The Indian Power Grid: If Renewables are the Answer, what was the Question?

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India has ambitious goals for renewable power, and while solar power has garnered much of the excitement (and recent investments), all forms of green power have Central government support. End-users? They worry about their lights being on (i.e., load-shedding), and while they might be philosophically supportive of green power, it's unclear how much premium they may be willing to pay for renewable energy (RE). This leaves the electricity utilities as key stakeholders, with different roles spanning generation, retail, distribution, transmission, and balancing the grid. Most states in India have unbundled the power sector (separating generation, transmission, and distribution), but regardless of institutional structure and reforms (or even state of finances, a critical topic), all power grids require balancing, i.e., continuously keeping supply in sync with varying demand (net of losses) in real time. This is the basic principle of the modern alternating current (AC) grid, which has a characteristic that electricity cannot be stored easily.

This is where the fundamental variability and stochasticity (randomness) of renewables become a challenge, more so for the Indian grid which is operated far from optimally (with outages and load-shedding, frequency drifts, etc.)

India needs to manage a capacity problem, unlike many countries seeing RE as an energy solution

How do other countries handle large RE inputs to the grid? They do what the power industry has always done – engineer for contingencies, with reserves and alternatives. Unfortunately, India is short of power, and thus, while other nations might see RE as helping an energy (kWh) problem, India also needs to manage a capacity (kW) problem, which is precisely where RE falls short. Renewables in India are different from renewables deployed in the U.S., Europe, etc. and understanding these differences is key to viable policies. The triad of "usual" challenges of renewables remains in India, such as (1) intermittency/variability; (2) location-specific potential (concentrated in areas sometimes away from consumers or the grid; and (3) higher costs. However, there are specific differences and needs that demand deeper analysis for the long-term viability of renewable energy. Making renewables viable for producers is easy—pay them enough—but can the rest of the system handle that? Because of pricing subsidies as well as high losses (both technical and commercial, i.e., theft), util-

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[1] *Portions of this chapter draw or are taken from a PlanetPolicy blog piece done by the author (http://www.brookings.edu/blogs/planetpolicy/posts/2014/05/21-renewable-energy-india-tongia).*

ities already lose on average about a rupee, if not more, per kilowatt hour sold, impacting the ability to finance all new generation capacity, just RE.

One of the typical calculations that power system operators do is estimate how much renewable power the grid can handle. Typical figures from elsewhere are in the range of 20-30%,[2] with more requiring significant investments in transmission or peaker plants. Of course, with more deployments and learning (and better predictions), the ability to handle RE is increasing, and, most importantly, every region is different. India's grid is weak and unstable, and instead of having a reasonable reserve margin (typically 15-20% in the west), there is a shortfall in the grid, officially in the range of 5% or so, but actually much higher. Even the Grid Code is modest, recommending (but not mandating) only a 5% margin. The grid is kept afloat through massive "load-shedding" (feeder-level supply cuts).

There are other technical reasons why the Indian grid is weak, including lack of ancillary services (systems designed to keep the grid stable, instead of just pricing kilowatt-hours), and even a lack of time-of-day pricing for bulk procurement of power. There are few peaker plants (which would operate only some 5-10% of hours in a year), since there isn't sufficient incentive for these. Without incentives for plants that can ramp up (or down) quickly but may not get used much, how will the grid handle 20% renewables? Even worse, the types of plants capable of fast ramping are limited in near-term growth in India—hydropower (due to land and social/environmental challenges) and natural gas (due to supply constraints). Hydropower has an additional constraint when considering peaking or storage – its additional duty for water management (irrigation) limits when water can be stored versus released. Overall improvements in the grid, including better balancing without resorting to load-shedding, should be key areas of effort, which would facilitate increased RE penetration.

More than just operations, even planning for RE integration is important, including coordination between the various stakeholders. At a 2011 Workshop on Wind Power in Karnataka, Karnataka Renewable Energy Development Ltd. (KREDL) proudly announced they had sanctioned windpower projects in Karnataka for roughly 12,000 MW of capacity (comparable to the total official capacity of the state), and that over a quarter had achieved financial sanction as well. The one catch, which came to light in the frantic discussions post KREDL's presentation, was that nobody from Karnataka Power Transmission Corporation Ltd. (KPTCL) (which was engaging with KREDL for the first time on such issues at the Workshop) was aware of any such developments, not even from a power evacuation perspective (availability of substations), let alone issues relating to handling the variability of windpower. The challenge, fundamentally, was one where the "makers" and "takers" of renewables didn't coordinate.

