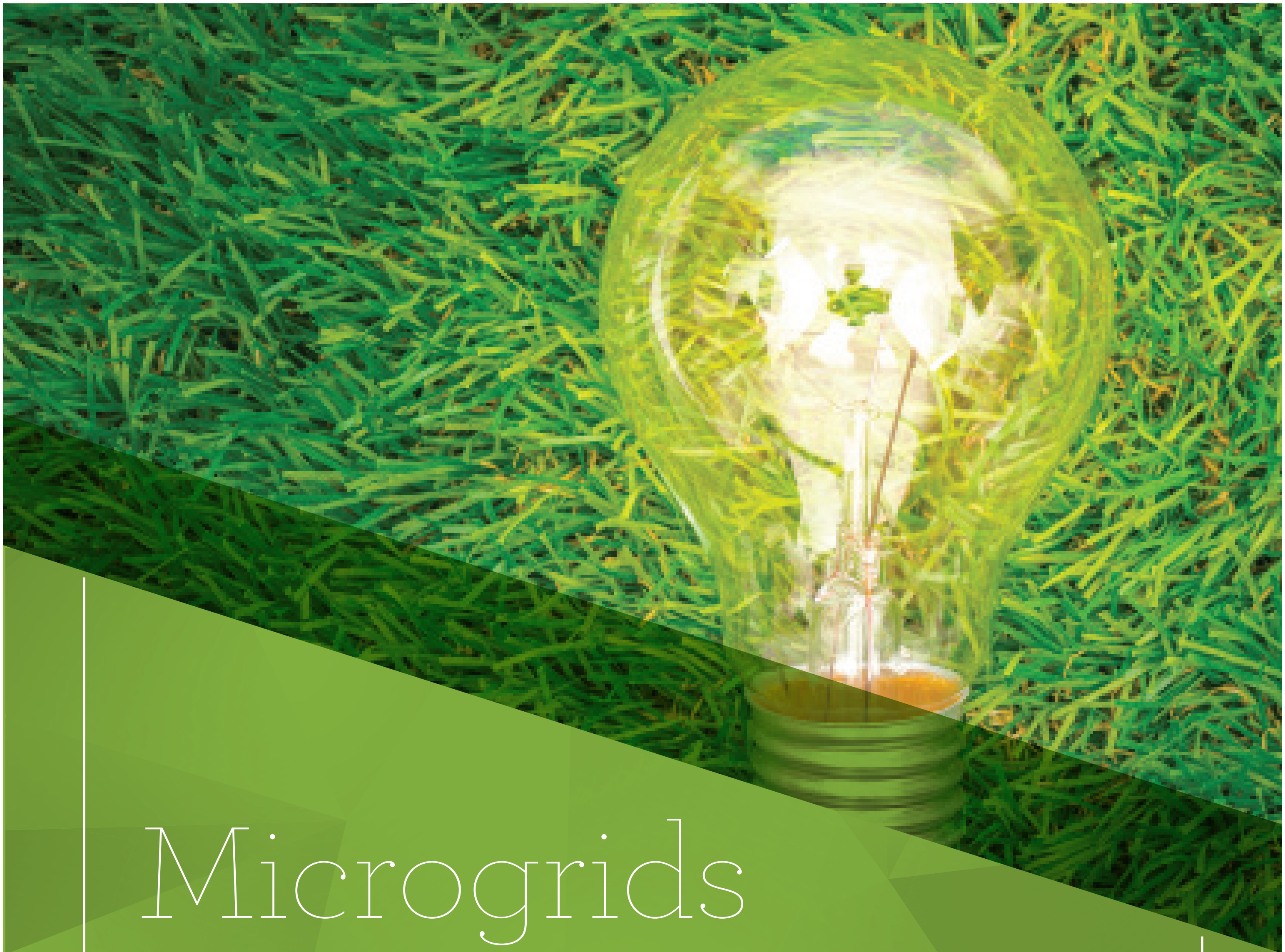

Microgrids *in* India

Myths, Misunderstandings, and the Need for Proper Accounting

By Rahul Tongia

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Key points

1) Many Indian microgrids have been a response to "bad quality" or unavailable grid supply – this model faces an existential threat as the grid improves.

- For much of India, the challenge has been one of last-mile connectivity to the home, as most villages now have the grid reaching them. *Last-mile connectivity problems remain with a microgrid*. Even "poor supply" as a driver is diminishing as the grid is improving.

- The government's *Saubhagya* household electrification scheme aims to address grid-based household connectivity within a few years, exacerbating pressure on microgrids.

2) While almost no microgrid today proclaims to be cheaper than the traditional grid (except in a few remote locations), reliability and quality have been its drivers. This is hard to achieve, except at a higher cost.

- Cheap Renewable Energy (RE) as a supply is a misnomer. Opportunistic RE (take it when it is available) may be cheap, but adding a battery or otherwise providing reliability makes this power very expensive.

- For any consumer of limited electricity, last-mile infrastructure fixed costs dominate energy costs. *This applies to both microgrids and the traditional grid.*

- "Right-sizing" a microgrid is very challenging, especially since almost all costs are fixed (especially if based on RE). Over-sizing a microgrid means costs are not covered, while undersizing it means the system does not have headroom for either growth or occasionally higher demand. The traditional grid enjoys far greater flexibility from both demand and supply diversity.

3) Microgrids may be best positioned to be hybrid (interactive) with the grid. This enables a long-term future where they do not become "redundant" and also allows for evolution of load and supply options.

- An interactive or interactive-capable microgrid can address a spectrum of objectives, ranging from primary supply, backup/secondary supply, islanding for stability reasons, to opportunistically cheaper supply (when available), etc.

- Grid-interactive microgrids can play into evolving business models and competition based on smarter systems that dynamically engage with the grid (and change the direction of power flow) based on a combination of local load, local supply, and external grid conditions. These cannot work with simple DC microgrids

4) Suggestions to improve microgrid viability as well as overall electrification include:

- Make subsidies, cross-subsidies, and other support offered to regular grid providers available to any third-party rural provider, including microgrids. Such support is not just for tariffs but up-front costs as well (explicitly and implicitly).

- Set power prices (tariffs) for the grid *at least* equal to the variable cost of supply at a fuel level (which might be ₹1-2 per unit in most states lagging household electrification, which are mostly near coal fields). More than creating a culture of paying, this overcomes utility resistance to serving such users, and also improves the benchmark for microgrids (but not enough for viability). For the truly poor, even at low consumption, one could provide a separate subsidy, perhaps a direct benefit transfer, for this electricity.

Microgrids and electricity supply

India has a vibrant market for batteries and inverters and even diesel generators – but a cynic could call these responses to the failure of the grid in providing quality supply. Are microgrids similarly stepping in to fill gaps in grid-based supply? This paper revisits the fundamentals and drivers for microgrids, and suggests that a "gap-filling" or competitive model against the grid may not be the most scalable solution.

There are traditionally a handful of arguments that favour microgrids, ranging from they are the best (if not the only) option, to they are cheaper, to they are cleaner.[1] Only one or more of these arguments might be true, but it is rare for all of these to be true. The economics especially depend on the specific situation and design.

In the past, there were a number of central electrification schemes based on microgrids, even for "remote" locations. However, most never came to fruition, despite funding support, as on-ground challenges have been greater than what on-paper economics may have suggested, especially relating to payments and collection. Importantly, if microgrids did not work in the past, won't higher competition from the regular grid only make things tougher? Of course, solar panels are much cheaper, but as we will see below, input energy costs are a small fraction of total costs.

