It is well established that access to energy is closely linked with socioeconomic development. India houses the largest share of the world’s population deprived of electricity with about 237 million people lacking access (International Energy Agency). At the same time, in India, many households that do have access to electricity lack an uninterrupted and quality power supply. A recent study conducted by the Council for Energy, Environment, and Water (CEEW) across six states (Bihar, Jharkhand, Madhya Pradesh, Uttar Pradesh, West Bengal, and Odisha), found that about 50% of the households had no electricity despite having a grid connection. This indicates that there is an immediate need to address the quality, affordability, and reliability of the power supply in addition to extending the grid footprint.

As shown in Figure 1, the CEEW report suggests that, despite thousands of villages being electrified over the past decade under the Government’s rural electrification program, over 85% of the households in five of the six states considered in
the study had electricity for less than 8 h (maximum load of 50 W) or no electricity at all. Moreover, these households were found to be experiencing blackouts for two to four days a week (A. Jain et al.). The situation in other states may be slightly better, but low-income homes in most parts of India have poor access to electricity. Overall, the problem of energy access in India is quite unique and requires a new approach that leverages modern technological innovations. One way India can overturn the whole narrative of energy access for low- and medium-income households is by adopting novel solar and energy storage technologies and promoting innovations, such as a direct current (dc) microgrid, which benefits the energy poor.

Analysis of the Existing Problem

Poor Economics of Power Connections

The apparent reason for a large number of homes remaining off the grid and those with the grid having long hours of load shedding is a shortage of power. India generates less power than it would like to consume, but this has been changing over the past few years. Power generation capacity is increasing, whereas consumption has not been increasing as fast. As a result, the demand–supply gap has been narrowing, and power shortages may no longer be the primary reason for the current situation. Even during peak-demand hours, the gap is no longer severe. The limitations of the power-transmission grid in some regions of the country were another reason that power did not reach power-deficit areas. Even this issue has been considerably rectified, as the power grid in the country has expanded its capacity. The shortage of power is therefore no longer the primary reason for a number of Indian homes having no power or power for limited hours.

Another apparent reason for a large number of homes being off the grid is that, even when the village has grid connectivity, the power lines have not been extended to each home. In fact, as per the definition provided by the Ministry of Power, India, “a village is considered electrified when 10% of the homes in a village are connected to the grid.” Even though it is a serious problem, this bottleneck could be overcome by extending the existing power lines to all since some remote homes in a connected village should not be very expensive or difficult.

The real reason for the current power situation may lie in the economics. First of all, can these homes afford to pay for power even at the currently subsidized power tariffs? Second, can the power distribution companies (DISCOMs) afford to supply power to these homes at subsidized rates? The answer to both these questions may not be in the affirmative, and, unless this issue is addressed, many of these homes may remain without access to electricity for a long time.

The power tariff for homes in India is about ₹5 per unit. (An exchange rate of US $1 = ₹70 is assumed in this article.) A small home that in a day uses two tubelights for 6 h, two fans for 12 h, two bulbs, a 24-in TV for 10 h, and a cell phone being charged for 4 h consumes a little over three units of power a day, costing about ₹500 a month. This would be expensive for at least 50% of all Indian homes and an even larger percentage of rural homes. Therefore, in many parts of the country, the electricity tariff is further

Figure 1. The households’ distribution across different electricity tiers (A. Jain et al.). Tiers 0–3 represent progression in the path to energy access. Households with no electricity fall under Tier 0. Households with capacities of 1–50 W and having power only for 4–8 h a day fall under Tier 1. Those with 50–500-W capacity and 8–20 h of power are Tier 2, and the rest are classified under Tier 3.
subsidized for the first 50 or 100 units. However, even half of ₹500 a month is not affordable for many of these households. It is possible that homes in the lowest-income group may manage with less power and use one tubelight, one bulb, and one fan instead of two. That will help, but the quality of life would suffer. Many of the households would still not be able to afford their power bills. At the same time, slightly better-off homes would like to add refrigerators, mixers, and computers, adding to the power bill and making it more unaffordable.