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GRID DETAILS, FUNDAMENTALS AND NUANCES

It's well known that the Indian peak demand (today and in the near future) is mostly in the evening. While it's obvious that the sun isn't shining bright then, even wind is often on a ramp-down, especially in some states. Thus, even if India adds 20 GW of solar, it still needs 20 GW of additional capacity to meet its peak, and the picture is almost as bad for wind because of its strong

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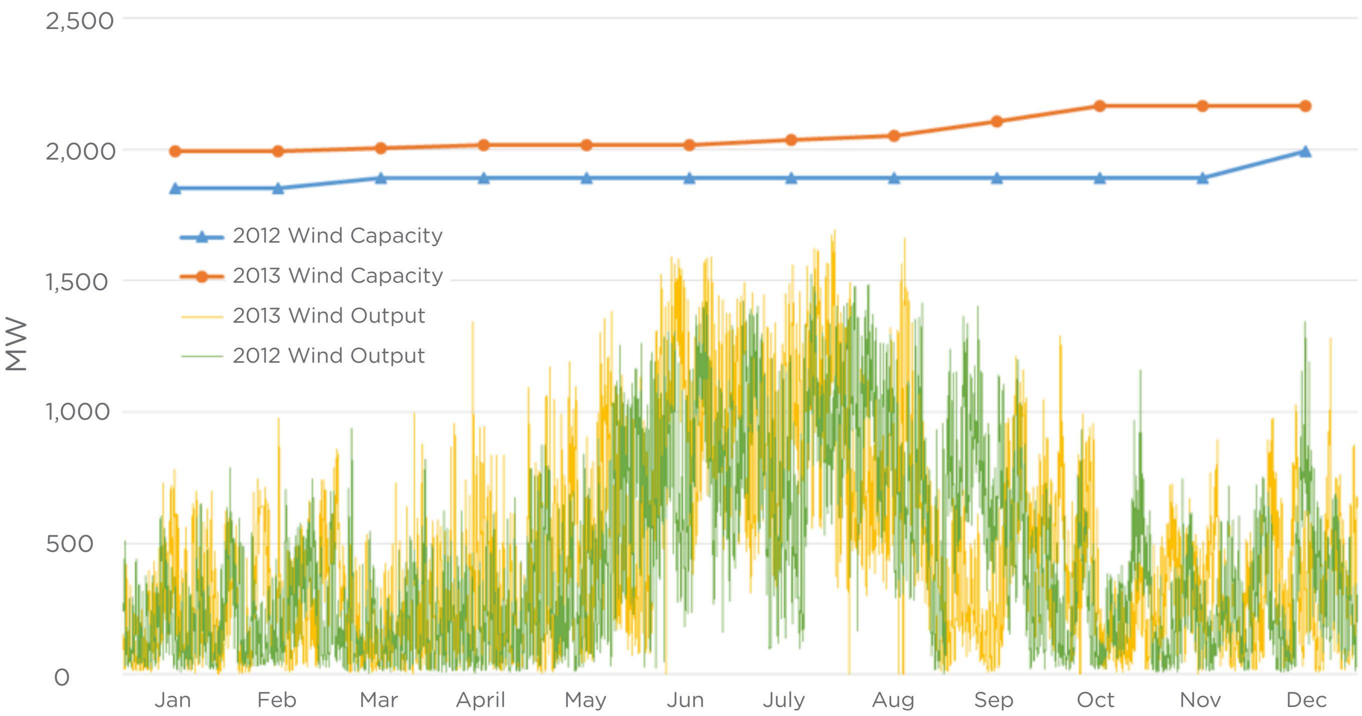
[2] *http://energy.gov/eere/wind/renewable-systems-integration.*

[3] *The official shortfall of power in India is now only 5%, but the actual shortfall is far higher. See Brookings India Discussion Paper 01-2014 on Re-thinking Access and Electrification in India: From Wire to Service (http://brookings.in/wp-content/uploads/2014/09/electrification-from-wire-to-service.pdf).*

seasonality. Actually, it's not quite as bleak, since RE offers some capacity value, but the exact amount it offers is modest vis-à-vis conventional fuels, and we need detailed calculations for these at a systems level, instead of simplified correlation studies. Only for illustrative purposes, the chapter on Economics of Renewables compares different pricing regimes factoring in the separation of energy and capacity.