In the Indian context, only 1,191 of some 600,000 villages are not electrified, as per the GARV website.[2] The current definition of electrification means having more than just a single wire in the village connected to the grid. According to new government regulations, at least 10 per cent of homes must be connected for a village to be called electrified. However, villages are just one part of the puzzle; it is households that are the real challenge for last-mile connectivity and quality supply. While quality should include issues like voltage and frequency, at the very least it should start with not being load shed. Even so, household connections are growing, and as per some estimates, it remains a matter of time before most homes in India are electrified, especially in light of the Central Government's *Saubhagya* household electrification scheme.[3]

[1] *As early as 2012, Prayas undertook a literature review of over 60 studies, models, and papers on microgrids in India in their paper "Decentralised Renewable Energy (DRE) Microgrids in India : A review of recent literature" (November 2012).*
[2] *Government of India's "GARV" electrification dashboard. (Source: http://garv.ddugjy.in/, accessed February 3, 2018.)*
[3] *Source: http://saubhagya.gov.in/*

For remote locations that are far from the grid, a stand-alone microgrid is likely to meet all three criteria above, but these are limited in scope. Additionally, which are these "remote" or "hard to supply" regions where the grid will not reach or provide quality supply? This is an ever-shrinking pool, and no government will declare an area to be the last that will get electricity.

Defining microgrids

Any economic calculation on microgrids depends on its design and assumptions. People typically associate microgrids with small, rural, renewable-powered and standalone systems that provide electricity to homes across the area. These are often non-governmental (community or commercial), and are in place due to the inability of the traditional grid to supply quality, affordable power. There are exceptions, however, and some planners think of microgrids for their reliability, especially in the U.S., where a major proponent of microgrids is the U.S. Department of Defence, with its military installations. In the U.S., microgrids are also popular in areas of severe and disruptive storms. In India, microgrids are increasingly being used in commercial or industrial parks that consider these an extension of captive power or at least mixed with back-up power. There are also some definitions that attempt to distinguish mini vs. microgrids, such as the 2016 MNRE Draft Policy,[4] but these are often artificial distinctions.

1) Design
2) Source of generation
3) Institutional framework

1) *Design* spans the following characteristics, often constrained by geography or underlying factors, such as available sources of power.

- How big will the microgrid be, both in terms of number of consumers (nodes) as well as the size of their connection(s)?

- Will these only be household connections, or will irrigation pumpsets (IP) also be covered?

- Are these AC or DC supply? The former looks very similar to the grid for an end-user, while the latter is of lower cost but also lower capability, and requires specialised equipment or appliances.

- What is the expectation of reliability? This is at a design

[4] *Source: http://mnre.gov.in/file-manager/UserFiles/draft-national-Mini_Micro-Grid-Policy.pdf*

(capability) level, as opposed to practical limitations, which the grid itself faces and manifests itself as load-shedding.

• How much headroom is there in connected or sanctioned load? How easily can one grow consumption?

• What are the pricing schemas – is it flat monthly, per size of connection, per unit of consumption, or a combination of these?

• How does this interface with the regular AC grid? Is it stand-alone? Is it used for periodic or opportunistic backup? Can it island itself, perhaps for stability reasons?

2) *Source of generation* is the type of supply feeding the consumers. There have been microgrids based on diesel generators, but the expectation moving forward is of greater reliance on RE. One major challenge is most that renewables, as used today, are opportunistic – only available when the sun shines or the wind blows. For such intermittent RE to truly become the sole source of energy, it inherently requires over-engineering as well as storage. Both of these significantly raise the costs of service.

3) *Institutional framework* relates to issues of ownership, pricing, regulation among others. Many microgrids are privately owned and function under the Electricity Act 2003, which allows rural distribution without a special licence.[5] The Government of India has had a draft microgrid policy for RE-based generation since 2016[6] and a few states have notified their own microgrid policies.

Many microgrids have higher costs per unit (kWh) than regulator-approved prices for regular (grid) licencees. There have been attempts at creating other business models, including centrally-supported microgrids with a capital subsidy, including for remote Distributed Renewable Energy (DRE) microgrids. However, these never scaled to meet the expectations of rural electrification. In the report, "Beyond Off-grid: Integrating Mini-grids with India's Evolving Electricity System" (Okapi, May 2017) such interconnections are structured into five categories based on the level and direction of power flow.[7] Ideally, a flexible framework and nimble design should be agnostic and enable any and all of the above flows of power.

[5]*Section 14 of the Electricity Act 2003 allows rural generation and distribution in rural areas without a licence (Source: www.cercind.gov.in/Act-with-amendment.pdf). Sections 4 and 5 are about creating new frameworks or policies for rural electrification in consultation with states; these have not materialised.*
[6]*Source: http://mnre.gov.in/file-manager/UserFiles/draft-national-Mini_Micro-Grid-Policy.pdf; this attempts to segment solutions into mini and microgrids.*
[7]*Source:http://okapia.co/serviceareas/blueprint/beyond-off-grid-integrating-mini-grids-with-indias-evolving-electricity-system*

The big picture of rural connectivity economics: it is expensive

At the risk of oversimplifying, there are three primary components of any rural household electricity system. One needs a source of electricity (generation), a means to deliver it (infrastructure) and a system to operate, maintain, bill, etc. it. Except for a household-level stand-alone system (such as a solar home system), popular with many rural homes, these three components are present and similar regardless of whether one is dealing with the traditional grid or a microgrid. Even in a microgrid, operational expenses (opex) are mostly fixed costs for manpower and maintenance contracts. Thus, lower energy consumption in a microgrid does not save that much money in an absolute sense – the per unit electricity cost rises non-linearly. In fact, at the margin, in a solar photovoltaic (PV) microgrid, lower consumption does not save any money.

We build out a simple model capturing all three aspects of connectivity costs, and compare and contrast the regular grid with microgrids, examining what factors matter for the latter the most. We begin our analysis with the last-mile, a current focus of attention in the country, and a bottleneck, without which discussions on supply are moot.

Fixed infrastructure costs dominate: last mile is a major challenge

By definition, microgrids involve last-mile connectivity, the only alternative to which would be solar home systems based on standalone PV per households. Having a microgrid allows greater diversity of demand, which is also important, since even RE supply has variability. This is also crucial since almost all RE solutions other than solar are village-sized or even larger (typically tens of kilowatts in size). Wind is actually the most cost-effective at megawatts scales.

Given that microgrids also need last-mile connectivity, for an AC microgrid the last-mile costs are similar to that of the traditional grid. The main saving in a microgrid could be that of the distribution transformer, which converts long-distance medium-voltage feeders into low-voltage or low-tension (LT) voltage suitable for homes. However, this is not really a saving, since most villages already have a distribution transformer. Adding even a hundred homes to this should not overload the transformer. (Irrigation pumpsets are a different matter, and not a focus of this paper.) Distribution transformers can also handle temporary overloading, albeit with higher losses and some impact on operation and maintenance (O&M) costs or lifespan. Thus, we can examine last-mile infrastructure costs independent of the grid type – micro or traditional.

What does connecting a home to any grid cost? It depends on the distance. If one is further than 40 metres from existing infrastructure, then one needs a new pole(s), which raises costs measurably. Most electricity distribution companies (DisComs) estimate the cost to be almost ₹200,000/km. Of course, some homes may be clustered so one often has a tree-structure, with a long trunk line and then shorter spurs, so the average costs would be lower than the average distance to the low voltage distribution grid. However, costs for wiring to the home are likely to be at least ₹5,000 per home or more and even higher for sparser or more remote locations and hilly regions. This per home cost should also factor in the cost of an electricity meter, now mandatory under the Saubhagya scheme, and important in a microgrid since supply is usually a bottleneck such that controlling consumption (and charging for it) is important for the system. Digital meters cost at least ₹650/meter, while pre-paid or smart meters are costlier.[8]

A back-of-the envelope cost estimate for monthly amortisation of just the wiring and meter costs could be as follows:

Table 1: Costs of wiring to the home in per unit electricity for different wiring, capex costs (low, mid and high).

		Low	Medium	High
Wiring CapEx	(₹)	5000	7500	10,000
Monthly payment	(₹)	45.9	68.9	91.8
Per unit cost based on varying capex and monthly consumption (₹)				
5	kWh/month / HH	9.2	13.8	18.4
10	kWh/month / HH	4.6	6.9	9.2
20	kWh/month / HH	2.3	3.4	4.6

This assumes a 20-year lifespan and 10 per cent interest rate.