On the other hand, DISCOMs lose money even when they supply power at ₹ per unit. The cost of power from plants using oil and gas (most of which is imported) is quite high in India. However, India can produce power from coal at a cost of ₹2 to ₹3 per unit (T. Buckley). Therefore, even though coal is a pollutant, power production using coal has been increasing rapidly in India. Even then, DISCOMs cannot break even when they supply power to homes. First, they have to take into account transmission and distribution (T&D) losses (for rural homes it varies from 40% to 70%). Second, coal power takes time to ramp up and to ramp down. Therefore, one cannot size coal plants for peak loads. One needs other power sources with faster responses. These are usually oil/gas-based plants, where the cost of generation is higher. This increases the cost of power for DISCOMs. With regard to this, once the costs of meter reading, billing, collections (for large numbers of homes, each paying small amounts), and the overhead costs are added, DISCOMs start losing money. When state governments push DISCOMs to supply power at subsidized rates (for example, lower tariffs for the first 50 or 100 units), DISCOMs lose even more. They have no incentive to continue to supply power or expand connections to homes not on the grid, as they know that these homes can afford (and pay) even less. Hence, at peak hours, they find one reason or another to carry out load shedding. One retired chief engineer of an Indian DISCOM remarked, “We are happy when there is load shedding as we lose less money.” This sums up the reality faced in India.

Can Rooftop Solar Panels Address These Issues?
Recently, rooftop solar panels have been touted as an alternative source for power generation. A 500-W solar panel in most parts of India could generate most of the power required. As there would be no T&D losses, the solution looks promising. At an installed cost of ₹50 per Wp, the rooftop solar photovoltaic (PV) would amount to a little over ₹3 per unit, assuming a depreciation over 20 years and an interest rate of 7%. (In India, the commercial interest rate varies from 13% to 16% today. Homes may be able to put their savings in fixed deposits and earn about 7%). This would be attractive. However, solar power is available only during the daytime, and even then, it fluctuates. On the other hand, DISCOMs face peak demand both in the daytime and in the evening. Hence, they are likely to resort to load shedding mostly during these times. Thus, a rooftop solar installation would require a battery, which increases costs considerably by almost four times, and as a result, solar power no longer remains attractive.

Furthermore, a solar PV produces dc power that needs to be converted to alternating current (ac) and synchronized to the ac grid. When 10-kW of dc solar power is converted and synchronized to ac, the conversion loss could be as low as 3%. However, when 250–500-W solar- dc power is used, these losses could be as high as 15% as long as the converter cost is a small percentage of the solar-panel cost (P. Kaur et al.). The problem gets further compounded as input and output power of a battery is only dc. Alternating current power needs conversion to dc before it charges the battery, and the battery output needs conversion to ac before it drives the load. Each of these conversions is also likely to have a 15% loss. In addition, there is battery loss (as high as 8%–10% for low-cost lead-acid batteries) and over half the solar power is lost before it reaches the load.

The approach looks more absurd when one examines the load to be driven. Some 62% of India’s home load is composed of ceiling fans and lighting (Global Buildings Performance Network). With the advent of brushless dc (BLdc) motors, a dc-powered ceiling fan consumes only 40% of the power consumed by conventional ac-powered induction-motor-based ceiling fans (Global Buildings Performance Network). If one uses an ac-powered ceiling fan, another converter with about a 15% loss will be required. Similarly, conventional ac-powered compact fluorescent lamp lighting is being replaced by light-emitting diode (LED) lighting. LEDs use dc power and are best powered by dc. Electronics (such as TVs, cell phones, and computers) are increasingly being used in homes, and all electronics need dc power. Taking solar power through multiple conversions to power the ac home grid and then converting it to dc to power each of these devices is indeed ridiculous. The stage is set for dc microgrids for homes powered by rooftop solar panels having batteries and connected to the incoming ac power through a converter as shown in Figure 2. This is the solar-dc microgrid for a home.

