India using solar mini-grids to provide electricity to rural communities.<sup>22</sup> We estimate that they collectively supply less than 1% of national solar output.



Source: ITT analysis based on disparate data sources.

#### Exhibit 7.

Most of the installed solar capacity (as of 2015) in India is dedicated to grid-connected urban and peri-urban systems, or systems supporting telecom towers and similar failure-averse users. Mini-grids, while being the ideal option for the majority of rural communities, are nascent.

As the next section discusses, mini-grids—despite being the ideal option for most communities without access to electricity—face a number of challenges, which are keeping them from proliferating. Unless these challenges are overcome, it is likely that solar electrification in India will largely focus on the more commercially lucrative urban and peri-urban installations connected to the main grid. Rural communities will have to make do with marginal systems that do little more than power LED lights and charge mobile phones. Addressing the technical, business and policy hurdles that face solar mini-grids, therefore, is a national imperative for India.

<sup>21</sup> ITT analysis based on disparate data sources.

<sup>22</sup> Global Network on Energy for Sustainable Development (GNESD), “Renewable energy-based rural electrification: The Mini-Grid Experience from India”, prepared by The Energy and Resources Institute (TERI) for GNESD, 2014.

The majority of India's rural communities live in areas which lend themselves to **mini-grids** of various sizes and configurations



## A number of significant hurdles are keeping solar mini-grids from becoming a large-scale reality

---

Off-grid electrification, a relatively new phenomenon in India, has become an increasing priority for the Indian government. As noted earlier, the government has launched major initiatives such as the *Deendayal Upadhyaya Gram Jyoti Yojana* and the associated Decentralised Distributed Generation scheme. It has also allocated a substantial budget (INR 87,765 crores, which is over \$1.25 billion) for rural electrification.

However, at the current cost of solar mini-grids (discussed below), this will provide meaningful access to electricity to fewer than 15 million additional people—a small fraction of the approximately 235 million currently without access.<sup>23</sup> Even if these funds were used exclusively for grid extension with conventional sources like coal, only a fraction of the population without access would be reached. This is because of the extremely high initial investment required to construct the new power plants needed to generate enough electricity.

This poses a difficult choice for the government, between improving electricity access and controlling its environmental footprint and related consequences for public health. Therefore, it is likely that the private sector—potentially working with civil society—will have to play a significant role in amplifying the government’s commitment, by developing innovative technologies to reduce the cost of solar mini-grids, and demonstrating that clean electricity can be provided to rural communities through financially sustainable models.

The typical solar mini-grid<sup>24</sup> in rural India provides about 15-30kW of power to serve a village of about 1,000 people (200 households), related business activities, as well as “anchor” users. As described in more detail later, anchor users ideally guarantee enough consumption to make the mini-grid financially viable. However, and not surprisingly, only a small percentage of Indian villages tend to have reliable anchor users. A typical household in such communities earns \$3-\$5 per day,<sup>25</sup> and cannot afford household appliances beyond LED lights and mobile phones (although anecdotal evidence suggests that a large number of low-income Indian households prioritise TVs over basic amenities). Such communities also have a small marketplace with businesses such as tea stalls, snack shops, small general stores (some of which own refrigerators), small clinics, telecom kiosks, and photography studios. Some villages have mobile phone towers. The capital expense (CapEx) to build such a 30kW mini-grid is currently approximately \$85,000 or about \$2.85 per watt (Exhibit 8).<sup>26</sup> Over the course of the lifetime of the system, this translates to a cost of about 40 cents/kWh. We assume an average lifespan of 10 years across the various components. While a number of components (panels, civil structures, cables) can last longer under favourable conditions, we conservatively assume that many of them will likely have shorter-than-advertised lifespans under India’s harsh climatic conditions (heat, heavy rains, dust etc.). Details of the various components are discussed later.

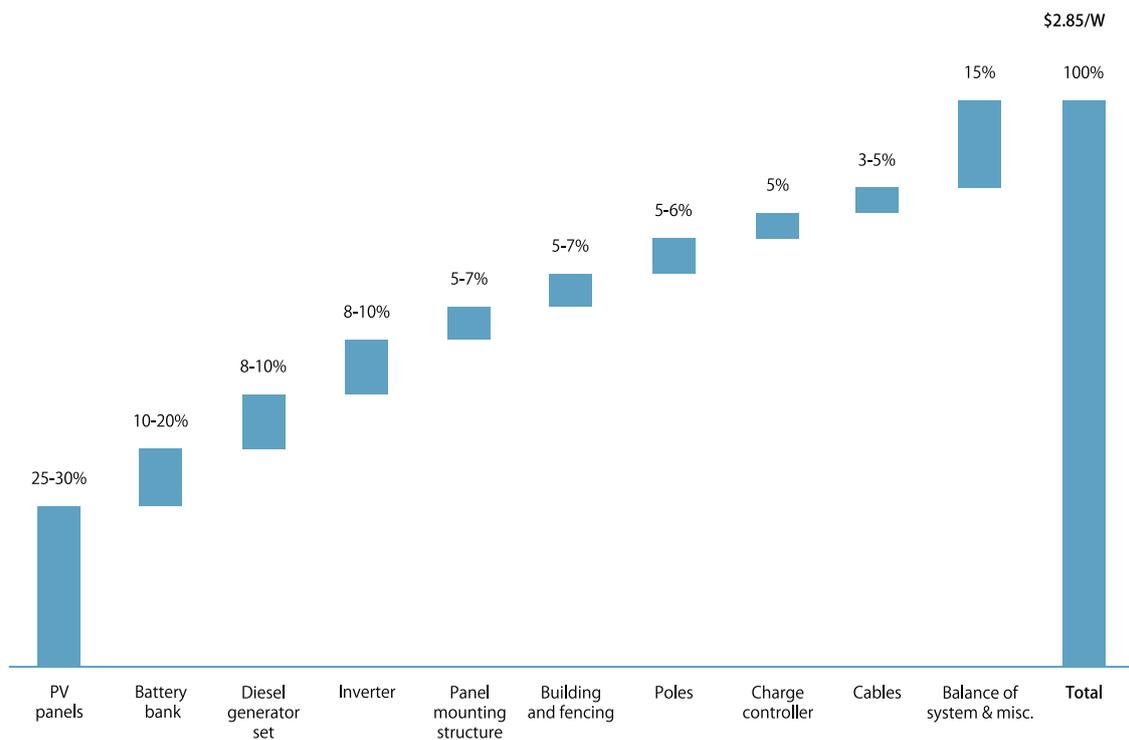
---

<sup>23</sup> It currently costs more than \$85,000 to build a mini-grid to electrify a village of 1,000 people. Hence, \$1.25 billion will electrify slightly more than 12,500 villages, or 12.5 million people.

<sup>24</sup> Please note that solar mini-grids are still new to the Indian context, and the typical configuration may change in the years to come.

<sup>25</sup> World Bank Development Indicators, 2015; R. Dholakia, M. Pandya, P. Pateriya, “Urban-Rural Income Differential in Major States: Contribution of Structural Factors”, IIM-Ahmedabad, 2014.

<sup>26</sup> The Rockefeller Foundation – Smart Power for Rural Development initiative.



Source: The Rockefeller Foundation.

**Exhibit 8.**

The typical 30kW solar mini-grid serving rural communities in India costs about \$2.85 per watt to build, i.e. the complete system costs \$85,000 when it is first set up. This CapEx is distributed over a large number of components, the most expensive of which are solar panels (25-30% of CapEx) and batteries (10-20% of CapEx).

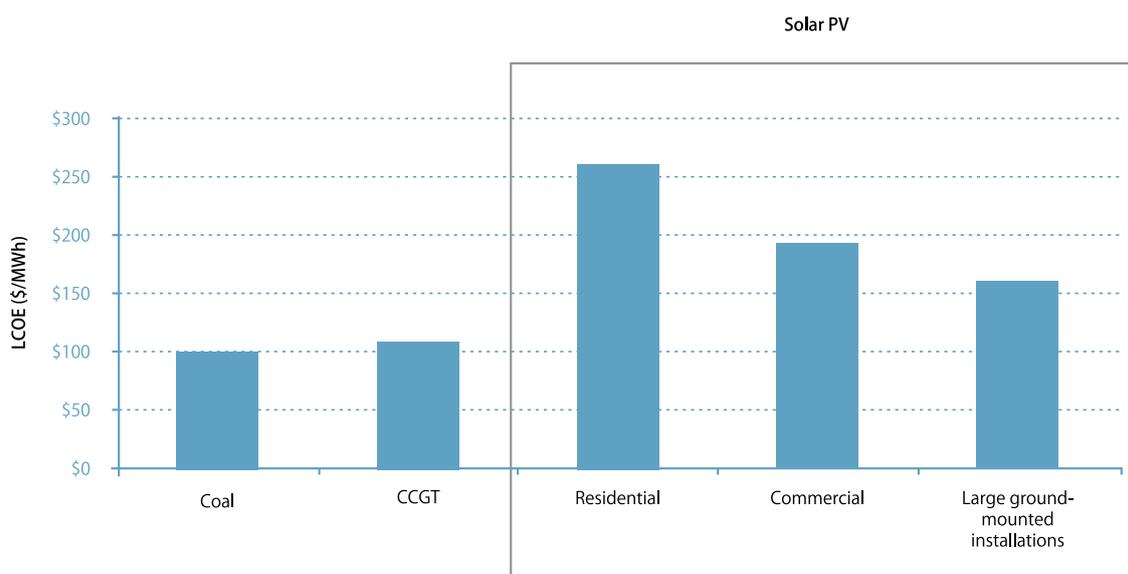
In this context, solar mini-grids, and utilities aiming to provide electricity to rural communities using solar mini-grids, face eight major challenges.

**CHALLENGE 1**

Solar power is much more expensive than conventional sources like coal.

Despite the decreases in the cost of solar PV, it is still significantly more expensive than coal, gas and other conventional sources (Exhibit 9).<sup>27</sup> This poses a difficult choice for the government, between increasing access to electricity and investing in clean energy. It is important to note that while the *levelized* cost of electricity currently favours coal and similar conventional sources, their scale of operations still requires significant investment to build, with limited scope for gradual ramp-up. Despite this, and the promising longer-term outlook for solar PV, the short-term challenges remain.

<sup>27</sup> International Energy Agency, "Projected costs of generating electricity", 2015.



Source: International Energy Agency, "Projected costs of generating electricity", 2015.