The fixed costs just for this infrastructure are far higher than most states' monthly retail tariffs for "fixed costs" vis-a-vis a 1-kW household connection or "sanctioned load", which is also often the minimum billing size. In per unit electricity terms, wiring costs are substantial, especially for low monthly consumption and/or high wiring capital costs. If a household had to pay, marginal users would likely

[8] *There are some microgrids that do not charge for usage but provide capped consumption or loads only (mainly for lighting), but these have obvious limitations.*

consume on the lower end of the range, but with "free electricity" or other government sops, consumption could be higher. However, currently these sops are only available with the regular grid.

How much would a newly connected household consume? A marginal or lifeline user might use, say, 50 watts for six hours per day, or about 10 kWh/month. From Table 1, we see that regardless of the capital expenditure (capex), plausible monthly consumption ranges mean the connection infrastructure costs are far higher than regular retail household prices for the grid for small consumers, and even higher than headline costs for solar PV power, which fell (for grid-scale power) to below ₹2.5/kWh.

Note that the above simple calculation does not factor in operations and maintenance (O&M) costs on the wire. In our simple model that we explain subsequently, we factor in O&M costs for all components, as well as their lifespan. For the wire to the home, we assume that even if a microgrid lasts only five to 10 years commercially, the assets have residual value and so assume a 20-year lifespan for amortisation.

These high costs of wiring remain for the regular grid. As a comparison, it is worth asking whether there is enough capital allocation in the regular grid for wiring up the unelectrified homes. If we consider the funding for the *Saubhagya* programme, the outlay of ₹16,320 crore (1 crore = 10 million) for 40 million rural households lacking a connection comes to just about ₹4,000/home, inclusive of a meter and basic home wiring (the kit for which reportedly costs a few hundred rupees). Clearly, this funding is on the lower end, and may need to be supplemented by state or additional central funding.[9]

What is key is to realise that *for both microgrids and the traditional grid, fixed costs of wiring and connectivity are very high for low levels of consumption*. Given that one cannot charge marginal users the true cost of wiring, there are two implications: First, one may need external support through subsidies, grants, etc. as is the basis of *Saubhagya*. This external support is not available to microgrids as of now. Second, for microgrids the only viable option remains to ensure that consumption is low such that even at a high per unit rate, the monthly total cost billed to consumers remains manageable. Many microgrid operators aim for ₹50-100 per home per month.

[9] *Anecdotally, there is evidence such as from states such as Uttar Pradesh that in the last one to two years, there has been a flurry of activity for extending poles across rural areas. If available, this will lower the consumer connection cost. However, consistent data for the same across states is not available. A good official number the central government should ask the states for and also track is the average distance from the grid for the unelectrified home. This number would likely increase over time (though on a smaller base), as nearer homes get wired first.*

Operating rural electricity supply: building it is the easier step

Managing electricity supply to rural areas is a challenge. Often, collection rates are poor, and losses are high, especially with theft and leakage. These are issues in some urban areas but on average rural areas fare far worse. The situation is further exacerbated when we have irrigation pumpset loads, which are mostly unmetered and obviously politically sensitive. For our microgrid, we assume a focus on household supply, given free power for pumpsets is not viable for the microgrid operator. In the regular grid, regulators have mandated that free agricultural supply should be paid for by the state governments. Even if this were made available to a microgrid operator, the typical payments–equal to the grid's cost to serve as calculated, often about ₹5/kWh–would be far lower that the real per unit costs of supply in a microgrid. On the other hand, this is a non-trivial amount of support which could be the difference between regular grid tariffs and a medium willingness to pay for consumers (higher than the regular grid but lower than fully loaded costs). In addition, the aggregate quantum of support should be modest, especially if we compare this to proposed solar pumpset subsidies.

In addition to billing and collection, physical maintenance of the lines is a key need and challenge. Weather and human intervention-based outages or failures are not uncommon, and a key issue is keeping spares handy. A single village-sized microgrid becomes a very costly proposition in terms of inventory, while a larger coverage area necessitates travel and transportation costs. Are we expecting that the same person can handle commercial and technical aspects of running rural supply? Or is there more than one person required?

At a minimum level, we assume that hardware O&M costs are a fraction of capital costs (baselined as 0.75 per cent per annum),[10] in addition to which there is manpower to operate the microgrid. We assume two persons are required to operate the microgrid, except for the smallest size deployment, in which case two people can cover two habitations or villages. We assume private sector level salaries, which are high for rural areas, but lower than official government salaries (technically, "cost-to-company").

In addition to ongoing costs, there are one-time up-front development and deployment costs, which also include training the local manpower. Estimating these is difficult because of the high variance based on the scale of the project

[10] *While this may appear low, we assume the microgrid's economic life is lower than the ultimate lifespan, and in the first 10 years, one would have lower failure rates of equipment. Real-world data can help update this figure.*

(are one or many microgrids being set up by the same entity?), past experience (first few versus n^{th} of a kind), and several other factors such as costs of surveying, planning, stakeholder engagement, and obtaining approvals and permissions. These are estimated as ₹3 lakh per village.

Energy supply: quality and other choices matter

For the regular grid, one assumes that generation is available *somewhere*. While mostly true, the grid operator, DisCom, or any other provider, must procure the said power. Ostensibly, the grid has sufficient capacity to meet such incremental demand. Even if one does not believe that there is a true surplus in the grid, shortfalls are falling rapidly,[11] and newly electrified households are likely to use a modest quanta of electricity at most. On a capacity basis, 100 watts of load for 40 million homes is only 4 GW of load, or 5 GW of gross capacity adding in technical losses and power plant auxiliary (in-house) consumption. This is less than a quarter of the *annual* addition of capacity in recent years.

Microgrids need explicit planning for their energy supply. What is the source of local generation for a microgrid? Many plans call for RE to supply the grid, but earlier deployments often relied on diesel generation. This was one factor why costs were always high and deployments never grew. Within the RE basket, not all types are the same. Economics aside, what is the supply technology's minimum or optimal scale? Other than solar PV, all other forms of generation are multi-kilowatt scale (many tens of kW), including biomass and microhydro, while optimal wind generation is megawatt scale. Thus, these all require last-mile connectivity, except home-level solar systems. Of course, that does not make a microgrid. Moving forward, we anticipate solar PV systems to dominate.

The main reason you would want a microgrid or other grid is for system diversity. If one built a system only for a single home, sizing it becomes a major challenge. Under-sizing would lead to failure to meet loads, while oversizing would bring an economic hit. Worse, both supply and demand are variable, so getting it right "on average" is not good enough – one cannot plan capacity simply by converting average demand via a multiplier. We revisit this issue subsequently.

News headlines talk of solar PV costs crashing to as low as ₹2.44/kWh for grid-scale projects. Even for small rural deployments, it is not unreasonable for the

[11] *The Central Electricity Authority's Load Generation Balance Report (LGBR) for 2017-18 indicates virtually no shortfall on paper (Source: http://www.cea.nic.in/reports/annual/lgbr/lgbr-2017.pdf). However, there are significant methodological flaws in how shortfalls are calculated (Source: https://www.brookings.edu/wp-content/uploads/2014/09/electrification-from-wire-to-service.pdf).There are likely some shortfalls, but certainly the trendline is positive.*

The fundamental challenge for microgrids is translating system design between energy (kWh) and capacity (kW).

costs to be as low as ₹5 or 6/kWh; although they are slightly higher due to not just scale issues but also higher development and deployment costs and also likely higher costs of capital for microgrids. In our model, we assume capital costs of solar PV plus inverter, charge controller, etc. at ₹50,000 per kW, excluding the battery.

For these calculations, we assume land is a modest rental for under-productive (but not quite not waste) land at ₹50,000/acre per year. This is high on a per-acre basis but quite low for the small area required (for a few tens of kW solar). This cost is only in the order of 10 paise/kWh. On the other hand, if rentals are higher as being a lump-sum cost not directly linked to land area per se, then a monthly rental of a few thousand rupees (which does not seem like much) becomes over one ₹/kWh. As a bounding exercise, we assume land is only the base ₹50,000/acre. We also assume there is no incremental land rental for poles or LT wiring, as these are as per village approvals or as per similar terms as per the regular grid (using government/village rights of way).