One of the key challenges in designing such a microgrid is to keep the losses low. The problem is not as straightforward as it appears. The solar-PV panel’s voltage [at a maximum power point (MPP)] would vary during the day. The battery’s voltage would vary depending on its state of charge. The grid power would be converted at an independent voltage, and the load would be expected to operate at some fixed voltage. If one uses dc-dc converters to connect these units together, the losses may not be very different from that of an ac home grid. The design would therefore require some smart power electronics such that the solar PV operates at its MPP and the battery is charged and discharged optimally while driving the load with minimal losses. As discussed in the subsequent section, this has been achieved such that for power in the range of 100–500 W, solar-PV power aided by a battery drives the
However, Can Solar-dc Microgrids Break the Logjam?

A dc microgrid for a home with a solar PV, a battery, and an incoming ac grid to drive dc loads can indeed help overcome many a problem. First, it would be highly cost-effective for off-grid homes as discussed in the “Economics of Off-Grid Homes” section. Furthermore, as and when the power grid reaches these homes, it can be connected to the dc home microgrid. Second, for homes that are already on the power grid but suffer long hours of power cuts, a solar-dc microgrid would ensure uninterrupted power. As shown in the “Economics of On-Grid Homes with Load Shedding” section, the power costs would be much less as compared to that for today’s home using an ac power line along with an inverter providing power backup. Third, as shown in the section “Economics of On-Grid Homes Without Load Shedding,” rooftop solar panels would lower the cost of power for most homes, possibly to a level that they can afford. This is achieved by first reducing power consumption by use of dc-powered dc appliances in place of today’s ac appliances and second by a rooftop solar PV, which produces dc power at lower costs than the current domestic power tariff. This is used to an advantage by keeping the conversion losses to a minimum. The key here is to use the battery minimally. A smart controller on the dc microgrid helps prioritize the usage of the solar panel, the grid, and the battery in that order. When this is followed and losses are kept to a minimum, the total cost of power to home owners comes down considerably, even though a battery is used. Finally, as rooftop solar panels start getting used widely, DISCOMs have to supply less and less power to homes. This would reduce the subsidy that they need to provide to the domestic sector and will help them break even more easily. Healthy DISCOMs can then expand their grid to most homes faster to ensure that no home remains dark.

Thus, a solar-dc microgrid could help in breaking the logjam that the domestic power supply currently faces in India. Over time, the solar power cost is likely to reduce, and better batteries will become available. The solution will therefore become more and more affordable. Finally, as 250 million Indian homes start adopting energy-efficient dc-powered appliances and rooftop solar panels, India is likely to become a green nation. This could alter the debate on climate change significantly.

Power Usage and Costs in a Solar-ac and a Solar-dc Home

In this section, the technoeconomic viability of a dc microgrid supplemented by solar power in juxtaposition with similar systems in homes running completely on ac is assessed. We present the simulation results of power usage in a solar-ac home and a solar-dc home backed up by actual data obtained from deployment to show that:

1) For off-grid homes, the cost of power per day is much lower for a solar-dc home as opposed to that for a solar-ac home. In fact, the results obtained will show that the per day power costs for a solar-dc home is comparable to the per-day power costs for an on-grid ac home today. As and when the grid is connected to these off-grid solar-dc homes, the per-day power costs will further reduce.

2) For an on-grid home with power cuts, the use of solar-dc power not only enables 24/7 power but also makes it available at a fairly low cost as compared to that for a solar-ac home.

3) Even for on-grid homes with no power cuts, considerable savings are possible using solar-dc power.

Assumptions and Methodology

Consider low- and midincome homes with the above power scenarios. To make sure that the systems are comparable, the following assumptions are made.

a) As a solar panel in India produces 4–4.5 kWh/kWp power per day (http://www.solarmango.com/faq/5), a
125-Wp solar panel was assumed to be producing 540 Wh of solar energy every day. Solar power is available from 6 a.m. to 6 p.m., as shown in Figure 3.

b) Table 1 presents the loads assumed in ac and dc homes along with their power consumption. It also gives the number of appliances used in each home along with their operational hours.