**Exhibit 9.**

Currently, solar PV still costs considerably more than conventional energy sources. This chart compares median levelized costs (\$/MWh, calculated at 10% cost of capital) observed at installations around the world, for coal, combined cycle gas turbines (CCGT), and three types of solar installations: residential, commercial and large ground-mounted.

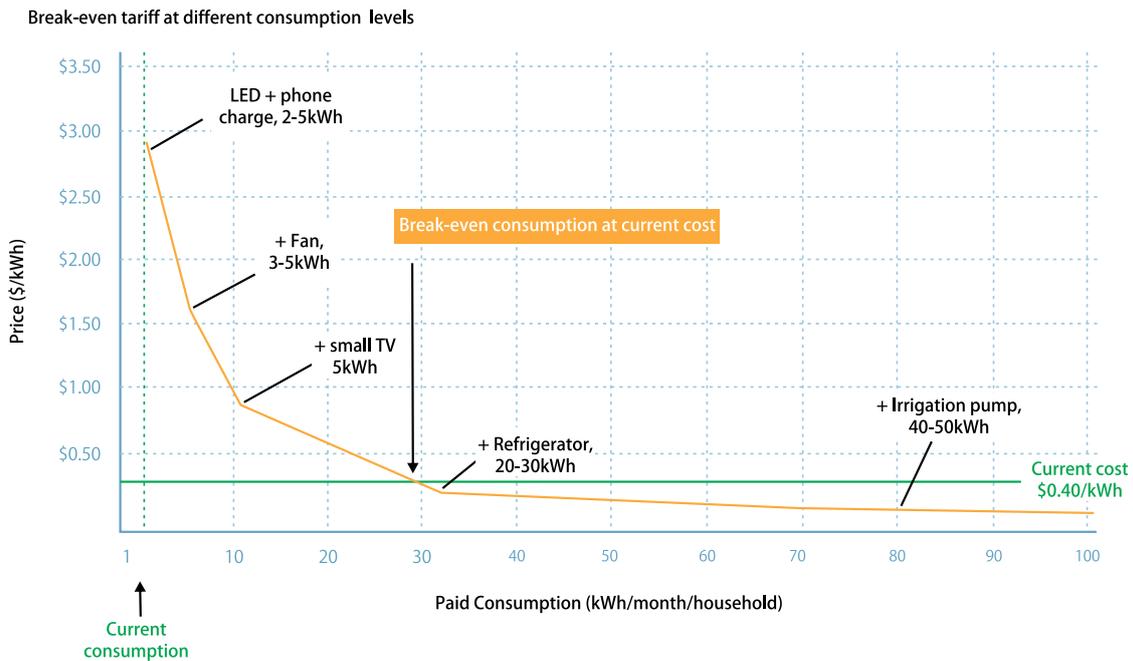
**CHALLENGE 2**

Currently, most low-income rural households cannot afford basic electrical appliances (beyond LED lights and charging of mobile phones). Even if low-cost appliances were available, these households cannot afford to power those appliances at the current cost of electricity provided by a solar mini-grid.

Access to electricity, unto itself, does not improve people’s lives. It is what people can do with it, that matters. To truly benefit from electricity, households and businesses need a range of appliances, such as appropriate lighting, refrigerators, fans or other space coolers, ICT devices (such as mobile phones, TVs or computers), irrigation pumps, etc.<sup>28</sup> Currently many of these appliances—with the recent exception of mobile phones and LED lights—are far too expensive to be affordable for the typical low-income rural household. For example, based on a survey of what is currently available in India, the least expensive (medium-sized) refrigerator costs approximately \$75. In the absence of financing mechanisms such as consumer credit, the only option for low-income households is to pay in lump sum. To put it in context, \$75 is approximately what a family at the \$3-\$5 per day income level spends on one month’s supply of food—the single largest regular expenditure for such households. Hence, few such households can afford amenities like refrigerators.

This economic equation poses a “chicken-and-egg” problem. Meaningful access to electricity requires an adequate (i.e. utility scale) supply of electricity, but utility scale electricity via solar mini-grids is still too expensive at current levels of utilization.

<sup>28</sup> Global Leap, Dalberg Global Development Advisors, and the Clean Energy Ministerial, “The State of the Off-grid Appliance Market”, March 2016.



Source: ITT analysis.

**Exhibit 10.**

Currently, typical low-income rural households do not create enough electricity demand to support or justify a solar mini-grid because they cannot afford basic appliances. All they can currently afford are LED lights and mobile phone charging. To break even at this level of consumption, utilities will have to charge significantly more than their current tariff of about 40 cents/kWh. Once households are able to consume 30kWh each month, the utility can break even at the current tariff. Note that this analysis is based on the typical mini-grid installation in India—30kW to serve a village of about 1,000 people; naturally, smaller installations would cost less.

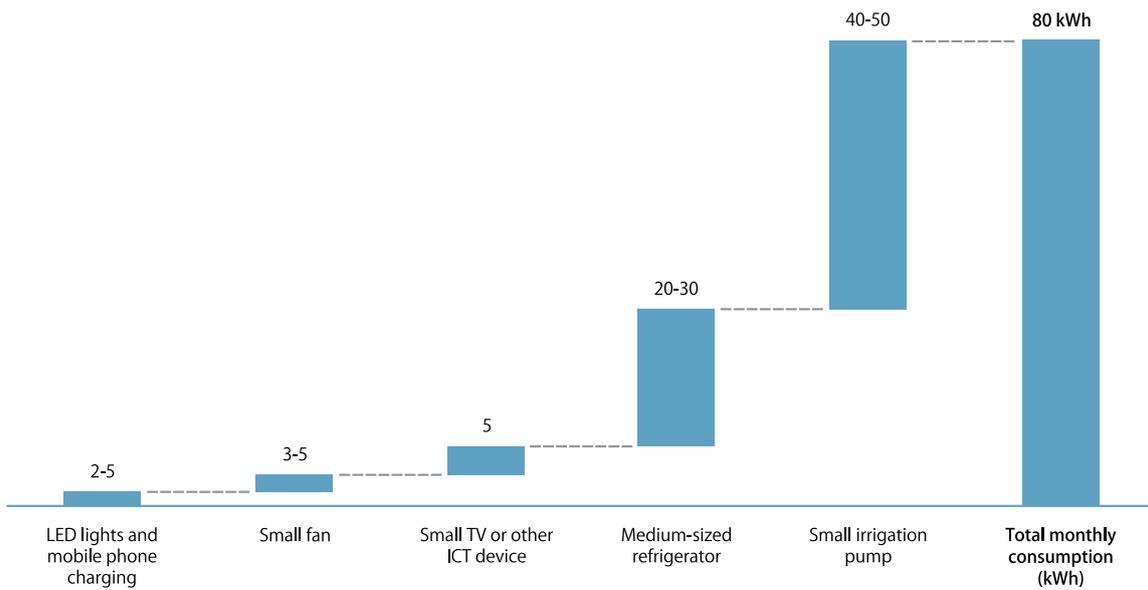
By definition, a mini-grid utility provider hoping to be financially viable needs to consistently do better than break-even. If consumption were limited to what the typical low-income rural household can currently use electricity for (i.e. LED lights and mobile phone charging), the utility would have to charge almost \$3/kWh (Exhibit 10). By comparison, the current market tariff for typical solar mini-grids serving rural Indian communities is about 40 cents/kWh. As consumption levels increase, the break-even tariff can decrease. To break even at current market rates, and current appliance energy-efficiency levels, the typical household would have to power (in addition to LED lights and mobile phone charging) a fan, a TV and a refrigerator. Alternately a heavy-duty motorised appliance such as an irrigation pump can also drive up consumption.

The full suite of the basic appliances, based on what appears to be available on the Indian market at the lower end of the cost spectrum, would consume 80kWh per month (Exhibit 11). Even if these appliances became affordable to buy, monthly consumption of 80kWh would make electricity bills unaffordable. At the current tariff of a solar mini-grid, this would cost approximately \$30 per month. By comparison, a household with adults earning \$3-\$5 per day can afford a monthly electricity bill of approximately \$7.50 per month,<sup>29</sup> barely 25% of what it would actually cost them (Exhibit 12). Households earning less fall even farther behind.

For a household at the \$3-\$5 per day income level, therefore, either the cost of the electricity produced by solar mini-grids needs to decrease by 75%, or the appliances need to consume 75% less electricity. Exhibit 13 illustrates this isoquant.<sup>30</sup>

<sup>29</sup> A. Hammond, et al., World Resources Institute, “The Next Four Billion: Market Size and Business Strategy at the Base of the Pyramid”, 2007.

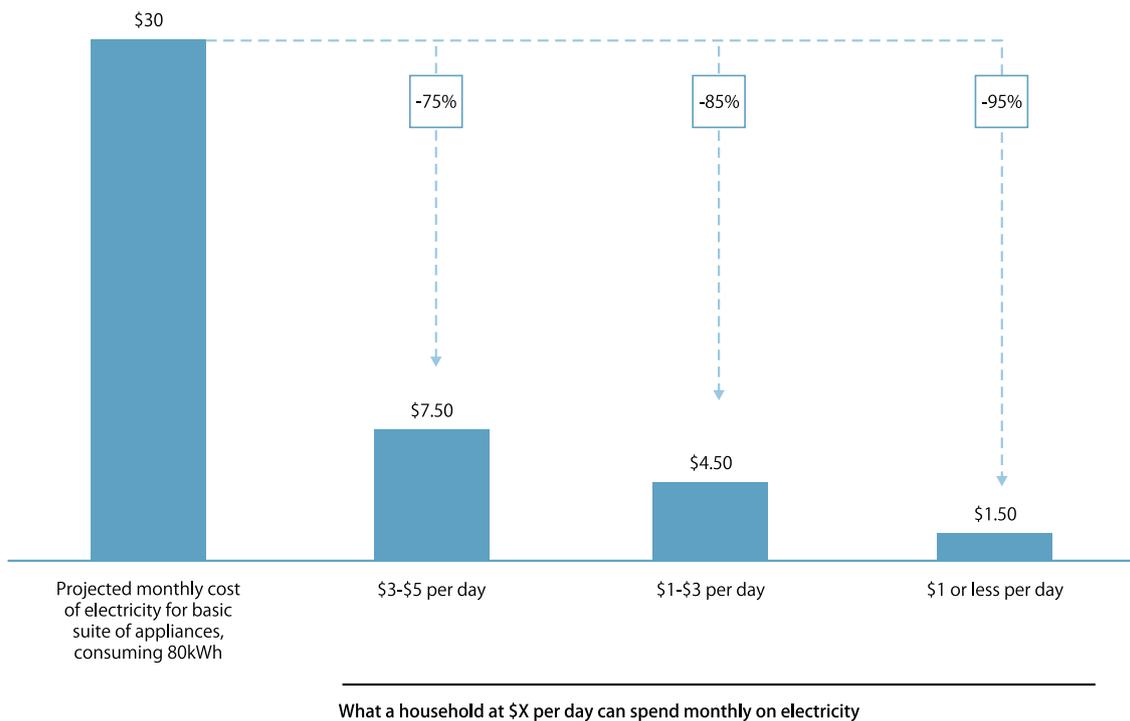
<sup>30</sup> ITT, “50 Breakthroughs”, 2014.