This translates to just under ₹4/kWh for the PV system capex excluding the battery, or just over ₹4/kWh inclusive of the land rental. These figures are with aggressive assumptions as above, as well as a healthy if not optimistic 4.75 kWh/kW per day output, which is just under 20 per cent output Plant Load Factor (PLF).

While this appears quite attractive, our calculation does not include the inevitable cost of battery. Given evening demands, batteries serve two functions other than just time shifting. They add to reliability[12] since one may have cloudy days (which unfortunately are seasonal and thus may come back-to-back). Second, they improve system economics by storing energy, without which we would have to further oversize the PV panels.

How much battery is needed is a design choice. Extending the simple calculation, one unit of evening load requires approximately 1.25 units of solar power as it will come through a battery (which has inherent losses). Just two days of continuous

[12] *Reliability was one of the biggest cost factors for biomass-based microgrids, since one needs a modular design with N+1 components to overcome expected downtime (for maintenance) of the gasifier/engine.*

dark and cloudy weather with a reduced 25 per cent solar output means one would have to more than double the solar panel (and battery) allocation to have a reasonable level or reliability. Thus, one would require 500 watts of panel and 2.5 kWh of battery to deliver roughly 1 kWh of energy over each of the three days--one full and two reduced sunshine days. Even with zero cloudy day coverage, one still needs a battery to time shift daily sunlight for evening demand.[13] With such a capital cost structure, even for zero cloudy days coverage, adding a base battery to the solar adds about ₹7.5/kWh even with "cheap" but lifespan limited lead-acid batteries (assumed at about ₹5,000/kWh and a five-year lifespan and only 10 per cent financing discount rate). This design for a five-year lifespan is only possible after right-sizing the battery and preventing over-discharge. One can find a little bit of savings via limited diversity factor across homes, but not much, not when the bottleneck is steady solar supply.

Table 2: Simplified rural microgrid access economics (₹/kWh)

Days of battery storage for cloudy days	0	1	2	3
Avg. Monthly HH Consumption (kWh)				
5	48.3	54.1	59.9	65.7
10	30.2	36.0	41.8	47.6
15	24.2	30.0	35.8	41.6
20	21.1	26.9	32.8	38.6
25	19.3	25.1	30.9	36.8

Assumed base conditions are:

- Average solar radiation at 4.75 kWh/kW per day
- AC LT wiring costs at ₹7,500 per node
- O&M costs at 0.75 per cent per annum, excluding an employee/contractor as required by size
- 10 per cent discount rate
- 200 consumers per village
- Battery designed depth-of-discharge of 60 per cent

(more details are in Appendix I)

We assume one always needs some hours of battery (for *daily* time-shifting) but could not one use a diesel generator instead of battery for the occasional *additional* days of battery storage (for cloudy days) shown in Table 2? Despite

[13] *Note, one kWh of energy can be more than for one home spread over three days – these are just calculations to help normalise the generation cost.*

100 million homes each using 100 watts of load would only require under 12 GW of centralised grid supply, inclusive of losses. The real challenge is the chain of proper supply procurement, allocation, accounting, enforcement, and acceptable cross-subsidy mechanisms.

the relatively low capex (but higher operating costs) for a diesel generator, the benefits are not so much, in part because of relatively high maintenance and O&M for a generator (with moving parts, wear-and-tear, etc.). Assuming a capex of ₹12,000/kW, and a 10-year life, per unit of household consumption, avoiding additional battery beyond the "zero days battery" still costs about ₹4/kWh of *total* household consumption via diesel. This is not much lower than the almost ₹6/kWh incremental cost for one day cloudy coverage via a battery, or roughly ₹11/kWh for two days. Diesel generation alone per unit costs on the order of ₹40/kWh, high because fixed costs rise enormously for low hours of usage by diesel generation. Appendix II has more details on diesel, which show some possible savings vis-a-vis additional secondary battery for cloudy days, but savings are assumption-driven for low diesel usage.

The number of consumers per village turns out to be less of a determining factor compared to the two factors of number of days of cloud coverage and monthly consumption (as shown in Table 2). Appendix I has more details on the microgrid model and its economics. The model is available online[14] so assumptions can be modified as seen fit. It is worth emphasising that many of the input costs and performance specifications are aggressive, relating to all components and assumptions being roughly best-in-class.

Coming back to the regular grid, while the economics appear better on paper (mostly driven by savings on generation), a catch has been lack of quality supply. It is a tough call on which is the better route - enhanced "centralised" supply or relatively expensive standalone supply. Different locations may offer different pathways as being the fastest means of quality electrification, and these needed not be viewed as mutually exclusive. If we care about speed

[14] *Model is at https://www.brookings.edu/research/microgrids-model/ and free to download and utilise; please attribute ©Brookings Institution India Center, by Rahul Tongia. Only for non-commercial use.*

as the most important factor for decision-making, microgrids have often had an advantage – with private and entrepreneurial capital, they can sometimes be faster than bureaucracy, but the latter can also marshal greater resources.

The traditional grid is improving measurably, with fewer shortfalls of power and a stronger push towards quality supply, including using online feeder monitoring to know the true picture of supply.[15] With concerted effort, the grid can meet rural demand from a supply perspective since rural household loads are modest. Estimating that 100 million homes that today have no or poor electricity supply (this being far more than the 40 million unelectrified homes as per *Saubhagya*), if they use only 100 watts of load, then even with technical losses, a centralised grid can meet this load with an incremental capacity of under 12 GW! The real challenge is the chain of proper supply procurement, allocation, accounting, enforcement, and acceptable cross-subsidy mechanisms, not to mention the focus on quality service provision.

Issues of control and enforcement remain serious challenges in microgrids as well. Some designs assume strict limits on loads which keeps costs down but limits energy usage growth and also mandates oversight. Even without strict limits, a mechanism for metering, billing, payment collection, etc. is essential. A flat-rate billing mechanism is simpler but also may be inefficient in capacity and risk allocation. This is before we consider issues of variance amongst load – some consumers will use more than others. Do we limit them? Or make them pay the true costs? Such higher-load consumers are actually good for the system as they help offset smaller users. Such issues of price averaging are there in the regular grid as well. The cost to serve different residential consumers in a coverage area will inherently vary – yet even in the regular grid most residential consumers pay a fixed rate per kWh, not even varying by time of day, let alone their location, distance from the grid, etc.

[15] *We write about universal real-time feeder monitoring. (Source: https://www.brookings.edu/opinions/a-game-changer-electricity-feeder-monitoring/ (2016)). A presentation to the effect was also made by Brookings India scholar at the Ministry of Power's 8th monthly review (RPM) meeting, "Data, Visualization and Smart Analytics (2015)".*

The real framework for evaluating microgrids: Allocation (of energy, risk and capital)

There is widespread agreement on, and our simple model demonstrates how, not only are the per unit costs high, they are skewed towards fixed costs including O&M as a major percentage.

	Traditional Grid	Microgrids	Notes
Last Mile Infrastructure	High component	Similar to traditional grid	These are for an AC microgrid; DC can be marginally cheaper
Energy Supply (Generation)	Lowest component	Higher than traditional grid	Microgrids have lower Diversity; Reliability means more capacity (N+1 model) plus batteries
O&M	Medium or high component	Similar to traditional grid	This assumes availability of such manpower

While many discussions of the centralised AC power grid talk about economies of scale, a more important criteria is the feature of diversity. With a hundred (identical) generators, if one goes down, the change in output is just one per cent.