c) Let us now take a deeper look at the solar-cum battery systems that an ac home (using ac appliances) and a dc home will use. Battery backup systems called inverters are widely used in Indian ac homes today. Rooftop solar PVs can be added to such systems, and we will call them solar-ac systems. These systems, shown in Figure 4, would have an ac-grid input, a solar-PV input, a two-way connection to the battery for charging and drawing out power, and an ac output to drive the home load. Table 2 presents the losses associated with such systems assuming the power used is less than 500 W. Such a system has zero GtoL loss when the grid directly drives the load. However, when solar power directly drives the load (without going through the battery), the StoL loss is 15% primarily due to an ac- to dc-converter, which also ensures that solar panel operates at MPP and is synchronized to the ac-grid power. When the grid charges the battery, the GtoB is 15%, and when the solar panel charges the battery, the StoB loss is 30% (due to two converters). Finally, the BtoL loss is about 25% with a 10% loss being contributed by the lead-acid battery. Measurements were carried out on several available commercial systems with these features at the Indian Institute of Technology Madras (IITM) (Center for Decentralized Power Systems), and the losses, given in Table 2 for the solar-ac system, are the best results obtained from any of these systems.

A dc home, on the other hand, will use a system, such as inverterless, shown in Figure 5. The system has been designed at IITM and is being commercialized by Cygni Energy Private Limited [see http://www.cygni.com/products-2/ for product-related information]. Special care has been taken to minimize the losses and yet keep the

![Figure 4. A solar-ac system with an inverter for an ac home.](image)

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**TABLE 1. Device power consumption, the typical number of appliances in a small home, and usage.**

<table>
<thead>
<tr>
<th>Appliance</th>
<th>AC-Powered Appliances in ac Homes</th>
<th>DC-Powered Appliances in dc Homes</th>
<th>Numbers</th>
<th>Number of Operational Hours/Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan(^1)</td>
<td>67</td>
<td>24</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Bulb</td>
<td>40</td>
<td>5</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>Tubelight</td>
<td>36</td>
<td>18</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>TV</td>
<td>40</td>
<td>30</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Phone</td>
<td>6.5</td>
<td>5</td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>

\(^1\)ac-powered induction motor fan at an average speed was used in an ac home, and a dc-powered BLdc fan was used in a dc home.

---

**TABLE 2. Power losses within the system.**

<table>
<thead>
<tr>
<th>System</th>
<th>StoB(^1) (%)</th>
<th>GtoB(^2) (%)</th>
<th>BtoL(^3) (%)</th>
<th>StoL(^4) (%)</th>
<th>GtoL(^5) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ac system</td>
<td>30</td>
<td>15</td>
<td>25</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>dc system</td>
<td>5</td>
<td>15</td>
<td>10</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

\(^1\)Solar-to-battery (StoB) loss.
\(^2\)Grid-to-battery (GtoB) loss.
\(^3\)Battery-to-load (BtoL) loss.
\(^4\)Solar-to-load (StoL) loss.
\(^5\)Grid-to-load (GtoL) loss.

---

**TABLE 3. Efficiencies in delivering power from the source to the load at homes.**

<table>
<thead>
<tr>
<th></th>
<th>AC Home Efficiency (%)</th>
<th>DC Home Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GtoL</td>
<td>100</td>
<td>94</td>
</tr>
<tr>
<td>GtoL via a battery</td>
<td>63.7</td>
<td>76.5</td>
</tr>
<tr>
<td>StoL</td>
<td>85</td>
<td>97</td>
</tr>
<tr>
<td>StoL via a battery</td>
<td>52.5</td>
<td>85.5</td>
</tr>
</tbody>
</table>
costs low. The ac-GtoL losses in this system are 6%, and StoL losses come down to 3%. GtoB losses are still 15%, but StoB and BtoL losses are down to 5% and 10%, respectively. The loss values are confirmed using extensive measurements.