Source: ITT, "50 Breakthroughs", 2014.

**Exhibit 11.**

A suite of basic lower-end appliances currently on the Indian market would consume approximately 80kWh of electricity per month.

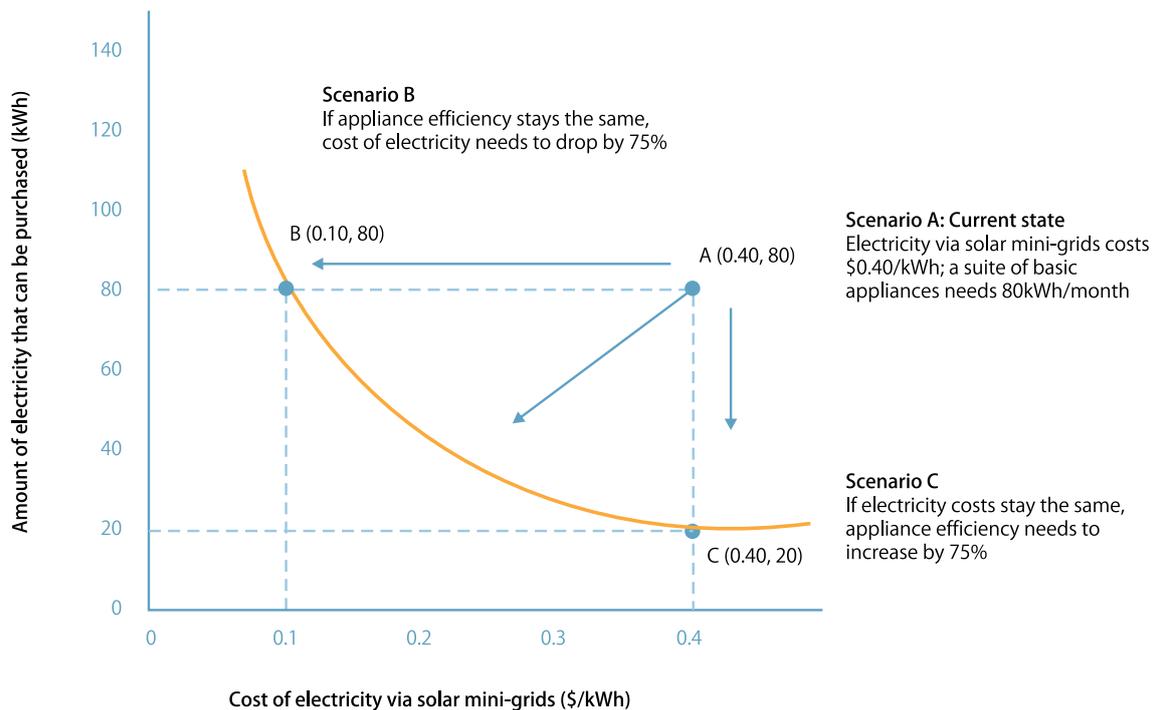


Source: ITT, "50 Breakthroughs", 2014.

**Exhibit 12.**

At the current cost of a solar mini-grid, the monthly cost of providing electricity to a suite of appliances described in Exhibit 11 is about \$30, which is considerably above what low-income households can afford. This exhibit shows estimates of what households at earning levels of \$3-\$5, \$1-\$3, and \$1 or less per day.

The electricity (kWh) that can be afforded by a household earning \$3-\$5/day (with an implied monthly electricity budget of \$7.50), at different prices of electricity



Source: ITT, "50 Breakthroughs", 2014.

**Exhibit 13.**

Currently, essential appliances are neither affordable, nor energy-efficient enough for low-income households to afford the cost of monthly electricity bills. For the electricity bills to become affordable, either the cost of solar mini-grids needs to decrease or the efficiency of appliances needs to improve. This exhibit illustrates that isoquant for households at the \$3-\$5 per day income level who can afford only 25% of the current cost of electricity required to run a basic suite of appliances.

**CHALLENGE 3**

There are no easy avenues for achieving major CapEx reductions.

As Exhibit 8 shows, the CapEx of solar mini-grids (including materials and labour) in India is distributed over a large number of components:<sup>31</sup>

- **Solar panels** constitute the single largest line item, 25-30% of the total cost. As shown in Exhibit 4, the cost of solar PV has been steadily decreasing over the years. This means that any future cost reductions in solar panels will have a lower and lower impact on the overall CapEx of the mini-grid.
- **Batteries** (for storing energy, to use when adequate sunlight is not available) constitute 10-20% of CapEx, depending on quality and level of redundant capacity built into the system. The typical batteries used in today's mini-grids in India are lead-acid, which have a host of problems (discussed below).

<sup>31</sup> Source: The Rockefeller Foundation.

- Most solar mini-grids also have a diesel generator for backup to ensure a reliable supply of electricity to their users, in case there is an extended period without sunlight (e.g., in the monsoon season), or if the batteries or related sub-systems fail. A diesel generator constitutes 8-10% of CapEx.
- The electricity generated by solar panels and stored in batteries is DC. To convert it to AC, the default mode for transmission of electricity over distances, an *inverter* (accounting for 8-10% of total CapEx) is required. To manage battery charge, a *charge controller* (about 5% of total CapEx) is required.
- The physical structures include panel mountings (5-7% of CapEx), the building and fencing (5-7% of CapEx, to house the batteries and other hardware, and to form a secure enclosure around the panels, respectively), poles (5-6%), cables (3-5%), and miscellaneous other items constituting the balance of the system (collectively 15% of CapEx).

Because the costs are distributed over a large number of components, there is no single “silver bullet” component that can dramatically reduce overall CapEx, as was the case a few years ago when solar panels were more expensive. Major cost reductions can only be achieved by aggregating incremental reductions across components or through innovative system integration. However, no clear path to large savings has yet been identified.

#### CHALLENGE 4

Lead-acid batteries—the standard method of energy storage for mini-grids—perform very poorly in typical Indian conditions. The only other technically viable option on the market (in India and other emerging markets), lithium-ion, is currently too expensive.

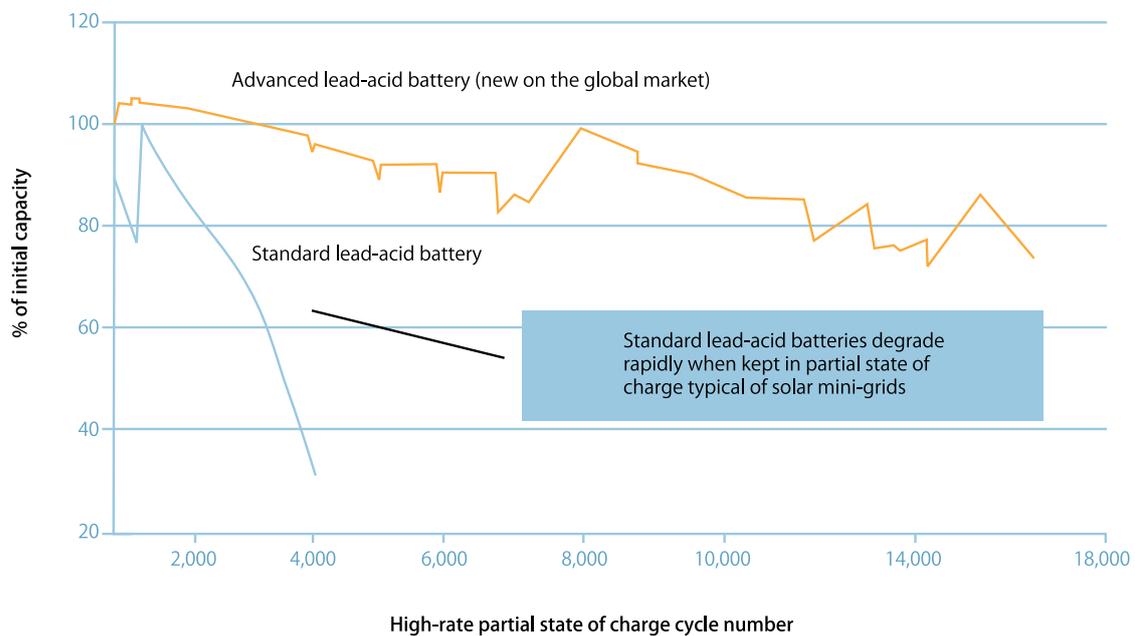
Batteries are a central part of mini-grid functionality, because they can store energy when the sun is shining, and provide it across the mini-grid when there isn’t enough sunlight. Unfortunately, they also represent the single most significant pain-point.

Lead-acid batteries often have advertised lifespans as long as 10 years. In reality, however, they tend to underperform and/or fail much sooner. If they are discharged below 50%, remain in an extended state of partial charge, or are exposed to the high ambient temperatures common through much of India, their lifespans and performance diminish. The capital cost of typical lead-acid batteries used in India, at the lower-end of the cost spectrum of lead-acid batteries available around the world, is \$150/kWh, with a levelized cost (based on advertised lifespans) of about 15 cents/kWh. However, because actual lifespans of the batteries are much shorter than advertised, the levelized cost can be two to four times higher than anticipated. Exhibit 14 shows the deterioration (in a lab test)<sup>32</sup> of standard lead-acid batteries over a relatively small number of cycles. By comparison, “advanced” lead-acid batteries—still new on the global market, and currently too expensive for the typical mini-grid application—demonstrate much stronger performance and longevity. Lead-acid batteries, if not handled properly, can also lead to environmental contamination and adverse health effects.

<sup>32</sup> Sandia National Labs, “Testing and Evaluation of Energy Storage Devices”, 2008.