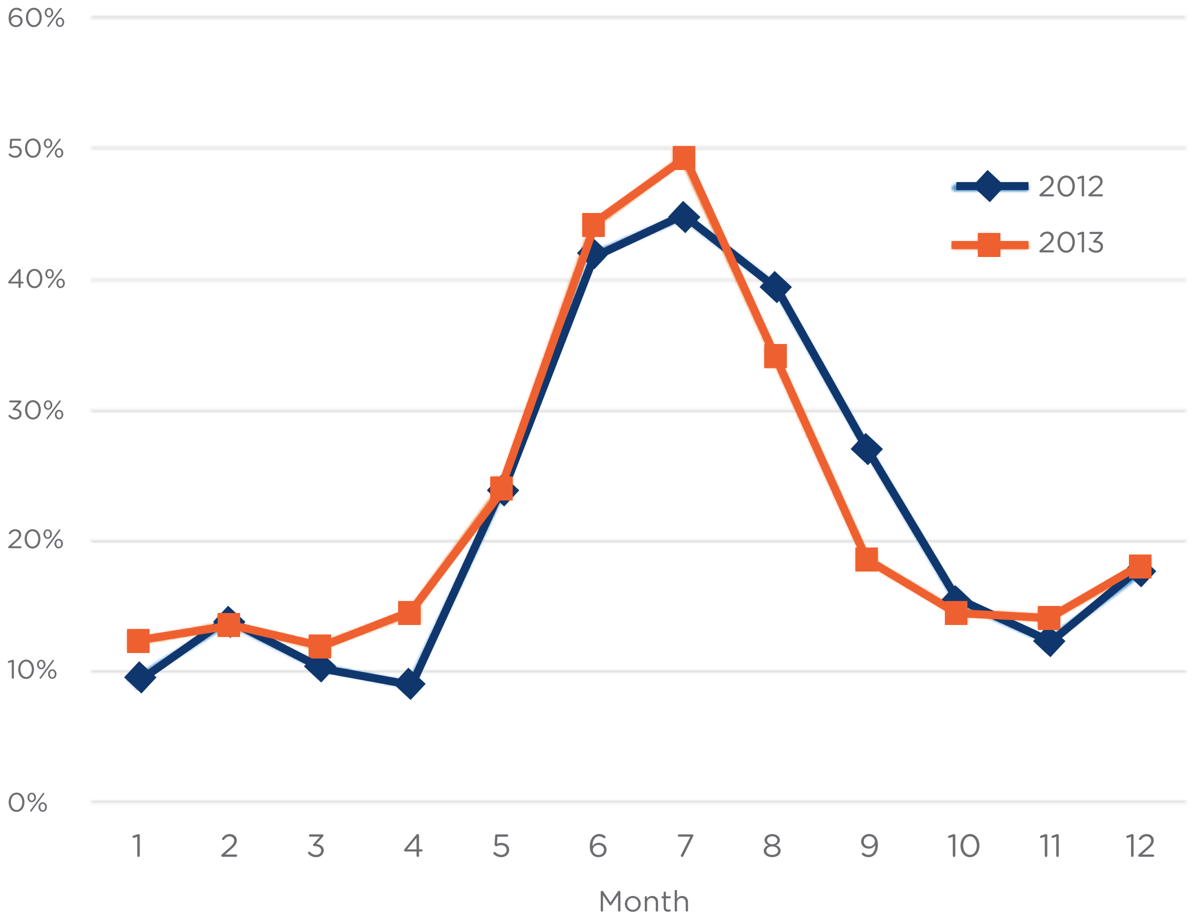
As we can see for the example of Karnataka (which may or may not match other states), there is enormous variance, on a nameplate capacity that started 2012 at 1,851 MW rising to 2,168 MW by the end of 2013. While the annual average Plant Load Factor (PLF) is just over 22%, not only is there strong seasonal variation, even during windy periods the output falls to near zero. Also, at least for Karnataka, the fact there are several windy zones separated by hundreds of kilometers doesn't steady the aggregate wind output very much. Converting these into month-wise PLFs, we clearly see the enormous variation. If the Indian grid had buffer capacity, and there were better regional interconnections with non-coincident peaks, then we could plan more in terms of RE and demand coincidence, like Germany and other countries, but as of now, even being opportunistic with RE, we still need more peak capacity.