These losses will amount to a decrease in efficiency, as power is delivered from a source (at the inlet of a home) to the load. Table 3 presents these efficiency numbers. Thus, if an ac home is powered 30% through the grid without a battery, 20% through a battery, 25% from a solar panel without a battery, and 25% through a battery, the total power efficiency will be 77%, whereas that for a dc home will be 89%. As the available grid power decreases (more load shedding), the efficiency of the ac home will become worse, whereas, that for the dc home will improve.

a) In the case of off-grid homes, it was assumed that the battery is consumed only when the available solar power is not enough to drive the load. For on-grid homes with load shedding, the priority of source consumption assumed was a solar panel, the grid, and a battery in that order.

b) The battery used here is a special valve-regulated lead-acid (VRLA) high-performance battery developed by Amararaja (see http://www.quanta.in/products.asp for product-related information) in technical collaboration with IITM. The VRLA are low-cost batteries used widely in India. A typical 1-kWh battery, priced at around ₹6,000 per kWh, can be charged and discharged 800 times at 0.1 C and at a depth of discharge of 50% at 30 °C. The high-performance VRLA 1-kWh 48-V battery was especially designed to double its life and the number of charge–discharge cycles. The cost is about 15% higher than the conventional batteries.

c) Per unit costs of power are assumed as per Table 4. The corresponding solar-ac and solar-dc systems include the costs of deployment and balance of systems. [Depreciation of 20 years for solar panels and interest rate of 7% are assumed in computations of costs. A 500-W solar system including rooftop deployment and cables is assumed to be at ₹50 per watt. The cost of the balance of systems for a 500-W solar panel is assumed to be ₹3,000 for inverterless (solar-dc system) and ₹10,000 for the solar-ac system but with a life (depreciation) of five years only. The costs for a lower wattage system may be slightly higher.]

Results and Discussions

Economics of Off-Grid Homes
To begin with, an off-grid ac home and a dc home with the same load and solar profile were considered. The simulation results obtained are presented in Table 5. As shown, the per day load requirement in the dc home was about 37% of that of an ac home due to lower consumption of dc appliances in comparison to ac appliances. Further solar power is delivered to a load (directly and through a battery) at 91% efficiency in dc homes as compared to 65% in ac homes. As a result, the per day cost of power was found to be around ₹12.6 for the solar-dc home, which is significantly lower than ₹50.6 for a solar-ac home. More interestingly, as shown in the section “Economics of On-Grid Homes Without Load Shedding,” the per day cost of power in a grid-connected ac home with zero load shedding is ₹16.3 for the same load, implying that for an efficient off-grid solar-dc home the power costs are lower than even the current grid-connected ac homes.

Recognizing that solar-dc technology has the potential to revolutionize and transition India’s power sector to a more sustainable one, the Government of India recently started supporting its deployment in 4,000 off-grid homes in Rajasthan. In December 2015, deployments started in Bhomji ka Gaon, a village in Rajasthan located in a region where the terrain conditions are harsh with no road connectivity, marked by frequent sandstorms and lack of resources. Each home is powered by a 125-Wp solar panel supported by a 1-kWh

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**TABLE 4. Per unit costs of power from different sources.**

<table>
<thead>
<tr>
<th>Source of Power</th>
<th>Per Unit Cost (₹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>5</td>
</tr>
<tr>
<td>Solar-dc system</td>
<td>4</td>
</tr>
<tr>
<td>Battery</td>
<td>12</td>
</tr>
<tr>
<td>Solar-ac system</td>
<td>5</td>
</tr>
</tbody>
</table>

**TABLE 5. Per day cost of power in off-grid ac and dc homes.**

<table>
<thead>
<tr>
<th>Type of Home</th>
<th>Load/Day (W H)</th>
<th>Cost/Per Day (₹)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ac home</td>
<td>3,266</td>
<td>50.6</td>
<td>65.1</td>
</tr>
<tr>
<td>dc home</td>
<td>1,212</td>
<td>12.6</td>
<td>91.4</td>
</tr>
</tbody>
</table>

Figure 5. A solar-dc inverterless system for a dc home.
battery to drive a dc fan, a dc tubelight, a dc bulb, and a socket-cum dc mobile charger as shown in Figure 6(a) and (b). The power is remotely monitored with power data logged onto a server using Bluetooth and a mobile handset. Figure 7 presents the solar power, the power flowing in and out of a battery, and the load for one such home on 25 February 2016. The captured data from homes validate the simulation results presented for a dc home in Table 5. The deployments have, on one hand, marked the arrival of power to these homes, which otherwise would have continued to be without electricity for a considerable period of time and, on the other hand, established that the future of power is solar-dc power.