How does the traditional grid work? Assuming we theoretically separate the DisCom from the generation supplier (GenCo), an end-user is supposed to pay for both the power consumed as well as for the infrastructure to deliver said power, regardless of energy usage level. The costs of infrastructure are often billed as fixed costs or capacity charges. In reality, capacity charges, especially for household users, are much lower than the actual costs of the last-mile distribution. We also find Indian DisComs pay a far higher share of their total costs for procuring power than their counterparts in many countries like the U.S., but part of this is because of under-investment in distribution and under-recovery of total costs.

Even electricity generation traditionally has a non-trivial fuel cost on average, which means if the consumption is lower, the average consumer cost is also a bit lower. While the use of RE is growing in the regular grid, in the coming decade, traditional generation (especially fossil fuels) is expected to remain dominant in India.

Thus, if one is on the regular grid, one pays a little bit for the *option* of getting electricity, and a modest amount for one's incremental electricity. (Actual rates vary based on type of consumer, level of consumption (aka slab or tier), etc). Generation charges ostensibly cover both fixed and variable costs. In contrast, if one is a microgrid consumer, not only is your generation more expensive (because of limited diversity factor and need for reliability), if it is based on solar power, there are no fuel costs, and one is only averaging out the fixed costs into *expected* consumption.

This leads to a fundamental challenge for design of microgrids: the translation between energy (kWh) and capacity (kW). In the traditional grid, this is handled via diversity, and the fact that the AC grid, at a last-mile level, has far more capacity than most individual consumers need. Even if the connection is billed as a 1 kW home connection, it could easily handle a load that is multiple times higher, and the same remains true for more than one consumer.

The first real level of bottleneck in the regular grid is the distribution transformer (DT) that converts medium voltage of about 11 kV into end-consumer supply, also called low tension (LT), equivalent to low voltage, of 220V or 400V as a three-phase supply. A single DT handles dozens, if not hundreds, of household consumers in urban areas, and is invariably "oversized" to allow for growth of loads. It can also temporarily handle much higher than specified loads, but with overheating and thus a possible reduction in lifespan.

In contrast, a microgrid often has far less headroom, not just in generation capacity but also in last-mile connectivity, especially if it is a "low voltage DC" microgrid. Turning to the demand side, consider 100 homes in a village, each allocated 1 kW of connection. At zero diversity factor, that means you need a little over 100 kW of supply (allowing for technical losses) to manage the demand. Most rural household loads will have a high level of coincidence. But if even 20 people double their consumption, that means the needed supply becomes over 120 kW – something that requires purposeful planning at the supply level. It can be done, but then if one does not realise the extra 20 kW of demand, or it is infrequent, then one is over-engineering by 20 per cent at the supply level. In the traditional grid, 20 kW is truly noise – the size of the Indian grid measured by load served as per the grid operator, Power System Operation Corporation (POSOCO), is over 160 GW (8 million times higher). 20 kW capacity on a 100 kW basis may sound like a lot, but it is likely insufficient, given the headroom required for both variance in demand as well as expected growth.

How much will consumption grow in rural areas, and how fast? It depends not just on economic growth but also on other factors that do not lend themselves well to an econometric analysis. If any election sops (which cover not just supply promises but free appliances), or even cultural changes occur in terms of expectations of quality supply or the need for a particular service, and one may find a hockey curve-shape sharp rise in demand over time.

In a microgrid, one has to charge per unit to cover the fixed costs of generation and the last-mile – it is unclear if consumers will be willing to pay high fixed costs regardless of usage. In a traditional grid, one can not only socialise (cross-subsidise) costs over a much larger base, one can also have a more micro-economically efficient split between last-mile, generation capacity, and generation variable (fuel) costs. If one assumes a coal-heavy system, with 80 per cent costs as per what DisComs spend on generation procurement. Assuming 50 per cent of coal electricity costs are fuel, then this bounding exercise indicates up to 40 per cent of costs can be fuel, and one does not need to pay this unless one uses such power. In a solar (plus battery) microgrid, virtually all costs are fixed. Note, that batteries dominate the supply costs, not the PV panel (see Appendix I for more details).

When we add in time of day for load, one finds a much starker issue for microgrids: where does the diversity factor come from? It is a separate story if one considers a rural grid supplying pumpsets, but many microgrids are not geared for such large loads, and are instead oriented toward providing household "basic services". Using a 100-home microgrid example, a simultaneous load of 100 watts each (enough for many LED bulbs, mobile phones, and even a fan and TV) still means only 10 kW of demand. In contrast, a single 10 horsepower (input-rated) irrigation pumpset converts to almost 7.5 kW of demand. What else drives load? Even adding limited street lighting, and a commercial shop, etc., the load is limited. There is no anchor tenant in many disperse rural areas. Cell towers are considered such a load, but many are not routinely near such "unconnected areas". Plus, newer mobile telephony systems do not require air conditioning, and now require much lower power.

Pricing is meant to not just cover costs, but also signal apportionment of underlying cost structures and risks. If consumers and loads were homogenous, there would be little difference in various pricing schemas, but how does one handle a single large user? A bursty user? Should someone with a hundred times the average consumption pay 100 times the average bill? This becomes non-academic when we consider not just basic household loads but also productive loads which are often commercial.

If we price usage based on share of capacity versus share of units, we would get different outcomes. A big user would not find a microgrid attractive if we linearly extrapolate high per unit costs for their larger total number of units. The basis for the theory of an anchor tenant also depends on economies of scale. These are only available to the extent that they increase the total consumption (give us a larger denominator), but the supply side has far lower economies of scale. If we average out the costs, we are directly cross-subsidising smaller users by larger ones. This may happen in the regular grid, but to a far lower scale. More likely, a large user (especially someone such as a cell tower) may build out their own standalone generation system, even with an individual battery.

Coming back to the regular grid, with regulator approved tariffs (even before special schemes for free power for Below Poverty Line households), the monthly bill would have been far lower. Assuming ₹30 as the monthly fixed charges for 1 kW of connection, and 5 kWh of low-level consumption @ ₹2/kWh, even with taxes added on, that comes to roughly ₹45/month. There is no plausible near-term scenario for a microgrid to compete on even a total monthly bill (which is low due to the subsidised per unit costs). However, it might compete on quality, service, and speed.

Policy implications and discussion: make microgrids synergistic instead of antagonistic with the grid

Everyone wants electricity to be affordable for the consumer, viable for the provider, high quality in service, and as environmentally friendly as possible. Do we need a microgrid to make any or all of these happen? One major problem with many analyses has been they fall prey to Parmenides Fallacy, which is comparing the future with the present, instead of to alternative futures. From a base of no electricity, anything can be justifiable, including kerosene, but the question remains, what else could we do? If we only need basic lighting services, solar is wonderful as a solar lantern or even small solar home system. The challenge becomes when we want to scale. This issue remains with a microgrid.

Capex is just one bottleneck: though a substantial fraction of costs regardless of model

Successive governments have targeted electricity supply as a priority, and current plans are to wire all homes not yet connected by 2019. This is a daunting logistical challenge as India has almost three times more homes without a connection than the next least-electrified country (a toss-up between Nigeria and Ethiopia). Leaving aside logistics or economics, is this capex-subsidy model sufficient for achieving this priority? This framework relies on the DisCom or utility to complete electrification and maintain quality service. On average, they have failed to do so in the past. Regardless of design, we have seen that capex is a big share of costs for rural access, and so some mechanism is needed to cover these costs. The *Saubhagya* programme is an evolution of existing models, though it does focus on household electrification for the first time.

Is building out the infrastructure enough? Consumers and their ability to pay matter. The traditional grid inherently cross-subsidises some users, especially the low volume, remote ones, with regulator-approved tariffs, thus not covering the *true* costs of service. Regulators may need to update their pricing calculations to reflect true costs to serve. Today, these are averaged out, without granularity of geography, distance, density, or time of day. As coal plants become more efficient through super-critical technologies, and coal capacity grows nearer coal mines (making coal-based power cheaper by reducing transportation costs), and the grid increases its RE, the gap between Marginal and Average Cost to Serve will only widen. Note, this is not to suggest consumer tariffs must become similarly granular – some amount of averaging will remain.