While the underlying chemistry required to improve conventional lead-acid batteries, to achieve the enhanced performance shown in Exhibit 14, is not complex, there has historically been limited market demand for it. The vast majority of lead-acid batteries are used in automobiles, for ignition. Hence, they are optimised for high power in a short burst, rather than high energy (i.e. relatively low power over a long period of time). Deep-cycle lead-acid batteries (optimised for extended energy) have been on the market for a long time, but have had a niche market for expensive recreational vehicles (RVs), and the like. In such applications, the cost of the battery is a tiny fraction of the overall cost of the RV, and replacing batteries every 3-4 years (as part of regular maintenance) is likely not a major inconvenience to the owner of the RV. Such market indifference has given battery manufacturers little incentive to improve performance. This may change if there is enough demand from solar mini-grids.

**Battery performance with partial state of charge cycling**



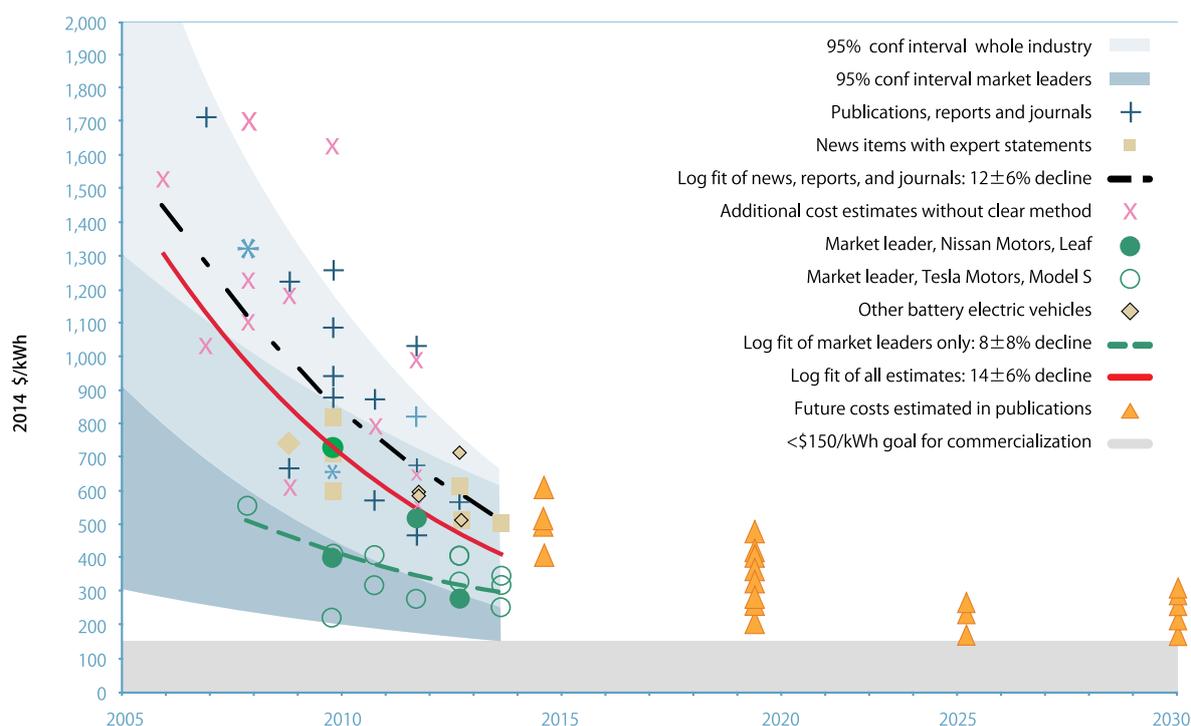
Source: Sandia National Labs, 2008.

**Exhibit 14.**

Lead-acid batteries, the leading choice for power storage for solar mini-grids in India, offer low initial costs. However, they degrade rapidly when subjected to deep cycling, high ambient temperatures, and extended operation in a partial state of charge. This increases their overall levelized cost. This exhibit compares standard on-the-market lead-acid batteries to an early-stage technology (“advanced” lead-acid batteries).

The other oft-mentioned battery technology for mini-grids is lithium-ion, used heavily in consumer electronics and more recently, in electric vehicles (EV). From the point-of-view of technical performance, lithium-ion batteries can be an ideal choice for mini-grids. The rapid growth of (and investment in) the EV market has led to significant reductions in the cost of lithium-ion batteries over the past five years, with market leaders offering batteries at \$300/kWh. Still, this is too expensive for the rural Indian context. Over the next few years, costs are expected to continue decreasing (Exhibit 15).<sup>33</sup> Projections, however, differ on when they will match the cost of existing lead-acid batteries—ranging from the early 2020s, all the way to 2030.

<sup>33</sup> B. Nykvist and M. Nilsson, “Rapidly falling costs of battery packs for electric vehicles”, Nature, October 2014.



Source: B. Nykvist and M. Nilsson, "Rapidly falling costs of battery packs for electric vehicles", *Nature*, October 2014.

**Exhibit 15.**

The cost of lithium-ion batteries—which perform well for mini-grid applications—has dropped significantly in recent years, but is still much higher than what mini-grids for developing countries can afford. There are varying opinions on how soon they will become affordable.

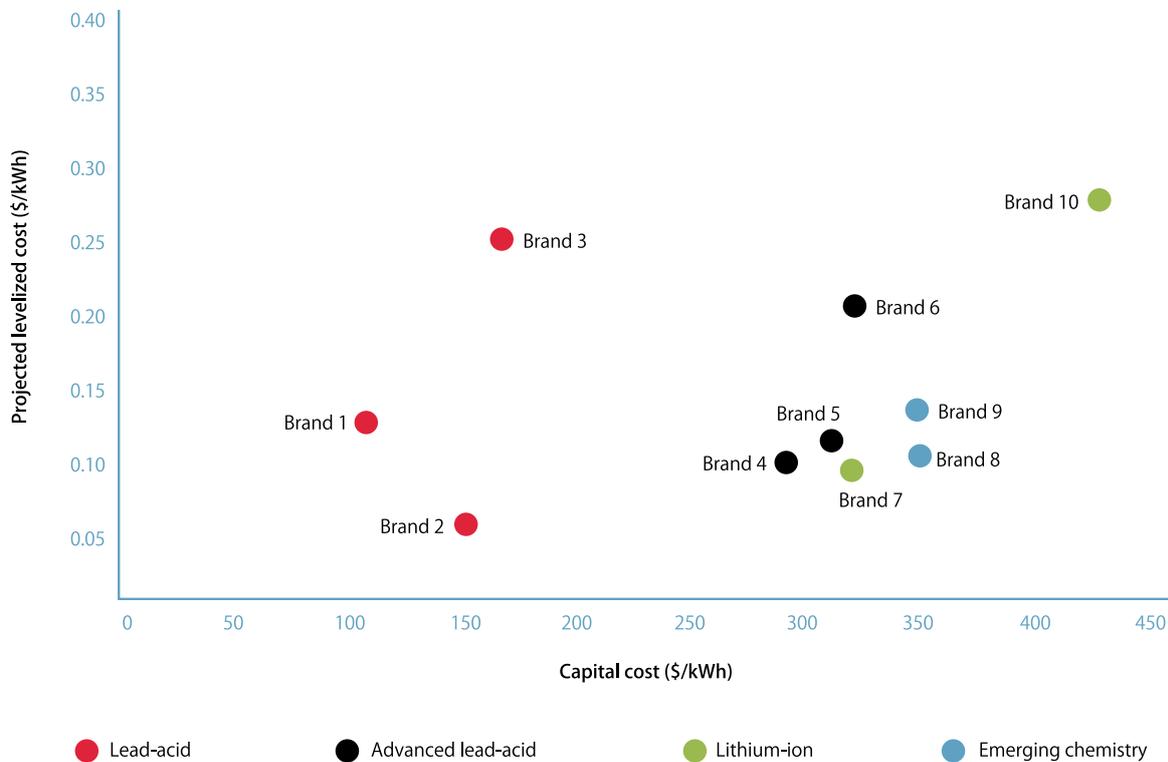
One potential long-term challenge with lithium-ion batteries is that the supply of lithium is currently restricted to a small number of countries. There are some concerns that skyrocketing demand for lithium-ion batteries, driven by the continued rapid growth for consumer electronics and EVs globally, may lead to supply shortages over time.<sup>34</sup> Even if the worst fears of dramatic supply shortages do not materialise, competing demand from profitable applications like EVs and consumer electronics may keep costs too high for mini-grids serving low-income rural communities. There are also a number of concerns regarding environmental toxicity in the long term.<sup>35</sup>

In our survey, a number of older chemistries were also mentioned by experts, but none of them appears suitable for mini-grids in rural India. Nickel-iron (the most common of the iron electrode family of chemistries) are extremely robust, and based on a very mature technology. However nickel is expensive and drives up the cost of these batteries. They also have very low power density and must be kept in well-ventilated rooms. There are many types of nickel-cadmium batteries, and while the performance standards vary across these types, they are generally very expensive (even more than nickel-iron), have low energy density, and can be highly toxic (due to the cadmium).

<sup>34</sup> H. Sandersen, Financial Times, "Tesla in stand-off over lithium supply", December 15, 2015. (<http://www.ft.com/cms/s/0/4a924a64-99df-11e5-987b-d6cdef1b205c.html>).

<sup>35</sup> D.H.P. Kang, et al, "Potential Environmental and Human Health Impacts of Rechargeable Lithium Batteries in Electronic Waste", *Environmental Science and Technology*, April 2013.

A number of other battery chemistries, aimed at mini-grid applications, are emerging—flow batteries, sodium-ion and zinc-hybrid. These are all in their early stages, and as yet have not been put to test in actual mini-grid settings, especially in developing countries. Exhibit 16 summarises findings from our market survey of the various mini-grid batteries on the global (i.e. not necessarily Indian) market. Note that brand names in this exhibit have been redacted to preserve confidentiality.



Source: ITT market analysis.

**Exhibit 16.**

There are a number of batteries on the global market that can be used for mini-grids. However, they vary dramatically with respect to initial purchase price as well as projected levelized cost over their lifetime. Please note that the brand names have been redacted in order to preserve confidentiality.

Even if one of these technologies proves feasible, a major manufacturer will need to make a long-term commitment to large-scale production in order to make the economics viable. Such a commitment, in turn, will require a similar long-term and large-scale commitment from a utility provider or another major actor in the market. These dependencies can fundamentally undermine the promise of new battery technologies.