FIGURE 1: Total Wind Power Output in Karnataka at 1-Minute Resolution



SOURCE: KPTCL Raw Data

FIGURE 2: Month-wise Total Windpower Plant Load Factor (Capacity Factor) in Karnataka. These are calculated from 1 minute data across the total state. The annual average PLF in both years is just over 22% (22.19% and 22.46%, respectively).



SOURCE: KPTCL Data

Variance is one reason why renewables aren't a panacea for rural electrification. Beyond the issue of the evening peak (demanding a battery if standalone RE or an isolated microgrid is to provide lighting), most optimal renewables (except solar) are village-scale, if not larger, not household. One still needs a last-mile connection. At that point, the grid becomes more attractive (given it reaches the vast majority of villages already), especially as demand grows rapidly once a household is electrified. However, for many users who need and are willing to pay for limited supply RE is already attractive today, since it is more reliable and in the individual's control. Witness how one of the world's largest solar markets is an open-air market in Bihar.

Balancing the Grid

Much more subtle than the challenge of meeting the peak is keeping the grid in balance. Germany now handles 25% RE without major investments into the grid, but the German Energy Agency (DENA) estimates further increases will need large investments in grid strengthening, especially high voltage transmission (reportedly some 4,500 km at a cost of 42.5 billion euros)[4] Much less appreciated is the fact 25% is for Germany alone, but Germany is actually well interconnected with the European Grid (more than 4 times larger), so one can easily give or take from outside, which is precisely what Germany often does (as does Denmark, another country famous for high wind power penetration).

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[4] *Sarah Martin, "Germany's Energy Transition: Changes and Implications on Generation, Transmission and Distribution" presented at the Future of the Grid Workshop, organized by WRI, Bangalore, November 19, 2014.*

The fact that we have a National Grid helps, but less than people realize. One could have power flow from Tamil Nadu (wind surplus) to Delhi (high demand) but it would be expensive, and require interconnections far stronger than today, which raises costs. The second problem is this ignores "control areas", which are areas of operational control (and have a specific technical meaning worldwide, but not operationalized in India), i.e., areas where supply and demand are meant to be in balance from an operations point of view. This is, today, the state, with a State Load Despatch Center (SLDC) trying to keep the balance. Sure, today a state can go above/below their notified demand, but they then have to pay for it, through Unscheduled Interchanged (UI) charges under the Availability Based Tariff (ABT) regime for central generation. Thus, the broader point isn't can the grid handle deviations, but at what cost? Increasing balancing areas would help grid stability and RE, but requires a re-think of state control, finances, operational boundaries, etc.

How much RE can the grid handle? Quite a lot, but with effort and at a cost

While the grid issue has been studied and a recommendation for Green Corridors (transmission lines for long-distance RE power flows) has been proposed, this ~Rs. 43,000 crore investment should be placed in context. First, the economics. The low Plant Load Factor (PLF) of renewables implies compared to the average transmission investment, the Rs./kWh cost of transmission could be not 25 paise/kWh but 3-4 times higher if the lines were mostly dedicated to RE. Or, the costs would need to be socialized. Second, the plans are based on static calculations, instead of properly factoring dynamics, which are difficult to operationalize given we don't yet have dynamic transmission pricing factoring in congestion (such as via Locational Marginal Pricing, or LMP). Without such fixes and revamps, we would continue to have even conventional power subject to the mercy of transmission constraints, which CEA estimated (in 2013) impacts almost 10% of generation capacity. Lastly, there remains the challenge of timeframe and coordination. This large investment might take several years, but there is a possibility that many renewables could be built up much sooner, not to mention in-state investments required for proper "on-ramps" for this transmission highway.

Of course, on paper one could choose to make transmission no-cost. CERC, in draft regulations from 2014, indicates that solar power projects commissioned within 3 years shall, for the life of their project, be free from inter-state transmission charges as well as losses on the same. But this doesn't affect the underlying fundamentals.

There are a number of studies making the claim that renewables aren't strongly correlated with demand, and thus manageable from the grid perspective. For starters, balancing should focus on a control area, rather, a load dispatch area, which is the state in India. Second, an average correlation number is misleading (periods of high positive and high negative correlation also lead to a net average correlation near zero). Third, states could cancel each other out in terms of national correlation. While they could theoretically balance each other, that means there has to be a large flow of power from one state to the other, something that may not be accounted for, either financially or in terms of grid planning.