**TABLE 6. Per-day cost of power in ac and dc homes with a grid and 4-h load shedding.**

<table>
<thead>
<tr>
<th>Type of Home</th>
<th>Load/Day (W H)</th>
<th>Cost/Per Day (₹)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ac home</td>
<td>3,266.00</td>
<td>28.9</td>
<td>88</td>
</tr>
<tr>
<td>dc home</td>
<td>1,212.00</td>
<td>7.3</td>
<td>93.3</td>
</tr>
</tbody>
</table>

**Figure 6.** Bhomji ka Gaon, Rajasthan. (a) A 125-Wp solar panel installed on a house, and (b) a family in a home with a solar-dc inverterless system. (Photos taken with permission of the family that owns the system.)

**Figure 7.** The power data measured over a day in an off-grid home in Rajasthan with a solar-dc inverterless system on 25 February 2016.

**Economics of On-Grid Homes with Load Shedding**

Now, let us analyze grid-connected homes and understand the impact of load shedding on power costs in the two types of homes. Table 6 presents cost per day when the grid has a load shedding of 4 h (2 h during sun hours and 2 h during off-sun hours). The per day cost for a dc home is as low as ₹7.3 even with 4-h power cuts, whereas the ac home power cost is about four times this cost. This translates to cost savings of about ₹650 per month.

These cost savings become even more prominent as the duration of load shedding increases as is evident from Figure 8. So for homes that have a grid supply only for a few hours a day as is the case with thousands of rural homes in India, solar-dc power becomes an efficient and more importantly an affordable solution. Also shown in Figure 8 is the power cost per day in an ac home but with energy-efficient ac-powered dc appliances, consuming 15% more power than dc-powered dc appliances. Here too, the costs are considerably lower than those for a conventional ac home with ac appliances; however, they are 10%–60% higher than that of a dc home, depending upon the extent of load shedding. There is no reason to go halfway; going with solar-dc power will be the fastest way for India to get to 24/7 power in every home. These lessons were used to pilot solar-dc power for grid-connected homes with significant load shedding. A solar-dc inverterless system powering a cluster of 27 homes and a school was set up in the village of Tirmal, Odisha, whose entire population is below the poverty line. Figure 9(a)–(c) shows these deployments. Figure 10 captures (via Bluetooth and a mobile phone) the solar power generated, the load, the grid power used, and the power in/out of a battery in a home for a few days. This data
captured from the homes validate the simulation results presented in Table 6 for solar-dc systems.

Economics of On-Grid Homes Without Load Shedding

Finally, consider power costs for the two kinds of homes on the grid with zero load shedding. Table 7 shows that a dc home scores significantly again in terms of power costs. The monthly power bill would come down from about ₹500 for the current ac homes to less than ₹200 for a dc home. This is huge for low- and midincome homes as they are often unable to power their homes because of the lack of affordability. Direct current homes, therefore, will go a long way in enabling them to afford power. Midincome homes can now also afford to consume more and add more dc appliances.

**Expanding the Solar-dc microgrid for multihomes**

So far, we have discussed how a solar-dc microgrid deployment within a home is highly beneficial in terms of energy savings and savings in power costs. It becomes imperative to analyze the impact when such a solar-dc microgrid is scaled to a cluster of homes. One of the advantages would come from the fact that the most expensive elements of a solar-dc system, that is, solar panels (power sources) and backup storage, would now be shared. The Inverterless-500 system has been designed to power a cluster of four homes using common solar panels and batteries on a 48-V dc power line. Similarly, the Inverterless-2500 system uses common solar panels and batteries and extends the dc microgrid to a cluster of 12/24 homes. As it is unlikely that each home will use the peak load at the same time, the system can be designed for average loads rather than peak loads; in other words, such shared systems can benefit from the different energy-usage patterns of individual homes by what is known as the law of averages. This also enables one home to draw more power when needed while other homes are not consuming much. Thus, in comparison to the sum of the sizing of the solar panels and batteries needed to power each home, the size of shared solar panels and batteries can be less, or better quality of service could be provided to each home by keeping the size the same.