## CHALLENGE 5

“Smart” meters for electronically monitoring and managing usage are too expensive, largely due to lack of scale given the current small market.

Metering is an essential mechanism to monitor usage and bill users accurately. It is also a mechanism to incentivise efficient and appropriate energy use by attaching a cost to excessive usage. In grid settings, “smart” meters, which electronically track usage and communicate with the provider via wireless networks, are emerging on the market. For off-grid applications, too, a number of promising smart meters, designed explicitly for the needs of developing countries, are now appearing on the market. However, due to the absence of a large and predictable market, these smart-meter manufacturers are operating well below the scale required to be financially viable. Based on the experience of such manufacturers, an increase in volume from 100 units to even 1,000 units reduces total per-unit cost by as much as 50% (Exhibit 17). Larger volumes (100,000 or a million units) can reduce costs even more dramatically. Unfortunately, the developing world mini-grid market is so small that manufacturers cannot even order components by the thousands, let alone millions.

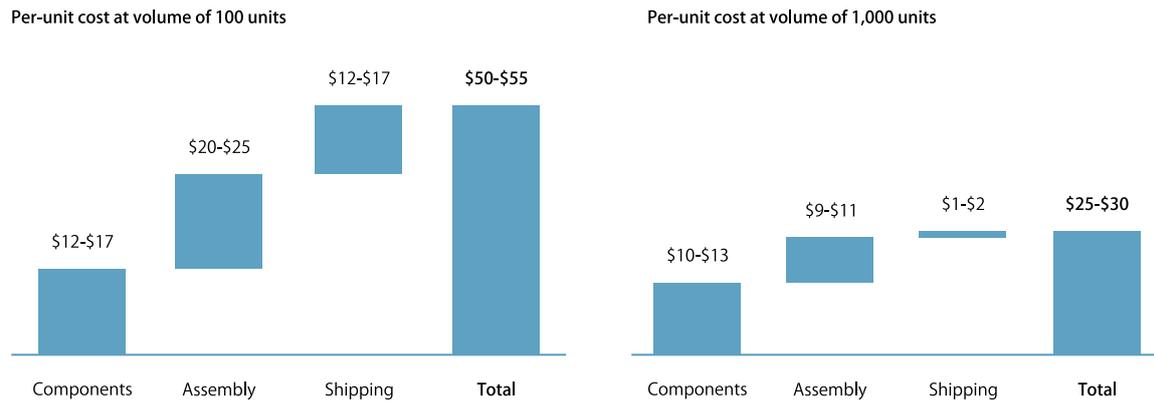
In the absence of affordable and accurate metering, mini-grid utilities are using load-limiters as a stopgap measure. With this mechanism, based on the appliances they have, users agree to a specific load profile and electricity supply is cut off when usage exceeds that limit. This is not a long-term solution. The household has no incentive to consume anything less than the agreed-upon limit. Moreover, there is a transaction cost involved in changing a household’s load profile every time it acquires a new appliance. As with the case of batteries, making smart meters a market reality at a meaningful scale will require a commitment from utility providers. It is important to note that smart meters can also enable a range of new business models and options critical for successfully operating in low-income markets, such as pre-pay vs. post-pay, load management and prioritisation, and on-bill financing of appliances.

In existing solar mini-grids in rural India, another challenge is that payments are made largely in cash. Fortunately, mobile payment mechanisms are becoming increasingly common, and will likely become available for mini-grid operations in the very near future.

Electricity theft is a major challenge faced by utilities in urban India. Smart meters are now being deployed as a mechanism to combat theft.<sup>36</sup> There is no reason to believe that this problem will be any less severe in rural areas. Hence, the absence of affordable smart meters exposes mini-grids to yet another challenge.

---

<sup>36</sup> The Hindu, “The ‘smart meter’ solution to the problem of power theft”, 1 October 2013; Times of India, “India to invest \$4 billion to tackle power theft”, 21 November 2014.



Source: ITT market research.

**Exhibit 17.**

Scale is a significant driver of the cost of smart meters. In the experience of some manufacturers, increasing production from 100 units to 1,000 units can reduce per-unit cost by half. Larger volumes (100,000 or 1 million units) can reduce costs even more dramatically. Unfortunately, the developing world mini-grid market is so small that manufacturers cannot even order components by the thousands, let alone millions.

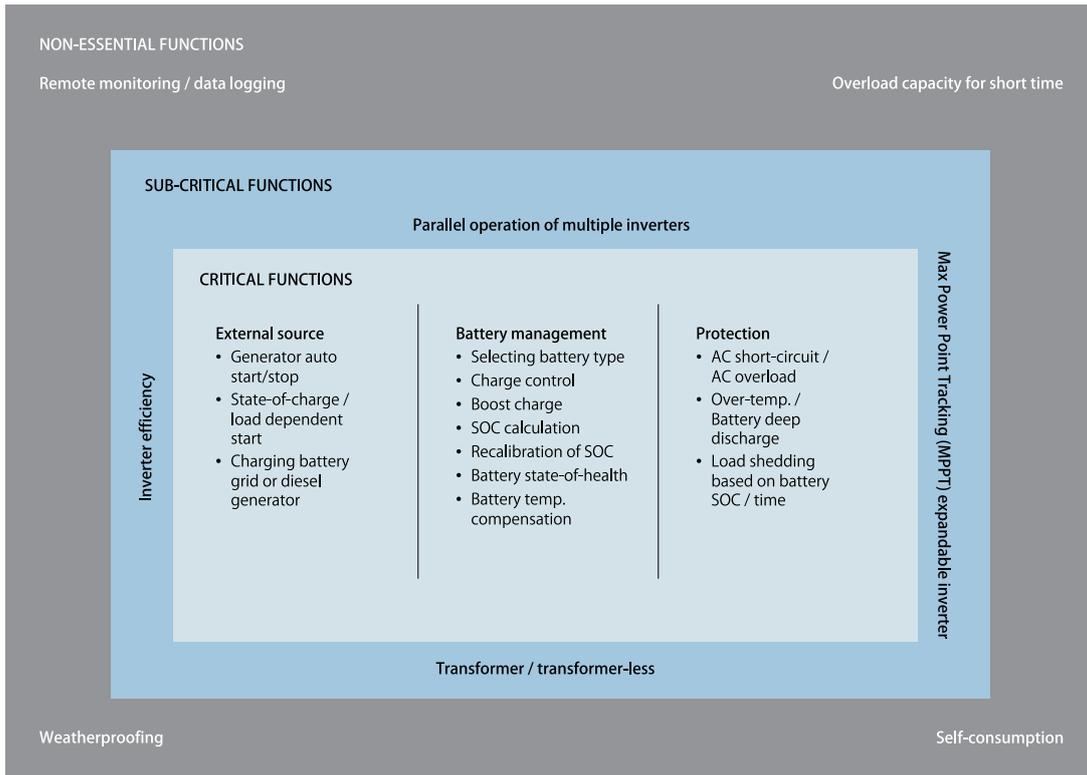
**CHALLENGE 6**

The mini-grid system does not work as an integrated unit, but rather as a loose assembly of non-standardised components; this leads to sub-optimal performance and operational leakages.

In India today, utilities wishing to provide electricity using a mini-grid have to install the entire system by themselves. There are few companies specialised in installing such systems, and the rest of the value chain is equally undeveloped. Hardly any standards exist to ensure that the various components optimise for overall system performance. For example, even though it is well understood that the inverter and charge control electronics need to be customised for performance specifications of the specific battery being used, there is simply no mechanism to accomplish that, especially with the inverters available on the Indian market. The absence of standards also forces mini-grid installers to choose between affordable but sub-par components, and expensive (typically Western-made) components, which can be over-designed and have more functionalities than what is required for a small mini-grid.

Exhibit 18 illustrates the example of a Western-made inverter with functionalities that may not be necessary for use in rural Indian mini-grids. However, as Exhibit 19 shows, lower-cost Indian-made inverters do not appear to be reliable (at least according to user perceptions, based on interviews by ITT).

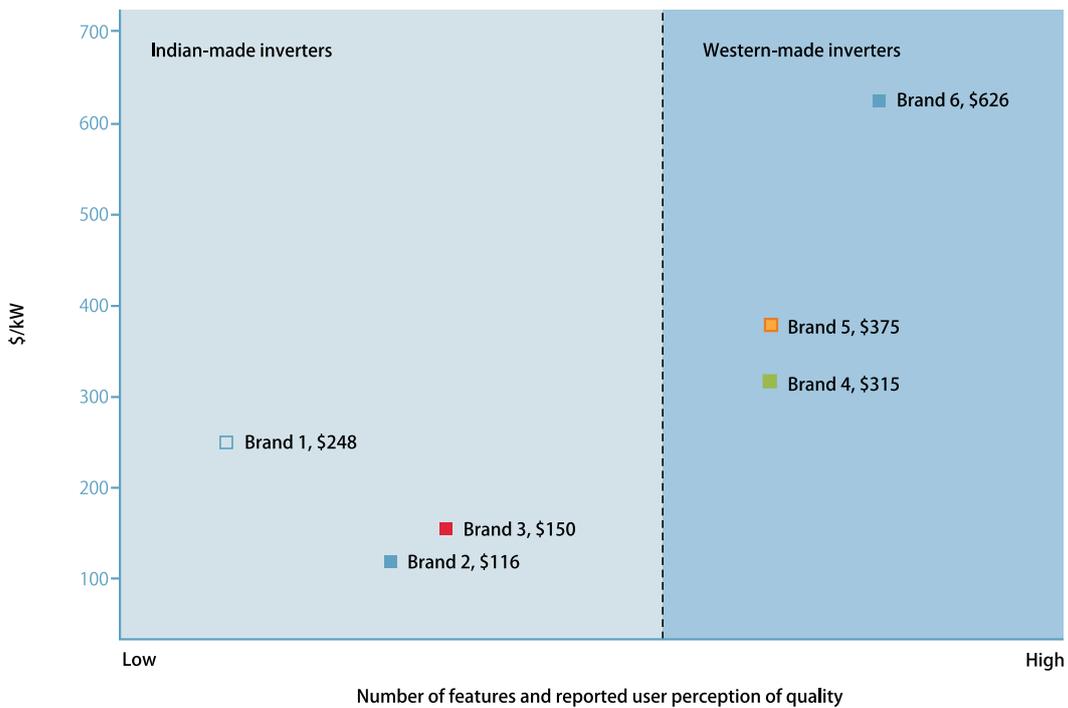
Poor manufacturing quality and the lack of standards can also cause weak electrical contacts, leading to line losses during transmission. In some of the current installations, for example, we observed significant voltage drops (from 220v to 190v) between the station and the first point of use. Such problems lead to degraded performance, higher-than-expected maintenance costs and system downtime, further exacerbating the already challenging economic equation.