From a balancing perspective, one also needs to understand the dynamics of changes in supply (and demand), i.e., ramp up and ramp down rates. One doesn't just need an alternative supply for when the wind dies (or when demand spikes up, a generator trips, etc.), that supply needs to begin supply very rapidly if not instantly. This is the essence of one of the some ancillary services, such as frequency regulation and ramp-up and

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[5] In reality, electricity flows like water based on potential differences, and most new capacity operates on a displacement mode (gets used nearby, instead of flowing far away, but making more available in other places). If one had dedicated transmission lines (and long-distance lines can be High Voltage DC, or HVDC), then one could have the actual flow travel long distances.

[6] http://www.cercind.gov.in/2014/draft_reg/Draft_noti7_2.pdf

ramp-down services. This is where wind and solar actually become different (with different time constants for unexpected change), and where the rest of the grid (i.e., alternatives) matter.

> ***Fundamentally, India's grid isn't really in equilibrium, and has relied far too long on the worst possible mechanism for grid balancing: load-shedding***

The challenges of the grid tie back to economics – RE is typically "must run" from a state load dispatch perspective – that means other generators often have to back down, even if their average costs are lower (which is what the state utilities often care about, though dispatch should be based on marginal costs). Using state level findings, the CEA Report on Renewables Integration pointed out that "…against a wind must-run generation with an average tariff of Rs. 3.56 per unit in June 2012, they had to back down cheaper generation of about Rs. 2.50 to Rs. 2.70 per unit." Gujarat asked NTPC to reduce its output when RE output is high, which has only worked because there were other takers for such power, but displacements only work for so long. New pricing and operational schemas will be required, not least because for now we are simply socializing the up-and-down (and wear-and-tear) on other generators, not to mention the higher emissions that come from fossil-fuel generators who have to cycle their output. Of course, with a larger balancing area (with requisite transmission), more flexible alternative supply, and a better managed grid, we should find far more flexibility for RE than we have today.

So if RE integration is such a challenge, how come more hasn't been done? How come we don't notice so many problems in India? Fundamentally, RE's contribution in terms of generation (not capacity) has been modest, but that is going to change soon. At a state-level, we already see many problems. Fundamentally, India's grid isn't really in equilibrium, and has relied far too long on the worst possible mechanism for grid balancing: load-shedding.[8] As long as this is allowed as a cheap fix (rather, cheap for utilities, passing on costs to consumers and national well-being), India can handle almost any level of renewables. India can do better.

IMPROVING RE GRID INTEGRATION

Analysis, Planning and Coordination

To improve the grid integration of RE, one has to improve planning and accounting for renewables (rather, for all generation), factoring in their burden on the rest of the grid such as transmission congestion. A few specifics for this are:

1) *Power evacuation planning.* The starting point requirement should be that if RE plants are being built (and they are growing in total wind/solar farm size to not just tens of MW but hundreds), there must be sufficient transmission capacity. This is often an intra-state issue for now.

2) *Enable inter-state RE.* This effectively increases the balancing area, and isn't so transmission burdensome when the favorable sites are near the border. The problem isn't the regulations disallow it, just that the present rules for inter-state transmission require 15 minute firm schedules, something impractical for renewable power. The use of power exchanges for improved (non-real-time) balancing is also an option (subject to transmission constraints), but this begs the question why are these used so little today, even when prices are ostensibly low, only a few Rs./kWh? The reason isn't technological but operational. Current financial settlement norms, while good for the exchanges' risk profiles, make it tough for states to buy much power since they have enormous liquidity problems.

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[7] Central Electricity Authority. (2013). Large Scale Grid Integration of Renewable Energy Source - Way Forward. CEA, New Delhi. Retrieved from http://www.cea.nic.in/reports/powersystems/large_scale_grid_integ.pdf

[8] In addition to load-shedding, power quality is also allowed to deviate more than desired, including frequency and voltage.

[9] Wind output varies enormously with topography, and developers will not rely on general wind maps or even measurements in the region. They will always put up wind masts to measure the wind over a long time period (dubbed "micro-siting"), an expensive process which is hard to finance (which limits small players and competition).