A multihome microgrid deployment requires the energy consumption of each home (from different sources) to be billed appropriately. The Inverterless-500 system, shown in Figure 11, is equipped with an inverterless remote unit (IRU) deployed at each home, which measures energy consumption and enables cutting off the supply in case the consumption exceeds the (configurable) threshold power consumption after generating a suitable warning signal. This system, however, measures only the total energy consumed by a home and does not separate the energy used from different sources (solar panel, grid, and battery). The Inverterless-2500 system, on the other hand, performs these measurements. These systems have a normal line and an emergency (low-load) line at each home. At the time when the grid and the solar panel are not feeding power

<table>
<thead>
<tr>
<th>Type of Home</th>
<th>Load/Day (W H)</th>
<th>Cost/Per Day (₹)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ac home</td>
<td>3,266.00</td>
<td>16.3</td>
<td>100.00</td>
</tr>
<tr>
<td>dc home</td>
<td>1,212.00</td>
<td>6.45</td>
<td>94</td>
</tr>
</tbody>
</table>

Figure 8. The variation in cost of power per day with the load shed duration for different types of homes. System 1: an ac home, system 2: an ac home with ac-powered dc appliances, and system 3: a dc home.

Figure 9. A deployment at Tirmal, Odisha. (a) A school running on dc power supplied by a solar-dc inverterless system, (b) a cluster of homes powered by a solar-dc inverterless system, and (c) a home in Tirmal, Orissa, with dc appliances powered by a solar-dc inverterless system. (Photos taken with permission of the family that owns the system.)
and the battery goes below a minimum level, the normal line is cut off, whereas the emergency low-load line continues to supply power for much longer durations.

The Inverterless-500 systems have been deployed at Kundithal, Neelgiris, where eight such systems powered 21 homes. The 48-V dc power used in the microgrid limits the maximum separation for homes in the cluster. As homes in Nilgiris were separated by long distances, each system could power between two and four homes. Each home is supplied 125 W with a cumulative peak consumption of 500 W. Every home is installed with an LED tubelight, a BLdc fan, a cell-phone charger, and a bulb. On similar lines, three units of the Inverterless-2500 systems have been deployed at Tirimal village in the state of Orissa, India; each of these systems powers about 30 homes. The amount of power to be supplied to each home can be configured remotely through the management system.

Conclusions and the Way Forward

A large percentage of the Indian population, especially the lower- and the middle-class homes, are denied access to quality power most of the time. The shortage of power and the lack of connectivity to homes were traditionally understood to be the primary causes for this lack of access. However, recent developments in the country and studies show that the actual reason for this state of affairs could be the lack of affordability even when the power tariff is subsidized. At the same time, power DISCOMs are not eager to supply power to such homes as the supply is not financially viable; their own finances are in dire states. India seems to be stuck in this logjam as power cannot be generated at much lower costs, even though it depends on environment-unfriendly coal-fired power plants.

Disruptive technology is needed to get India to break this logjam. A solar-dc microgrid for homes seems to be an answer. In the article, we have illustrated that a 48-V dc microgrid for each home powered by a rooftop solar panel, connecting to the grid through an ac–dc converter wherever the grid is available, integrating a small sized battery, and powering dc-powered dc appliances, could overcome a multitude of problems. As a result, the power costs for homes could be drastically reduced and could become affordable in the presence of a 24/7 grid for grids with significant amounts of load shedding and in the absence of the grid. In addition, homes will draw limited power from the grid, significantly cutting down the losses for DISCOMs. Finally, when homes use energy-efficient dc-powered dc appliances and generate power from a solar panel on their rooftops, the nation moves toward becoming truly green.