Source: ITT market research.

**Exhibit 18.**

Typical Western-made inverters are much more expensive than those made in India. While the former tend to be of higher quality, they also have a number of functionalities that are not essential for typical use in rural mini-grids in India. The question, therefore, is whether cost can be reduced by removing non-essential functionalities without compromising quality.



Source: ITT market research

**Exhibit 19.**

While a number of India-made inverters are available, they are generally not considered at par with their Western-made counterparts.

## CHALLENGE 7

“Anchor” users to ensure adequate and predictable consumption can be hard to find and manage.

The lack of demand and economic activity from rural households and small enterprises can force mini-grid providers to seek “anchor” users who can reliably consume enough electricity to ensure financial viability. Across much of India, telecom towers have become a common and preferred anchor client. However, such anchor users have tended to use the mini-grid only as their backup electricity source. Consequently, they either consume the bulk of the mini-grid’s supply when their primary power source is unavailable, or none at all when the primary power source is available. To compensate for this unpredictability, the off-grid systems powering them need diesel generators to ensure reliable power for other paying consumers. For a utility providing the electricity, the lack of predictable demand (and revenue) can exacerbate an already difficult economic equation.

## CHALLENGE 8

While the rural Indian market can be massive, it is currently considered risky. Consequently, no established incumbent in India’s energy sector has yet made the pivotal first investment. The lack of financing further limits investments.

As noted earlier, the Indian government’s commitment to rural electrification provides a very promising platform to address the problem. However, as also noted, its financial commitment of \$1.25 billion will be sufficient to provide electricity only to a fraction of the 235 million people who currently do not have access to it. Therefore, it is likely that the private sector will have to play a big part in addressing the problem at a larger scale, much like it has in urban India where many of the utilities are public-private partnerships. As such, it has to be a financially viable proposition for businesses—across the value chain—to introduce critical and innovative new solutions. A utility will invest in the infrastructure needed to provide electricity only if it has access to reliable, cost-effective equipment, and if there is enough revenue from consumption to recoup its investments. Equipment manufacturers will invest in innovative new technologies and the infrastructure to manufacture them, only if the utilities are willing to buy them. Appliance manufacturers will invest in low-cost energy-efficient appliances only if they believe there is real market demand from low-income users who care about energy-efficiency. (Low-income urban consumers in India have not needed energy-efficient appliances because they are connected to the grid, and the associated subsidies make electricity relatively affordable. Also, in many areas, low-income urban communities have unauthorised connections that can afford them free electricity.)<sup>37</sup> In other words, the whole value chain is caught in a “chicken-and-egg” problem, in which no single significant actor is willing to make a major investment unless others across the value chain do it first.

Large institutional funders like the World Bank and the IFC finance much of the infrastructure in developing countries. Funding from such institutions is projected to fall significantly short of what is actually required to achieve universal electrification.<sup>38</sup> To make matters worse, such institutional funders do not yet seem to be investing in mini-grids because they are still considered risky investments. At the same time, the existing economics of mini-grids are not attractive enough for small and medium (typically private) investors. Such investors tend to require shorter payback periods than is possible today with the current market economics of low-income rural areas.

<sup>37</sup> The Hindu, “The ‘smart meter’ solution to the problem of power theft”, 1 October 2013; Times of India, “India to invest \$4 billion to tackle power theft”, 21 November 2014.

<sup>38</sup> International Energy Agency, “Renewable Energy - Market and Prospects by Technology”, 2011; “World Energy Outlook”, 2011.

India's regulatory and operational framework for electricity is governed by an assortment of central and state bodies. While the regulations for grid electricity are clear, regulations for off-grid electricity are still emerging. In recent months, a number of noteworthy changes have begun to emerge on this front, such as the National Tariff Plan, policy initiatives by the Ministry of New and Renewable Energy, and policies driven by individual states like Uttar Pradesh.<sup>39</sup> Key questions include: what happens to a private mini-grid when the main grid eventually reaches that area; and whether and/or how a private mini-grid can utilise any existing public infrastructure in an area that has government-built poles and cables, but no actual electricity. Lack of clarity on such regulations may add to the broader perception that investing in solar mini-grids in India can be a risky proposition.



© The Rockefeller Foundation

<sup>39</sup> Office of the Prime Minister, January 2016 ([http://pmindia.gov.in/en/news\\_updates/cabinet-approves-amendments-in-power-tariff-policy-to-ensure-24x7-affordable-power-for-all/](http://pmindia.gov.in/en/news_updates/cabinet-approves-amendments-in-power-tariff-policy-to-ensure-24x7-affordable-power-for-all/)); MNRE draft of National Renewable Energy Act 2015 (<http://mnre.gov.in/file-manager/UserFiles/draft-rea-2015.pdf>); Uttar Pradesh New and Renewable Energy Development Agency, February 2016 ([http://upneda.org.in/sites/default/files/all/section/Minigrid\\_english\\_Approved.pdf](http://upneda.org.in/sites/default/files/all/section/Minigrid_english_Approved.pdf)).

# The roadmap to achieving the dual electricity imperative: A combination of technology, business and policy innovations

Despite the challenges, solar mini-grids offer the most viable path to rural electrification in India, and can become economically sustainable. A number of breakthrough technologies can make this happen, but technology alone will not solve the entire problem. Investment from a pivotal at-scale business is essential for catalysing investments from other actors along the value chain, which in turn, can help all of them realise economies-of-scale. Importantly, a number of innovative policy changes will be required to build on the Indian government’s existing commitments. A combination of such initiatives can achieve what none of them can individually, even with significant funding.

## ROADMAP PART 1

### Technologies to address both supply and demand sides of the equation

The current cost of operating a mini-grid, with respect to both CapEx and levelized cost of energy over time, is too high. In addition, the lack of affordable, quality assured and standardised equipment leads to a number of unforeseen operating challenges, which lead to higher-than-projected costs and lower-than-projected revenues. This exacerbates an already challenging economic equation. The absence of affordable, energy-efficient appliances poses a major barrier to sufficient and reliable consumption.

Four breakthrough technologies can address these challenges. Each requires a different body of work to bring it to life.

**1** **New battery technology: Current lead-acid battery technology is not the solution of choice in the long run. Recognising the challenges of lithium-ion even after their costs plateau in the future, there is likely a need for a solution specific to mini-grids in developing countries.**

There are currently three potential options:

- Advanced lead-acid batteries which reduce sulphation due to deep discharge or partial charge, and improve battery life in high ambient temperatures. Another advantage of this technology is that it will require only incremental changes to current manufacturing processes and facilities for conventional lead-acid batteries—of which there are several in India. One example of companies developing this technology is Ecoult Energy Storage Solutions, which combines an ultracapacitor and proprietary catalyst with existing lead-acid chemistry to achieve improved results. It is important to note that while this technological advance may overcome the performance challenges related to conventional lead-acid, the environmental concerns still remain.
- The recently-developed sodium-ion chemistry from Aquion Energy is showing promise in its ability to perform in the conditions common to rural India, and can be cost-effective if scale is achieved. The challenge, however, is that it will require a manufacturing facility unlike anything that currently exists in India, and it is not clear whether the market is appealing enough to attract the necessary investment. Shipping these batteries to India from their current manufacturing sites does not appear to be economically feasible.

- A hybrid system comprised of an electronic charge control mechanism to combine lithium-ion as the first-stage storage mechanism carrying a portion of the load (e.g., the first one-third), and conventional lead-acid as the secondary storage mechanism carrying the remaining load. If the usage loads are favourable, such a system can combine the cost-effectiveness of lead-acid batteries with the resilience of lithium-ion. It can be relatively easy to develop and deploy, because the electronics are uncomplicated, and can be easily manufactured in India. Reliable lithium-ion and lead-acid batteries already exist in India. In principle, therefore, this can be a quick win. On the other hand, it may still be vulnerable to some of the challenges described above, and does not address the issue of environmental toxicity.

Each of these battery technologies needs to be rigorously tested for performance under a range of stresses common to rural India: exposure to high ambient temperatures (30°C-50°C); deep and rapid discharge; extended operation in a partial state of charge; exposure to dust and moisture; wear-and-tear and abuse. It will be important to thoroughly analyse and identify all potential failure modes for these technologies, so that appropriate fail-safe measures can be put in place. In addition, it will be important to assess the business dynamics necessary to make these batteries succeed in India's challenging market.

## 2

An integrated "utility-in-a-box" suite of components with (i) standardised components; (ii) metering with automated billing, collection and shutoff; and (iii) inverter optimised for the specific battery technology and usage patterns.

Unreliable components designed to different specifications, combined with poor installation, pose a major hurdle in enabling smooth operation of mini-grids. This problem is compounded by the ad hoc nature of metering and collections, and inverters that are either too expensive or sub-par. We do not believe investment in one-off technologies (e.g., meters or inverters) will be sufficient. It is important that new technologies address the whole system, rather than one-off issues. Indeed, companies developing promising new one-off technologies are struggling to expand beyond their niche. We believe that an integrated "utility-in-a-box", combining the most important components (batteries, charge controller and inverter optimised for the battery chemistry, metering, assembly fixtures), is the solution. In addition, electronic payment mechanisms can enable business innovations like on-bill financing for appliances. Early analysis suggests that such an integrated system can reduce CapEx by 10-20%, deliver superior functionality, and be more robust—by "productizing" a system of otherwise disparate and non-standardised components.

Bringing such a "utility-in-a-box" to life will require the development of an innovative blueprint which addresses four issues: cost reduction by simplifying or eliminating components; cost reduction via economies-of-scale and bulk procurement (which may require innovative business partnerships and leverage of procurements by those partners); performance improvement by adding new functionalities which address the many pain-points described above; and ease of installation and maintenance.

### 3 Affordable refrigeration, for both household and commercial use, is one of the most important technology breakthroughs required to increase demand for electricity.