However, better signalling of costs and prices will be important as we consider the impact of any averaging out across diverse consumers. Down the road, regulators may need to consider benchmarks for costs of service that capture variance. Once we recognise that some consumers are more expensive to serve than the average, this will help estimate how much money is on the table that can be available for other models including microgrids. This can reduce the costs of the grid by taking over these "expensive" and "underpaying" consumers.

Setting grid tariffs *at least* equal to the marginal cost of supply is important to ensure that utilities or service providers do not find these consumers loss-making, at the margin. Raising minimum tariffs just a bit would also help microgrid operators, who otherwise face consumer expectations based on the grid benchmark (which is very low if not free). For those consumers who cannot pay even this amount, a direct benefit transfer (DBT) scheme would set up not just expectations for consumers to pay, but also signal that electricity has a cost, and should not be wasted. Else they may buy inefficient bulbs, appliances, or even pumpsets.

Thus far, we have suggested signalling equal to at least the marginal costs – ideally the prices should cover the average costs, but that is even harder to roll out. Prices set at marginal cost levels, perhaps at ₹2 or ₹3 per kWh, would still entail an average loss. The good news is this total loss, to be made up through subsidies and cross-subsidies, would be modest, given the low base of newly electrified household consumption. For new and marginal users (say, 100 million homes), 10 kWh/month of consumption is only on the order of one per cent of the electricity in India, something that can be cross-subsidised easily.

Most entry tiers (slabs) for household supply enjoy large price support, paying very little for their first few units of consumption. More starkly, agriculture severely underpays for its electricity consumption, ranging from flat-rate costs, including horsepower pumpset, or even free supply, where the balance is ostensibly paid by the state government. Plans to shift these pumpsets to solar are being explored, but it is not clear if there is an easy link to local microgrids. For a number of locations and cropping patterns, solar pumpsets have improved economics when interconnected to the grid, otherwise on days when no water is required, surplus electricity is wasted. The link to microgrids becomes one of size and scale. With many solar pumpsets, "other" consumption could not absorb their surplus supply. There are also reported concerns on watering fields mid-day when solar is available, but evaporation is also the highest, and farmers avoid going into the fields when temperatures could be dangerously high.

Plan for scaling and interacting with the grid: and enable Smart Systems

Understanding the *energy ladder* is an important aspect of system design. Consumption is not just about total kilowatt-hours but also about when and how bursty the load is.[16] This is the challenge of converting between kWh and kW that was discussed earlier. Studies have shown that simply providing a lightbulb, while societally important, does not improve incomes or household consumption of goods and services.[17] Productive loads are key to economic development (above and beyond the obvious pumpset for agriculture). Headroom for not just growth but productive loads is one reason larger microgrids make more sense, beyond benefits due to economies of scale. Finding an anchor tenant or non-household major load(s) is reported to be a helpful factor for microgrid viability.[18]

A grid-interactive hybrid microgrid is operationally the most cost-effective – one could operate it as needed, ranging from back-up for when the grid is down, to primary supply as desired. Any "surplus" in the microgrid could also be fed into the regular grid, for which the equivalent of net metering policies need to be designed. Here, simply valuing the energy at marginal retail tariffs (prices) may not be enough, especially if the designated retail tariff is a low-tier residential connection. There is another design benefit to such a microgrid – it would reduce the need for over-engineering. Assuming a solar-powered microgrid, cloudy days are a major reason for over-engineering capacity, especially via a battery. But for the rest of the grid, these are precisely the days of lower demand (water pumping/ ACs) and so it could be easy to take lower cost power from the grid.

These points suggest that we need a fundamental rethink of what a microgrid is, and how it should behave. Standalone is easy to demarcate intellectually, but a more dynamic microgrid may be the future. At an extreme level, if one needs a battery in a distributed fashion, then why must one only use local RE to charge the battery? Can it not be charged, *in some circumstances*, via the regular grid? Such a model would truly reduce costs given that designing for the "last 10 per cent" of extreme conditions leads to disproportional costs in microgrid (or any grid) design. Maybe solar can provide, say, 90 per cent of the expected

[16] Rangan Banerjee (2016) shows generation cost calculations per kWh mostly well above ₹13/kWh for many microgrid systems, and these exclude the wiring infrastructure costs. Even with a fall in technology prices (for PV and batteries), the total cost is measurably high and, ultimately, a bottleneck beyond a limited (lifeline) demand. (Source: http://www.ese.iitb.ac.in/~rb/Professional%20Activities/Microgrids%20in%20India.pdf)

[17] Study on electrification vs. development (which is not geared specifically towards microgrids but any electrification), by Fiona Burlig and Louis Preonas (2016). (Source: https://ei.haas.berkeley.edu/research/papers/WP268.pdf)

[18] Paper by Smartpower India (2017), (Source: http://www.smartpowerindia.org/documents/SmartPowerIndia_report_April_2017.pdf)

energy and the regular grid can provide the last few per cent. This still meets the goals of substantial but not 100 per cent carbon reduction, just at a much lower cost. Today, many regions have parallel supply grids that unofficially use existing wiring to provide diesel power to overcome frequent supply outages of grid power. Instead, we can make them official and synergistic, which would also enhance safety.

Over time we expect battery costs to fall measurably, but it is not clear that they would fall enough to be "grid-competitive" for marginal users in the coming five-seven years, which is a plausible window for many microgrid deployments. In urban areas, batteries are commonplace for back-up power, especially in standalone homes, which clearly shows that for some users, quality of service beats raw tariff comparisons.

The newer future that dynamically balances local and grid supply with local demand requires smarts – if supply is constrained, one needs to limit local loads. Conversely, during "oversupply" one wants to encourage consumption, especially consumption amenable to time shifting. This suggests that all such microgrids should be smart. A smart meter needs to include a load-limiting switch (based on current-limiting, which also makes this a remote connect-disconnect switch). This is also required in many microgrids, where current-limiting is vital, as aggregate supply (and even the lines) is limited in capacity. If one has a smart metering infrastructure in place, and extends this to pumpsets, one can improve operations and reduce technical losses as well by staggering pumpset loads as per local and grid conditions.[19]

Rural areas have traditionally been last on the agenda for smart grids which instead focus on "paying customers". If we factor in the costs of kerosene, which are not just retail costs but also subsidies or cross-subsidies offered by oil companies who do not recover the full costs, there is enormous money on the table if one could use LEDs and electricity instead.[20]

The real challenge has remained utilities' wariness to connect the last set of users, who have always been both expensive to connect as well as non-remunerative on

[19] *Today, pumpsets are controlled ("rostered") at a feeder level. This could ideally be done at a sub-feeder level. Given practical and political economy constraints on metering individual pumpsets, this could perhaps be done at clusters or the distribution transformer level. Halving the instantaneous current can reduce technical (I2R) losses by 50 per cent in aggregate.*

[20] *The efficiencies are also far higher. CEEW/IISD's 2016 paper on rethinking kerosene subsidies (Source:http://ceew.in/pdf/CEEW%20-%20Reforming%20Kerosene%20Subsidies%20in%20 India%204May16.pdf), and a budget-oriented framing for the same by Tongia (2016). (Source: http:// www.livemint.com/Opinion/2nIdtdQ9k4J99O1hMJ5cGN/Rethinking-the-budget-in-a-postGST-India.html)*

Understanding current limiting and the differences between paper, instantaneous, and billed loads

On paper, most household connections are for a certain sanctioned capacity, for example, 1 kW. How does a utility know if that is all they are using? At an energy level, use 1 kilowatt (kW) for an hour, and one uses 1 kilowatt-hour (kWh) of energy, and all meters should capture this. However, analog meters have no means of knowing how much the peak demand was in a month. Static or digital meters are capable of measuring the peak demand (kW), but for households, most utilities do not record the maximum demand (MD) of the consumption. Even MD is itself an average over 30 minutes for billing purposes. One can burst far higher temporarily and the grid is designed to allow this. This is a good feature, given the surge in current with many types of loads such as motors and microwave ovens, among others. This also is the reason the fuse cutout is not a meaningful current limiter – it is always over-sized (for technical reasons above, not to mention for convenience).