3) *Improve measurements, predictions, and analysis for RE generation, including data sharing.* This could be through the proposed Renewable Energy Management Center(s) (REMC), which should also coordinate with state and regional load dispatch centers. Data sharing is especially important for wind power, which has much more granular variance than solar power, especially on a kilometer scale.[9] REMCs need not be a large or complex institution – these could be envisaged as virtual centers in synergy with Load Despatch Centers.

3b) *Demand best (reasonable) predictions from generators.* CERC attempted to mandate wind generators to predict, day ahead, their output in 15 minute blocks with a tolerance of 30% (with some corrections allowed in 3 hour blocks), beyond which they would need to pay UI (unscheduled interchange) charges as per the current Availability Based Tariff (ABT) as a Renewable Regulatory Charge within the Renewable Regulatory Fund. There was opposition, and the proposal is currently on hold, pending validation (technically, predictions are asked for, but penalties not enforced). Improved predictions and nimble grid operations are better than of simply socializing the prediction variation costs.[10]

While I cannot offhand say what the state-of-the-art predictions could or should offer, let alone the financial implications of the same (since UI charges are themselves unknown, and vary with grid frequency), some norms are required. Much more importantly, the 30% norm should be updated to reflect the particulars of the state (or balancing area). If windpower is 40% of a state's capacity versus 2% in another state, the implications of a 30% deviation are obviously different. In addition to share of wind, alternatives available in the area matter – if there is more hydro or fast-ramping gas turbines available (or, storage), then the threshold for deviation penalties can be more tolerant. Lastly, dynamics matter (how much the demand is, and how much slack there is in the system). Thus, penalties should not be the same based simply on 30% deviation, but rather state of the grid. UI, while it has improved grid discipline, isn't an ideal signaling mechanism since it is only frequency based, but doesn't reflect state of the grid (demand as well as available generators and their characteristics). Any demand deviation settlement mechanism has to recognize that the absolute variance of RE varies by state, with larger RE states facing hundreds of days of >1000 MW variance (some beyond forecasts), in addition to differences with respect to state of the grid.

Improvements via Grid Operations

1) *Make balancing a proper grid requirement.* While there is now a separate entity for Regional and National Load Despatch (POSOCO), India needs a completely independent Regional Transmission Operator (also called an Independent System Operator in some parts of the world). Such an RTO/ISO must also coordinate with state Load Despatch Centers, balancing their financial needs with grid operations. Importantly, all despatchers must be discouraged from a mindset of load-shedding as a balancing mechanism. One simple option (as a thought exercise for now) – treat load shedding as having a cost, say, equal to the next available resource in terms of merit-order despatch. (In reality, load shedding's cost may be far higher to society overall.)

2) *Strengthen the grid.* Even before we think about ancillary services, there need to be basic improvements to operations, including the use of Primary frequency control from generators with free-governor mode of operations, whereby deviations in frequency automatically signal the generator to increase/decrease output. No generator should be allowed to ignore or bypass control signals like some reportedly do today. In the future, frequency tightening can be achieved by the use of Automatic Generation Control (AGC) based on Area Control Errors (ACE) as signaled by an Area balancing authority.

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[10] *Socializing costs was planned under the 30% wind power prediction schema, for deviations below 30%; above 30% would be paid by the wind farm operator. Note solar was to be exempt from prediction requirements.*

3) *Add dynamics and granularity to the calculations.* Congestion in the grid is dynamic, and requires dynamic pricing for transmission, such as through the use of Locational Marginal Pricing (LMP), which combines marginal cost pricing for generation, transmission, and grid congestion. This is before the obvious need for Time of Day retail pricing. With proper generation pricing signals, we could perhaps find more value to a wind farm in a different location with lower variability (or better peak correlation) instead of just maximum kWh generation. Ultimately, more than dynamics, implications of supply (and demand) must factor in marginal costs. As mentioned in the Introduction and Policy chapters, variability of RE impacts fossil fuel cycling, which impacts pollutant emissions.

The century old grid is changing, and the question becomes is this a managed transition?

Adding dynamics and granularity changes the discourse on technical loss reductions. As an aside, this is one reason that distributed RE generation won't reduce the losses nearly to the extent often claimed in the press. For starters, the average total losses aren't all technical losses (nor theft – these might be about equal). Second, other than per household RE (such as roof-top solar), most other RE still requires "last-mile" distribution, sometimes even at a medium voltage level. Not only does this entail costs, this is a source of perhaps 2/3 of the total technical losses (applying a rule-of-thumb for transmission versus Distribution). Thus, from, say, 28% losses of today, a system of nearby (not household) RE might still have 14% non-technical losses plus some 8% distribution losses. Of course, the grid needs to improve in terms of loss reductions.