It will also address a range of critical human development needs such as improved nutrition (by preserving perishable fruits, vegetables, dairy and meats), higher incomes (by enabling agricultural cold chains in rural and remote areas), and improved healthcare (by helping preserve temperature-sensitive pharmaceuticals). There is strong evidence to suggest that there will be tremendous demand for lower-cost refrigeration in India.<sup>40</sup> While prices for refrigerators and other appliances are dropping in emerging markets like India and China, they still cost more than \$75 a piece, consume a lot of energy, and can be of questionable quality. Some new technology innovations, such as thermoelectric coolers, are beginning to appear on the market. However, thermoelectric chips have fundamental limitations on how much heat they can transfer, and it is unlikely they will be powerful enough for true refrigeration. Even as no new clear technology breakthrough appears to be on the horizon, it will be important to evaluate all potential current and emerging technologies, and determine which can be enhanced, in order to make low-cost, energy-efficient refrigeration a reality.

### 4 Brushless DC motors for fans and irrigation pumps.

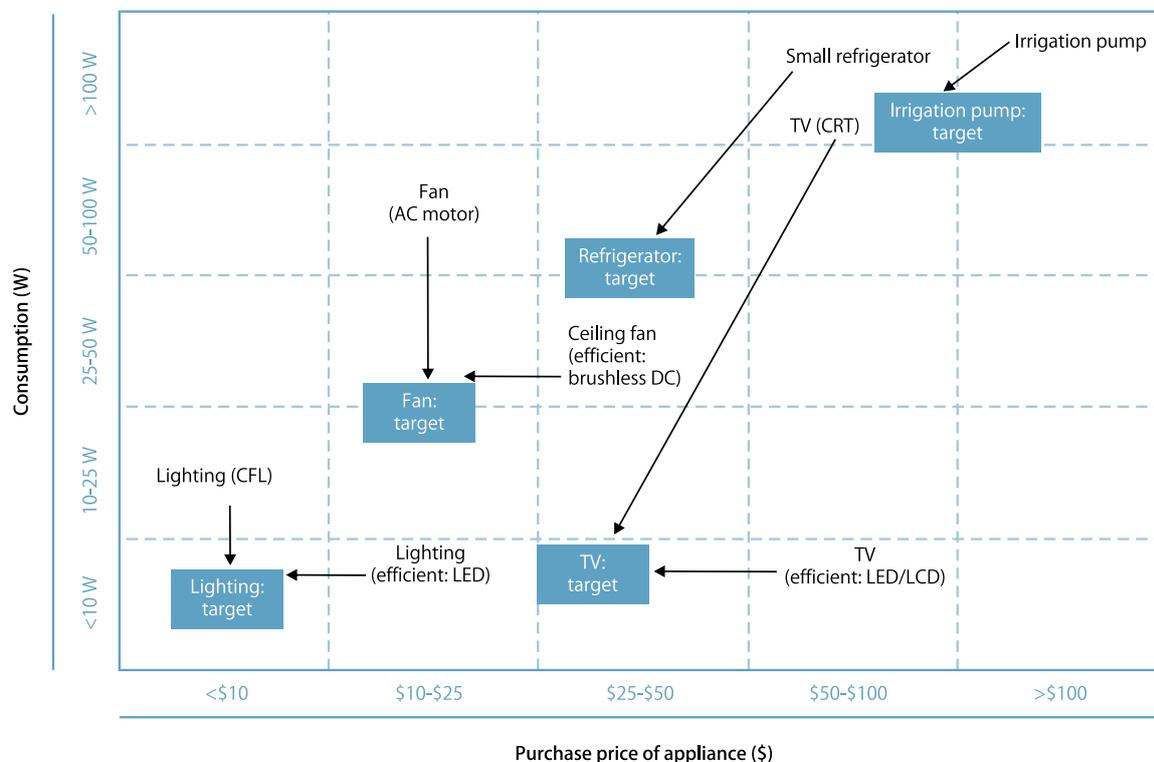
Currently, many heavy-use motorised household and small enterprise appliances, such as fans and irrigation pumps, use AC motors that are—by virtue of their intrinsic design—simple and robust, but energy-intensive. As a result, fans are affordable to low-income households, but consume too much energy relative to what they can pay in electricity bills. The alternative, DC motors, are more energy-efficient but less robust, and are used in appliances with less continuously heavy usage (e.g., sewing machines). Currently, a very small number of appliances (e.g., printers and photocopiers) use brushless DC (BLDC) motors, which combine energy-efficiency with robustness. In principle, BLDC motors could be used to increase the energy-efficiency of fans and other motorised appliances. Unfortunately, BLDC motors require more components than both AC and regular DC motors, and are hence more expensive. A small number of startups are introducing BLDC fans and irrigation pumps, but they are in their early stages and still sub-scale. We recommend evaluating these products to determine what technical improvements (if any) can reduce their cost. Our early assessment suggests that cost reductions for such products are more likely to be achieved through large-scale procurement of components, rather than technical improvements. Hence, opportunities for aggregating procurement (e.g., with manufacturers using similar components, even if they are for very different purposes) should also be explored.

As a somewhat lower priority, we also recommend examining the role of TVs in increasing demand for electricity. TVs have consistently been in high demand even among low-income households, especially in urban areas. LED/LCD TVs are showing some promise as an energy-efficient solution, but are currently too expensive (\$75 and above) for low-income households. It is likely that only minor technology improvements are required to decrease the cost of these TVs, and that scale and competition will lead to meaningful cost reductions. However, existing brands may have limited incentive to introduce lower-cost TVs, because there is already such high demand for current models, and the lower-cost models may only cannibalise their current market. This may create an opening for disruptive new brands. We recommend exploring opportunities with both incumbent brands as well as innovative startups.

---

<sup>40</sup> Wolfram, et al., “How Will Energy Demand Develop in the Developing World?”, Haas School of Business, University of California – Berkeley, January, 2012.

Exhibit 20 shows the level of cost savings and energy-efficiency gains required for various appliances relevant to low-income rural households.<sup>41</sup> Exhibit 21 shows power and energy consumption patterns of motorised appliances in a village in Bangladesh (Sandwip island), which was one of the first in South Asia to be powered by a solar mini-grid.<sup>42</sup>

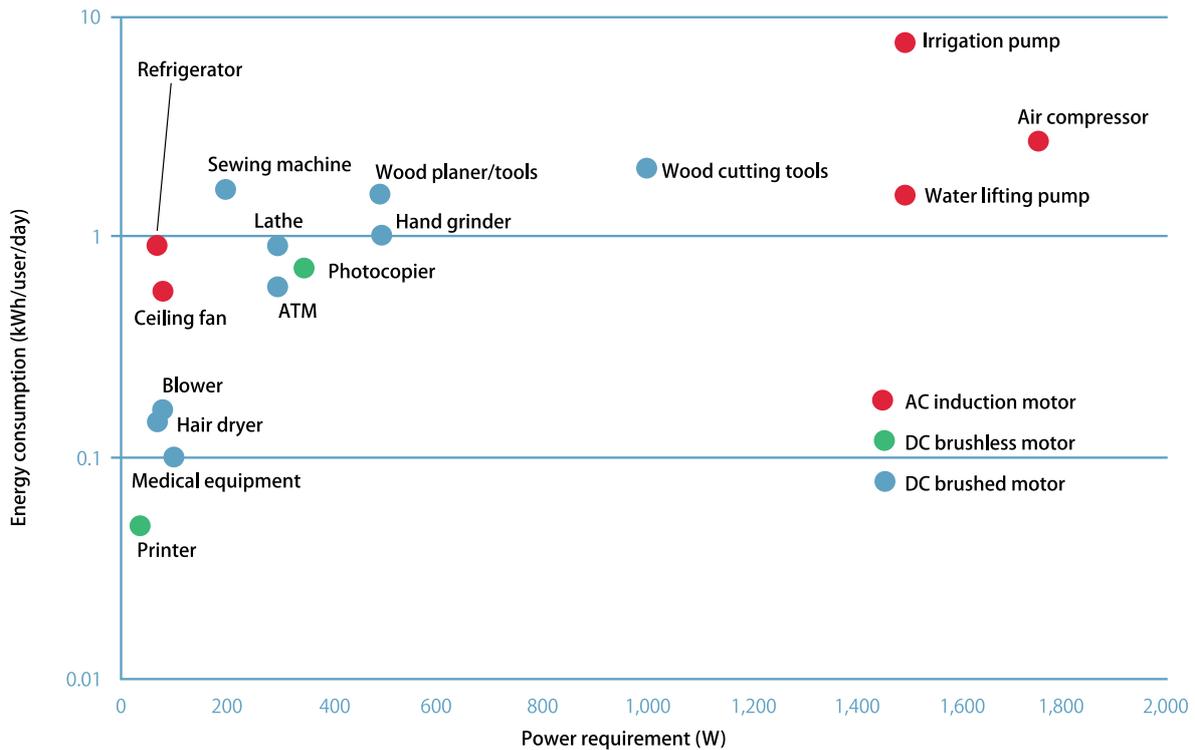


Sources: Phadke et al., "Powering a Home with Just 25 Watts of Solar PV"; ITT market research.

**Exhibit 20.**

There are a number of appliances which—if made more affordable and energy-efficient—can increase demand for electricity. These appliances can also lead to tremendous improvement in the lives and livelihoods of low-income rural communities.

<sup>41</sup> A. Phadke, A. Jacobson, W. Y. Park, G. R. Lee, P. Alstone, and A. Khare, "Powering a Home with Just 25 Watts of Solar PV: Super-Efficient Appliances Can Enable Expanded Off-Grid Energy Service Using Small Solar Power Systems", April 2015.  
<sup>42</sup> Source: PSL Bangladesh.



Source: PSL Bangladesh.

**Exhibit 21.**

Appliances of potential use in rural India are powered by a combination of AC, DC and brushless DC motors. This exhibit shows energy consumption patterns for a village (Sandwip island) in Bangladesh, which was one of the first rural areas in South Asia to be powered by a solar mini-grid.

**ROADMAP PART 2**

Financially viable businesses up and down the value chain

It is important to note that for each of the above innovations, the best technology may not be the eventual winner in the marketplace. A number of important considerations have to be taken into account, including demand from potential customers (businesses or consumers) down the value chain, the level of capital investment required in manufacturing, the strength of the supply chain, and availability of the necessary materials and workforce. As indicated earlier, bulk procurement of components can sometimes achieve significantly higher cost reductions than a technology innovation.