Eventually, whether in a microgrid or not, smarter systems will need to understand peak loads in a far more granular manner, and we will need pricing schemas to ask those who contribute to the peak to pay for it. Time of Day (ToD) pricing is just one of the many mechanisms available for this. This becomes especially true as India's energy (kWh) deficits reduce, but peak shortfalls may remain. In addition, the rise of renewable energy means we should not treat all electricity the same – when and where matters a lot.

an ongoing basis. A current limiter can help overcome their worries of over-usage of subsidised supply, especially during peak periods. Over a decade ago, people were using electric coils for heating/cooking as electricity was unmetered; today we see a growth of induction cookstoves in some rural areas that have reasonable quality supply. An interesting question becomes: do we want to subsidise electricity for cooking, even if it reduces pollution impacts in the home? This is a subset of a broader discussion on how far up the energy ladder should subsidies go? Of course, political choices often mean subsidies for the middle class or even the rich, like those seen in Delhi where six months a year, over 90 per cent of households enjoy state-government provided subsidies of 50 per cent on their electricity consumption.[21] The beauty of a smart metering system is that it can help differentiate lifeline from "other" consumption, allowing innovating pricing mechanisms that balance equity with a willingness to pay (which depends on alternatives and backstopping technologies).

Why bother with microgrids?

If a standalone microgrid is challenging, why bother with an interconnected or hybrid microgrid, which would only be more complex and slightly more expensive? As we have already discussed, one of the reasons is the flexibility of use cases that such systems provide. In addition, we should not be linear in our chronology of microgrids as being "inferior" to the grid and only where the grid is failing. There are plausible future scenarios where hybrid microgrids operating as federations become the preferred choice.[22]

Microgrids also offer additional possible roles. First, there is a need for any good solution in many areas – even if "niche" in the grand scheme of total villages in India – where a microgrid is likely to come up before quality, stable centralised supply. The catch is the uncertainty of timeframes for the grid to not only arrive, but become stable. Often, deploying the last-mile infrastructure is the key challenge, so let it start in a microgrid manner in some places.

Second, there can be new models to look at the value of microgrids. If we consider the three segments of value, viz., (1) physical infrastructure, (2) running the systems (including keeping losses low, managing collections, and maintaining

[21] These taxpayer subsidies are above and beyond regulator-approved cross-subsidies in the tariffs, where the lowest tiers of consumers pay far less than the costs to serve (Source: https://www.brookings.edu/research/delhis-household-electricity-subsidies-highly-generous-but-inefficient/)

[22] Islanding for reasons of grid imbalance and stability in a "federated" manner is a relatively new design that was not part of the original thinking for a centralised grid. At a logical level, Mumbai could be thought of as a microgrid compared to the rest of Maharashtra state since it was able to island itself to maintain supply even when the rest of the state faced shortfalls.

the system), and (3) input energy (generation), the third is where there is least value. In fact, one could increase RE in the centralised grid in a cheaper manner (at scale), but the catch is, without a redesign of systems and control, one has no means of ensuring that a particular generation "elsewhere" is delivered to the particular geography. Hence, keeping the generation inside the microgrid area can ensure we have supply for local needs. This is where we should value microgrids not merely for their overall service provision (which requires all three segments) but also especially for the weakest links (the last-mile infrastructure and operating the system at the local level).

Grid interactivity also benefits from better supply-demand matching. Given the expected variance in supply and demand, there will be periods where any local generation can exceed the demand or need, inclusive of any storage. At those periods, instead of throwing energy away, feeding it into the grid will help microgrid economics.

Ultimately, we may want to experiment with new models of operations. Setting up the infrastructure is relatively easy – it "only" takes money and a one-time effort, which has itself proven challenging in many regions. Running a system well is usually much harder. Encouraging cooperatives and new models of entrepreneurial operations may be the most effective solution if we can change how they are allowed to price or be supported. Just like we observed a challenge of not having cross-subsidies in operations or up-front costs available to a microgrid (which the regular grid enjoys), if a local operator is more efficient in local operations, they should be rewarded through a similar outside pool of money. This may require a new benchmarking system for rural areas. Thus, if consumers in an area engage well such as paying regularly and do not have much leakage, then they should both get better quality supply, and also get a benefit in their bill. As we have seen, this "subsidy" will not be much in aggregate if we only consider lifeline or marginal (new) household electricity consumption.

Just like there are franchisee models where third parties operate some portions of licensed grid areas, rural operations can be given to local operators who not only manage the system, but also can encourage local generation which can be viable as it cuts down technical transmission losses. In many areas, generation is secondary – local operations are the bigger challenge, and hence microgrid models may allow far greater oversight and local control. Deeper local engagement is also more feasible.[23]

[23] In the US, according to National Rural Electric Cooperative Association (NRECA) data, 834 electric distribution (rural) cooperatives serve 75 per cent of the US national territory (but only about 13 per cent of consumers). This coverage includes 42 per cent of distribution lines.

Such rollouts should also become far less expensive as technology improves to provide cheaper solutions for interactive microgrids. At the extreme level, there are discussions for blockchain technologies to enable micropayments towards microgrids, which should ultimately be envisaged as systems for prosumers (producer-consumers). That is, anyone with a PV panel can feed into a system, and it is the local management that keeps the system in balance, not a top-down system of supply to match demand. This brave new world includes dynamic demand response to system availability-of-generation signals, not to mention more storage, including in electric vehicles (EVs).

Policy tweaks, innovation and experiments may help change the conversation amongst stakeholders

Smart systems are just one tool available for improved future outcomes. No amount of "enforcement" towards payments or preventing pilferage is likely to be palatable unless a carrot accompanies the stick, such as through assurances of quality supply. Overcoming this trust deficit is a key part of any future for electricity access in a viable ecosystem.

There are a number of other innovations and experiments that can be tried, especially given that we need credible and long-term viable systems:

1) *Make supply availability transparent in real time:* This is already being planned, such as through government portals like *Urja*; this needs to be accelerated.

2) *End load-shedding in phases:* The first step may be ending unscheduled load-shedding. This requires feeder-level monitoring and transparency. Utilities and the government should make credible promises and stick by them. Else, consumers may think of these as wishful thinking or election promises, and will not keep their end of the bargain.

3) *Create an explicit Universal Service Obligation Fund* like telecom has.[24] Making it explicit and transparent can help provide focus and predictability. Else, utilities remain a potential prisoner of political whims. This can also be a vehicle for holding some of the cross-subsidy money by so-called "paying customers" such that the money

[24] *Source: http://www.usof.gov.in/usof-cms/home.jsp*

truly helps the most deserving, instead of covering up any DisCom inefficiencies.

4) *Allow pre-paid (but smart) metering, with payment flexibility*: It is a recognised challenge that collection in rural areas may be cyclic – only after the harvest do many farmers have cash to pay. If one has to choose a support instrument, zero or nominal interest payment options for marginal users over multiple months are a small and worthwhile cost.

5) *Monetise poles and rights of way for telecom and other users (including cable TV)*: In the US, many states regulate this, allowing multiple service providers to share poles. Naturally, electricity goes on top, for safety reasons.

6) *Focus on ultra-efficient appliances*, which disproportionately help the viability of microgrids, but help the broader system as well.

7) *Bring in predictability and consistency:* If there are areas ripe for microgrids, enable and empower them for success. Even if these are "niches", these can, in total, be bigger than countries in Europe.