4) *Begin ancillary services in the grid.* These value grid support mechanisms beyond simple kilowatt-hour generation, such as the ability to ramp-up/ramp-down rapidly. Today, either the grid is left unstable, or such services are provided by the sub-optimal provider (coal plants aren't designed for cycling production), without appropriate compensation.[11]

5) *Move towards robust RE technology.* Technologically, RE could provide more than simple kWh generation, such as reactive power, if it were incentivized to do so. In addition, India must plan for the ability of such generators to handle Low Voltage and Fault Ride Through capabilities, something China grappled with but ultimately enforced in recent years. The difficulty of a weak grid is exacerbated when RE generators cannot handle low voltages or faults – they trip, further weakening the rest of the grid. The good news is that most newer turbines, technologically, could actually do this – the problem remains for existing capacity – should these be upgraded?

6) *Deploy smart grids to make demand more dynamic and grids robust.* This extends to storage solutions (which often finds value not in energy (kWh) arbitrage but also in providing ancillary services). Both of these are discussed in more detail in a separate chapter in this volume.

Broader Changes in Grid Policy – The Future of the Grid

For all the policy changes in the RE space, policy changes and transformations in the broader electricity sector will have a greater impact. Some changes may appear to hurt renewables, e.g., Time of Day might not help given the Indian peak is in the evening, but the daytime is certainly not off-peak. In addition, improved pricing should also reflect the marginal cost of power, which will be higher than the average price of power as procured by states (see the Chapter on Economics for more on this).

ToD pricing is talked of for end-consumers, but that involves new metering infrastructure. A starting point should be not just bulk consumers (that too with meaningful ToD differentials, unlike today's), but the bulk procurement of power by utilities (today's mostly bi-

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[11] *CERC has issued draft notifications for ancillary services, but the 2014 draft formulation doesn't specify how (the market mechanism details) for these. More importantly, CERC's frequency support ancillary services are designed for periods of wide frequency deviation, instead of more traditional ancillary services which operate all the time (and thus avoid the frequency deviation itself).*

lateral contracts are based only on units generated and capacity, without a ToD component). As and when we unveil ToD pricing, this will add incentives to solar thermal power, which inherently or at least cheaply can store energy for a few hours (until the evening peak). 100% electricity access and ending load-shedding will put additional pressure on peak generation. This will inherently drive a push towards ToD prices, at least for procurement if not retail.

Thus far, discussions have often focused on treating RE as just another generation source for the utility (albeit one that is variable). A far greater transformation will come when end-users opt for RE on their own. While the Economics chapter discusses this in more detail (one should not compare bulk procurement prices with end-user retail tariffs), the first question from a grid perspective becomes is this for on-site consumption or to be fed into the grid? If the former, it is easy, but the latter requires a re-think of business models (including cross-subsidy surcharges, wheeling charges, etc.).

Roof-top solar PV often relies on feed-in tariffs, which can and should go beyond "simple" net metering (equivalent to a meter spinning backwards). That is because consumer tariffs vary, the incentives for these might need to be higher than the consumer's tariff, at least in the short run, or one may need a generation based incentive. More importantly, planners must understand and plan for (price for) the variability of end-user generation, which would be opportunistic in the absence of a battery. One point worth bringing out is the consumer mindset – anyone investing in a solar PV system would expect it to provide power during grid outages. But traditional grid-tie (feed-in) inverters specifically cut off supply when the grid fails, for safety reasons. What we need are hybrid inverters than can both feed in and safely isolate the end-user for supplying power when the grid has failed.

The century old grid is changing, and the question becomes is this a managed transition? Renewables aren't just inevitable, they should be supported and scaled up. However, part and parcel of such efforts must be investments in (and accounting for) expenditures and effort on grid infrastructure and operations. Even if done right, grid integration is a challenge. Done without proper planning, renewables will amplify if not exacerbate the weakness of the grid (stability, reserves, balancing, etc.) The good news is much of what needs to be done isn't a technological unknown – it just takes planning, coordination, investment, and a change in operations to handle well. Combined with improved pricing, storage technologies, and a Smart Grid, the policy push for generation investments in green power can be not just sustainable, but even help meet the broader goals of the Indian power sector, viz., access and affordability.