Hence, in addition to evaluating and developing technologies, it will be critical to conduct a thorough operational analysis to determine the feasibility of large-scale manufacturing of each of these technologies in India. We believe that an established utility provider already serving other parts of the Indian market—with the wherewithal to achieve scale, withstand short-term and medium-term financial risks, and negotiate the various accompanying policy challenges—will need to be involved, and commit to large-scale advance procurement guarantees. Such a commitment can unlock the market for rural electrification in other developing countries as well. Similarly, it will be important to identify high-potential equipment manufacturers for the other technologies identified above.

## ROADMAP PART 3

### Policy changes to build on the government's stated commitments

The Government of India has laid out a number of targets with respect to clean energy and rural electrification, and has followed it up with financial commitments. A number of targeted policy changes can make these commitments come to life. As noted earlier, recent regulatory changes at both national and state levels offer a strong platform for continued policy enhancements.<sup>43</sup>

#### 1 Public-private partnerships (PPPs) with utilities.

It will be difficult for the government to undertake the massive task of building a national network of mini-grids. We recommend that the government develop public-private partnerships for rural electrification, much like those used to supply electricity to urban centers through joint ventures. One example of such a PPP in urban settings is Tata Power-DDL, which distributes electricity to a large portion of New Delhi at rates set by the government, with agreed-upon service levels.

#### 2 Allow access to existing infrastructure.

Currently, it appears that only private enterprises are providing electricity via solar mini-grids to rural communities. In order to do so, they have to build the entire pole-and-cable infrastructure, even in communities where the government has already built it. This constitutes an avoidable cost of 10-15% of CapEx. As such, in areas where there is already a government grid but an unreliable or inadequate supply of electricity, we recommend that the government allow local (even private) mini-grid utilities to use existing infrastructure. In such cases, it will be important to guarantee that the electricity produced by the mini-grid remain local. Over time, as India's overall electricity production increases to meet demand, the electricity produced by these mini-grids can be incorporated into the rest of the grid, potentially leading to decommissioning of polluting energy sources elsewhere in the country.

#### 3 Incentives for community electrification.

The *Swachh Bharat* initiative, which provides subsidies to households for building toilets, is credited with a substantial increase in the number of toilets around the country.<sup>44</sup> Through the chain of various political structures, the construction of these toilets and payment of subsidies are ultimately managed by the *Gram Panchayats* (village-level governing bodies). This initiative also rewards communities for successfully becoming free of open defecation. A similar mechanism to incentivise community-level electrification—in which, for example, households are provided one-time subsidies for getting connected to the mini-grids, with additional community-level incentives for consistent payment of their utility bills—can go a long way in improving access. Even if consumption of electricity is initially low, it is likely that increased rural supply will spark the introduction of affordable and energy-efficient appliances targeted at low-income households.

<sup>43</sup> Office of the Prime Minister, January 2016 ([http://pmindia.gov.in/en/news\\_updates/cabinet-approves-amendments-in-power-tariff-policy-to-ensure-24x7-affordable-power-for-all/](http://pmindia.gov.in/en/news_updates/cabinet-approves-amendments-in-power-tariff-policy-to-ensure-24x7-affordable-power-for-all/)); MNRE draft of National Renewable Energy Act 2015 (<http://mnre.gov.in/file-manager/UserFiles/draft-rea-2015.pdf>); Uttar Pradesh New and Renewable Energy Development Agency, February 2016 ([http://upneda.org.in/sites/default/files/all/section/Minigrid\\_english\\_Approved.pdf](http://upneda.org.in/sites/default/files/all/section/Minigrid_english_Approved.pdf)).

<sup>44</sup> Y. Sharma, *The Economic Times*, "Swachh Bharat Abhiyaan: Government builds 7.1 lakh toilets in January", 17 February 2015 ([http://articles.economictimes.indiatimes.com/2015-02-17/news/59232518\\_1\\_india-open-defecation-swachh-bharat-abhiyan-toilets](http://articles.economictimes.indiatimes.com/2015-02-17/news/59232518_1_india-open-defecation-swachh-bharat-abhiyan-toilets)).

Ultimately, electricity is a public good, and the vast majority of those who have it—in developing and developed countries alike—benefit from government policies which have made access to electricity a priority. Low-income rural populations, who are arguably the most in need of such government support, should not have to rely only on the private sector for these basic services. However, the private sector can catalyse innovative solutions to this vexing problem, and thereby build a platform for longer-term government ownership.

ITT and Tata Power DDL have recently launched an initiative to find innovative solutions in the first two of the three areas described above: breakthrough technologies that can improve both cost and performance of solar mini-grids, and innovative business models for Indian companies (working with the government) to make electricity a reality for the hundreds of millions of Indian citizens who need it.



For more than 100 years, The Rockefeller Foundation's mission has been to promote the well-being of humanity throughout the world. Today, The Rockefeller Foundation pursues this mission through dual goals: advancing inclusive economies that expand opportunities for more broadly shared prosperity, and building resilience by helping people, communities and institutions prepare for, withstand, and emerge stronger from acute shocks and chronic stresses. To achieve these goals, The Rockefeller Foundation works at the intersection of four focus areas—advance health, revalue ecosystems, secure livelihoods, and transform cities—to address the root causes of emerging challenges and create systemic change. Together with partners and grantees, The Rockefeller Foundation strives to catalyze and scale transformative innovations, create unlikely partnerships that span sectors, and take risks others cannot—or will not.

To learn more, please visit [www.rockefellerfoundation.org](http://www.rockefellerfoundation.org).

## TATA TRUSTS

The Tata Trusts are amongst India's oldest, non-sectarian philanthropic organisations. The Trusts own two-third of the stock holding of Tata Sons Limited, the apex company of the Tata Group of companies, and therefore two-third of the profits of the entire corporate group are dividend out by Tata Sons Limited to the Trusts. In this manner, the profits that the Tata companies earn go back many times over to the communities they operate in. These funds have been deployed towards a whole range of community development programs across the country, for over a 100 years now.

Since the inception, Tata Trusts have played a pioneering role in transforming traditional ideas of charity and introducing the concept of philanthropy to make a real difference to communities. Through grant-making, direct implementation and co-partnership strategies, the Trusts support and drive innovation in areas of Natural Resources Management, Education, Healthcare & Nutrition, Rural Livelihoods, Enhancing Civil Society & Governance, Arts, Crafts & Culture and Diversified Employment. Trusts engage competent persons and government bodies, international agencies and like-minded private sector organizations to nurture a self-sustaining ecosystem that collectively works across all these areas.

The Tata Trusts continue to be guided by the principles of its founder Jamsetji Tata. With the founder's vision of proactive philanthropy and his approach to 'giving', the Trusts catalyse societal development while ensuring that initiatives and interventions have a contemporary relevance to the nation. In addition to promoting and facilitating initiatives in elementary education, Tata Trusts also award fellowships, merits and scholarships to students pursuing higher studies. It grooms social scientists, cancer specialists, nuclear scientists and distinguished institutional administrators who in turn, have strived to make the country a power to reckon with in various fields including science and technology. The Trusts also support causes and initiatives that provide disaster relief and aids rescue work in case of calamities. The Trusts not only assist by providing grants and helping mobilise funds, they also offer on-ground support directly as well as in partnership with other stakeholders.

In order to enhance impact and ensure that interventions are sustainable, they have adopted a cluster-based approach, supporting multiple interlinked activities in identified clusters of contiguous villages across select geographies across India. Coupled with this, is the Trusts' strict adherence to robust financial systems being put in place with all partner organisations. Today, spread over 16 states and 170 districts across the country, programs supported by the Trusts reach over 800,000 households through an efficient network of 450 partner organisations. Additionally, the Trusts' grants and initiatives especially in the area of educational attainment, significantly contributes to building intellectual capital in the country.



## TATA POWER-DDL

Tata Power Delhi Distribution Limited (TPDDL), is a joint venture between Tata Power and the Government of Delhi. Since its inception in 2002, TPDDL has been able to successfully set new benchmark performance standards in distribution of electricity in India. TPDDL supplies power to the North and North-West parts of Delhi, covering a population of nearly 7 million, with 1.5 million connections. Today, the Aggregate Technical & Commercial (AT&C) losses in TPDDL area covering an area of 510sq km stands at a single digit level of 9.87% which is an unprecedented reduction from an opening loss level of 53% in July 2002.

TPDDL has been able to achieve this kind of performance due to its innovative adaption and deployment of state-of-the-art technologies. The company has been a pioneer in introducing new Smart Grid Technologies in the Distribution Sector including SCADA, Distribution Management System, Distribution Automation, 100% Consumer Indexed using GIS integrated with Outage Management System and CRM using SAP ISU to name a few. Many of these technologies are implemented for the first time in India. TPDDL continues to develop new and innovative technologies, which are cost effective, scalable, delivering value and improving quality of life of its consumers and the society.

TPDDL has recently set up India's first "Smart Grid Lab" in Rohini, Delhi. The Lab is set up to provide continuous support for product & process innovation and futuristic solutions development in a collaborative environment, with Industry, R&D and Educational Institutions, for the Electricity Distribution Sector. This Lab also creates cost effective and scalable solutions, intellectual property, and business value for its customers and serves as a test bed for scaling up of strategic initiatives and services in the area of new and emerging technologies.

---

## ACKNOWLEDGEMENTS

We would like to thank the following individuals and institutions for their input:

Lawrence Berkeley National Lab: Nikit Abhyankar, Vincent Battaglia, Ranjit Deshmukh, Anand Gopal, Ashok Gadgil, Robert Kosteci, Amol Phadke, Ravi Prasher, Nihar Shah, Venkat Srinivasan and Michael Stadler.

Arun Majumdar (Stanford University); Daniel Kammen (University of California–Berkeley); Amos Winter (MIT); Sudipto Mukherjee (IIT-Delhi); Rajesh Manapat, Sasan Aminpour, and Catherine Zoi (SunEdison); Mitra Ardron (Lumeter Networks); Peter Adelman; Sarraju Narasihma Rao (OMC Power); Ben Shepherd (Ecoult); Mathias Hermes and Jay Whitacre (Aquion Energy); Syed Zaeem Hosain and Harry Plant (Aeris); Gaurav Gupta (Dalberg Global Development Advisors); Kaysar Ahmed Sagor and Rafiur Rahman (Prokaushali Sangsad Ltd.).

Special thanks to Praveer Sinha, Ganesh Das, Nilesh Kane and Satyanarayan Mahapatra (Tata Power DDL), Sanjay Khazanchi, Sharad Tiwari, and the Development Alternatives Group.



The next generation of breakthrough technologies  
to combat global poverty

[www.TransformativeTechnologies.org](http://www.TransformativeTechnologies.org)