Policy-makers have to prioritise electrification. Instead of viewing microgrids as standalone, they should be viewed as tools within the portfolio of coverage. Today, we have segmentation of coverage between the grid and microgrids, often with microgrids being viewed as a stop-gap solution. Instead, both should be encouraged in areas where they respectively make the most sense, even if there is potential or future overlap. Timeframes matter (we want electrification fast), and here microgrids can help, bringing in new entrepreneurship and even capital. It is OK for microgrid infrastructures to not last as long as optimal or theoretically possible (10-20 years) – even a five-10-year microgrid is worthwhile, as long as it is predictable and the business model plans for viability accordingly. One challenge is the sheer number of moving parts in this calculus, including technology cost curves, rise of the regular grid, etc. Not all "support" via regulation is helpful – regulations often have a counterproductive side, especially if they assume costs and cost recovery models.[25]

[25] *UP's Mini Grid Policy 2016 aims to streamline approvals, and offers a subsidy if required, but to avail the subsidy, the tariff must be capped based on size of interconnection (50 watts and 100 watts, with a monthly charge of 60 and 120/month for eight hours of minimum supply, i.e., three hours morning, five hours evening). Higher loads are allowed to have any tariff as mutually agreed upon. The price levels are low enough to require substantial subsidy, and would likely go over the 30 per cent subsidy notified as available via viability gap funding aka reverse bidding. (Source: http://upneda.org.in/sites/default/files/all/section/Mini%20Grid%20Policy%202016.pdf)*

Policy-makers must realise that one cannot rely on “the market” for wiring up the last sets of consumers, or even for making them pay their true marginal costs of connection. One needs cross-subsidy mechanisms, and those should be available to the regular grid as well as microgrids. It is entirely possible that with the rise of RE and smart grids, even the “regular grid” will start to have interactive microgrids as its building blocks. This is a much more plausible and exciting future, one that enables maximum RE from the edge, and even consumer participation. Who knows, with one future with a large number of EVs, these can enable ad-hoc microgrids as and when required, for RE grid balancing or stability reasons. We have to rethink not just what we mean by microgrids, but even the grid itself.

Appendix I: Simple microgrid economics model

Below are a few details of a simple microgrid model as deployed in the Analytica modelling environment. Analytica has a free player available online (www.lumina.com). The model focuses on parametric analysis for handling uncertainty, but also includes a parallel model that is probabilistic (under "Type" being "para" or "prob"). The probabilistic model is only for illustration and lacking true distributions for uncertainty, we chose a simple 10 per cent uniform distribution for the uncertainty from the mid/base values. This should not be taken as reflective of reality since the uncertainty can be higher for various components, and some components have a higher range as a choice. E.g., days of cloud cover can vary not just by 10 per cent but multiples.

	[Units]	Min	Mid/Base	Max
Village				
Number of consumers		100	200	500
Average monthly consumption per home	kWh	5	10	25
Solar and Battery System				
Battery and System efficiency			80%	
PV Capex per kW panel	₹/kW		50,000	
Output per day (kWh/kW) average		4.5	4.75	5
Output on very cloudy days			25%	
Days of cloudy stored via battery		0	2	3
Battery depth-of-discharge		0.5	0.6	0.7
Wiring				
LT wiring costs per consumer	₹	5000	7500	15,000
Opex				
Monthly salary of employee	₹		7500	
Minimum coverage of employees (shared across villages if number of consumers is lower than this)	homes		200	
O&M rate (per capital costs)	per annum	0.5%	1%	15%

Capital Conversion

Discount Rate		7%	10%	13%
Lifespan – Meter	years		10	
Lifespan - LT Wiring	years		25	
Lifespan - PV Panel	years		25	
Lifespan – Battery	years		5	
PV capex per kW	₹		50,000	
Battery capex per kWH	₹		5000	
Meter capex	₹		800	

Assumptions

1 There is no cost allocated for a distribution transformer; assumes it exists and has headroom for small household consumption

2 The battery is sized to provide coverage for chosen number of cloudy days as per design, but the PV panel is not oversized to charge the battery in full daily; this assumes some trickle charge is enough, and cloudy days are handled predominantly via the battery and not oversized PV to charge the battery to full each and every day. “Zero days battery” does not mean zero battery since daily consumption is estimated to be predominantly in the evenings (and mornings).

3 Assumes an inexpensive lead-acid battery with low capex, but a low lifespan. Depth-of-discharge is a behavioral issue, not just a design parameter. Higher discharge impacts lifespan.

4 This is a digital meter, but not a smart meter.

5 This exercise assumes relative homogeneity or averaging in terms of distributions of loads, distances per household, etc. If there are outliers, these would raise costs.

6 The per household consumption is an average, which is actually higher than the expected consumption leaving a little headroom for commercial/productive loads in the village (but not irrigation pumpsets).

7 PV costs are inclusive of balance of systems, installed, excluding the battery.

8 4.75 kWh/day average output per kW PV panel converts to a healthy or even generous 19.8 per cent utilization factor (PLF)

9 Distribution losses (technical) are assumed to be very low due to low loading and are also embedded into the system design (which has a small buffer for sizing to meet the load).

A breakdown between capex and opex is shown for base conditions. Analytica allows easy n-dimensional space calculations. We see that O&M costs fall dramatically with increased loads. O&M links to capex as a component is based on a percentage of capex. Note the O&M costs have a discontinuity between 100 and 200 homes covered – we assume if a village or microgrid is smaller than 200 homes, the staffer covers more than one location. In reality, O&M costs will likely be higher than 0.75 per cent of capex, in part due to the remote location – these figures should be viewed as indicating trends (how load and number of consumers matter) than providing exact numbers.

O&M costs (₹ per kWh)

		Number of consumers				
		100	200	300	400	500
Average Household Monthly Consumption (kWh)	5	17.32	17.13	12.07	9.54	8.02
	10	9.11	9.02	6.49	5.22	4.46
	15	6.38	6.31	4.63	3.78	3.28
	20	5.01	4.96	3.70	3.06	2.68
	25	4.19	4.15	3.14	2.63	2.33

Average Daily Solar Insolation (kWh / kW per day)	4.75
Days of cloudy covered	2
LT wiring costs per node (/ consumer)	7,500
O&M rate (fraction of capex - annual)	0.75%
Battery Depth of Discharge	60%
Salary of field staff (/ month)	7,500
Land rental per acre (/ year)	50,000

Capital Costs (₹ per kWh) by Component

	Days of Cloudy Covered			
	0	1	2	3
Meter	1.08	1.08	1.08	1.08
LT wiring	6.89	6.89	6.89	6.89
Solar PV panel	3.97	3.97	3.97	3.97
Battery	7.53	13.17	18.82	24.47
Up Front Costs	2.03	2.03	2.03	2.03
Total	**21.50**	**27.15**	**32.80**	**38.44**

Average Daily Solar Insolation (kWh / kW per day)	4.75
LT wiring costs per node (/ consumer)	7,500
Battery Depth of Discharge	60%
Up-front (one-time) costs ( )	300,000
Discount rate	10%
Number of consumers per microgrid	200
Average monthly household consumption (kWh)	10

Appendix II: Diesel economics for secondary back-up to solar

Assumptions for the Diesel Generator (DG) [some assumptions vary and are handled parametrically]:	
DG Size:	Identical to kW solar panel
DG cost/kW:	₹12,000
DG AMC rate:	10% of capex
DG Lifespan:	10 years
DG Hours of use:	[200, 300, 400]
Diesel Cost:	₹55/L
DG Efficiency:	[3, 3.5, 4] kWh generation per L diesel
DG Avg. Loading (when in use):	[30%, 40%, 50%, 60%, 70%]

These lead to a per unit of consumption cost for DG as shown below (based on the total higher household consumption inclusive of non-DG), as shown below. Within this, capex is higher than fuel costs only because of the low number of hours of use per year.

Table 3: Diesel Generation (reliability) costs in ₹ per unit household consumption.

	Efficiency -> (kWh / L Diesel)	3	3.5	4
Average DG Loading when in operation	0.3	3.46	3.29	3.17
	0.4	3.86	3.63	3.46
	0.5	4.26	3.97	3.76
	0.6	4.65	4.31	4.06
	0.7	5.05	4.65	4.36

This is the cost per unit total monthly consumption, and not per unit diesel generation. Diesel is naturally more expensive per kWh generation, but only a small fraction is required compared to the total consumption. This is using diesel as secondary back-up to the PV system, for cloudy days.

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