Solar-dc microgrids for homes may make immense sense in this context. Yet, they face tough challenges. First, there has to be a change in the mindset that the ac versus dc debate was settled a century ago and that we are going backward when we talk about the dc microgrid. Appliances in homes and offices have quietly become dc over the past few decades, and it will be a step forward into the future when we power them using a dc microgrid rather than using ac–dc converters for each of them. The second bottleneck is the lack of standardization. There is no accepted
dc-power standard for home wiring today, even though the telecom and automobile industries use 48-V dc widely. The IEEE Low-Voltage dc Forum in India proposed 48-V dc power as a standard for home power involving low-power appliances. The Bureau of Indian Standards is now working on such standards and is veering toward the 48-V dc standard for homes with low-power appliances and 380-V dc for larger microgrids involving higher power usages. The International Electrotechnical Commission has set up a subgroup to examine dc-power standards for homes and other usages. But for now, there is no acceptable standard that can be used by appliance manufacturers and installers. This could be the primary reason for the third bottleneck—the lack of availability of standardized dc-powered dc appliances. Unless such appliances are widely available at prices comparable to their ac counterparts, users are unlikely to bite. This is so even when dc-powered appliances have the benefit of avoiding ac–dc converters and, thereby, reducing costs and increasing reliability. Even the power-factor correction that ac-powered appliances need will no longer be required. Despite these hurdles, countries, such as India, can benefit immensely by adopting the dc microgrid for homes and powering them using rooftop solar panels. Difficulties cannot stop the future, and solar-dc microgrids for homes is the future. India needs to lead rather than wait for the difficulties to be resolved.

For Further Reading

Biographies
Ashok Jhunjhunwala (ashok@tenet.res.in) received his B.Tech. degree from the Indian Institute of Technology (IIT) Kanpur, and his M.S. and Ph.D. degrees from the University of Maine. From 1979 to 1981, he was with Washington State University and has been at IIT Madras ever since, where he leads the Telecommunications and Computer Networks group. He is the director of the Board of Tata Teleservices (Maharashtra) Limited, Polaris, Sasken, Tejas, Tata Communications, Exicom, Mahindra Reva Electrical Vehicles Private Limited, and Intellect Design Arena Limited. He was also a member of the Prime Minister’s Scientific Advisory Committee from 2004 to 2014. He was bestowed with the Padma Shri in 2002, the Shanti Swarup Bhatnagar Award in 1998, the Millennium Medal at the Indian Science Congress in 2000, and the H.K. Firodia for “Excellence in Science and Technology” in 2002, among several others. He is chair or member of several committees, including the Technology Information, Forecasting, and Assessment Council’s vision 2035 for Electronics and Information Technology; Information Technology Institute for the Tribes of India; Mobile Payment Forum of India; Technology Advisory Committee of the Securities and Exchange Board of India; Biotechnology Industry Research Assistance Council; and the IIT committee for solar energy installation among many others. He is a Fellow of the IEEE, the World Wireless Research forum, and several Indian academies.

Aditya Lolla (aditya@tenet.res.in) received his B.Tech. degree in chemical engineering from Osmania University, Hyderabad, India, in 2012 and his M.Sc. degree in sustainable energy systems from The University of Edinburgh, United Kingdom, in 2013. He is a project officer at the Center for Decentralized Power Systems, Indian Institute of Technology, Madras, and is a recipient of the Queen’s Jubilee Scholarship from the British government. In his previous roles, he worked on different projects encompassing renewable energy, sustainable development, and energy policy. He researched microbial fuel cell technology with a specific focus on analytics and has worked as a research intern at FloWave TT, Edinburgh, specializing in tidal energy systems. His current work includes energy policy, data analytics, and decentralized solar power.

Prabhjot Kaur (prabhjot@tenet.res.in) received her B.Tech. degree from Punjab Technical University in 2001 and her M.S. degree in engineering from Punjab University. She completed her Ph.D. degree at the National Institute of Technology, Jalandhar, in 2013. She is currently working as principle scientist in the Department of Electrical Engineering at Indian Institute of Technology (IIT) Madras, and she also serves as deputy director at Telecom Centre of Excellence, IIT Madras. Prior to this, she worked as associate professor at NorthCap University (NCU), Gurgaon, India, where she also served as deputy dean (research, development, and industrial liasoning). At NCU, she formed and led the research group on wireless communication and was also a lead for Change Initiatives for Education Reforms and practices in the university. She has been conducting faculty development programs and also delivered some invited talks on varying fields of interest. Her recent research revolves around green technologies encompassing renewables, batteries, and electric vehicles.