

**Smart Grids White Paper**  
**WH-1:14.8.2009**  
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**Abstract**

“Smart grid” is a nebulous term spanning various functionalities geared towards modernizing the electricity grid. At its core, a smart grid utilizes digital communications and control to monitor and control power flows, with the aim of making the power grid more resilient, efficient, and cost-effective. Some of the desired functionalities include:

- Knowing the status of the power system in great detail and granularity (ideally in real-time)
- Reacting to any changes in supply (disruptions) or demand
- Enabling small-scale (distributed) storage and power generation (especially renewables)
- Controlling loads as per either operational conditions or financial incentives (through, e.g., time of use or real-time pricing)
- Enabling new solutions for improved customer service, reliability, and future offerings

Smart grids are still under evolution, and different utilities will need different solutions as per their underlying infrastructure, legacy requirements, and business case. Most ingredients of a smart grid exist today, but have not been fully packaged into integrated solutions. The price points also need improvement, especially for residential deployments and developing country roll-outs (where the per user loads are lower). Despite all the challenges, there are large benefits to smart grid technologies, especially as the solutions mature and volumes grow, which will be spurred by the adoption of standards. Smart grids will be an important enabler to make the power system more environmentally sustainable, and represent an opportunity for developing countries to leapfrog in the growth of their power sector to more manageable, reliable, and scalable designs.

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This White Paper is directed to a broad audience interested in Smart Grids. It focuses on the US and India as representations of developed and developing countries, with both similar requirements and as well as different underlying conditions and drivers.

“Smart grid” is a broad, general term, and this paper presents a general set of definitions and interpretations, and highlights some of the challenges in smart grid deployments. This White Paper isn’t meant to be exhaustive, and other references may convey a slightly different focus or emphasis.

## What is a Smart Grid?

“Smart grids,” as the name implies, are sophisticated, digitally enhanced power systems where the use of modern communications and control technologies (the former also known as ICT, or Information and Communications Technologies) allows much greater robustness, efficiency, and flexibility than today’s power systems. Designers also aim for smart grids to save money. Additional terms used include a “Self-healing grid,” which can repair itself in the event of any failure or attack.

There is no single definition of a smart grid, nor is there any standard architecture or design for a Smart Grid. This makes things difficult for utilities, planners, and the government, but it also highlights the enormous potential and opportunities in this space.

Smart Grids are best defined by *functionality*, especially since the underlying technologies for achieving these goals are still under evolution. The US Dept. of Energy lists seven objectives of a Smart Grid:

1. “Enabling informed participation by customers
2. Accommodating all generation and storage options
3. Enabling new products, services, and markets
4. Providing the power quality for the range of needs in the 21st century economy
5. Optimizing asset utilization and operating efficiently
6. Addressing disturbances through automated prevention, containment, and restoration
7. Operating resiliently against all hazards”

## The “Dumb Grid”

To better understand a Smart Grid, one might start with understanding the alternatives. Today’s power systems are similar in many ways to those that began operations over a century ago, where there is minimal control of the power. Power flows based on the laws of physics, somewhat like water flows, from areas of high potential to low potential, overcoming resistance along the way. Many of the measurements are limited, and end-user measurements are mostly with billing in mind, not control.

Since electricity cannot easily be stored in large scales, one always needs enough supply to meet the demand (including the losses along the way, in transmission and distribution). In fact, utilities strive for surplus capacity since some generation capacity may become unavailable at short notice or demand may simply spike suddenly. Maintaining peak supply generation units is a necessary

but expensive proposition since these generation units might only be used for a few hours or dozens of hours per year.

Of course, in today's system, most end-users (except larger ones) are shielded from these issues – they simply pay a flat tariff for consumption of energy (say, 10 cents per kilowatt-hour, or 4 Rupees per kWh). But we know that power consumed at 5 PM costs more than power at 5 AM. Thus, one of the drivers of the smart grid is the need to control peak loads. In the general context, a rule of thumb is that a 5% peak load reduction results in a 25% generation cost saving. In the Indian context, the peak is actually not served (load-shedding), so reducing peak demand helps avoid brown-outs and black-outs, and would have even greater value.

### Components of Power Systems and Changes in a Smart Grid

*Generation* in most modern power systems is a mostly centralized affair, with a wide portfolio of generation technologies based on availability of primary fuels as well as costs. In the US and India, coal dominates generation. Larger and larger generating stations have been built over time, typically with economies of scale in mind.

*Transmission* lies in the “middle” of the power system interconnecting generation with distribution systems. Transmission lines are typically long distance and high voltage. Since waste heat losses are proportional to the square of the current, which is inversely linked to the voltage, transmission is high voltage or extra high voltage – hundreds of kilovolts are common. Voltages are stepped up (or down) using power transformers, which are present at a number of stages of a power system.

*Distribution* is the last physical component of a power system, and is usually the retail end of the system (though retail can be separated from the physical distribution system). Distribution is also like transmission in the sense that this carries power towards consumption points, but there are two main differences. First, the voltages are lower (perhaps tens of kilovolts at most, before being converted to 120V or 220V for end-users), and second, the branching of lines is usually in the form of a tree structure. In transmission, different circuits interconnect, even forming loops for managing bulk power transfer. Distribution is mostly unidirectional power flow, going from the sub-station (where the power transformer separates it from transmission) to the consumer.

A smart grid impacts all the components of a power system. Generation is likely to change with a drive towards more renewable and distributed generation. Of course, some renewables like wind farms are large scale and interface with transmission networks, but many renewables are small-scale, and hence appropriate for interconnecting at the distribution level. This fundamentally changes the design of the grid, beyond any policy or regulatory changes distributed end-user generation entails. Other changes in a distribution system include greater automation and switching, allowing for more physical control over which lines are opened or closed. Smart systems also allow better use of variable capacitor banks or static VAR compensators (which improve power quality from inductive loads like motors), automatic reclosers (which overcome temporary outages), etc. While these power engineering technologies are also used without a smart grid in place, a smart grid allows far greater control and measurement than available today, allowing greater optimization.

Transmission will change in a smart grid with several upcoming technologies. First is the use of phasor measurement units (PMUs), which can precisely measure the state of a power grid. Given electricity operates at 50 or 60 Hertz (cycles per second), minor changes are hard to measure today, especially across a large transmission system covering tens of thousands of route kilometers. Given the improvement in measurement, communications, and analysis techniques (i.e., computing power), we can now accurately measure the state of the system. This is important because now small deviations or jumps in operating parameters (such as the phase of the power) can let operators know when something is amiss. This is useful for preventing sudden blackouts or widespread

(“cascading”) failures. It turns out that there is often a fair amount of time to fix problems before problems spread causing a system-wide failure; the August 2003 blackout in Northeastern US actually had somewhere close to an hour where something drastic such as cutting off an entire city could have been tried to isolate the problem.

The alternating current (AC) power grid operates in a synchronous manner (in phase), and power flows are limited over transmission lines not because the wires cannot take the load (thermal limits are usually higher) but because different segments can slip out of synchronization if there are sudden stresses (e.g., the loss of a major interconnection tie line). With PMUs in place, we can more safely increase the power transfer capacity while simultaneously knowing more about the risks of wide area grid level failures.

The other major change in transmission systems may come from the use of Flexible AC Transmission Systems (FACTS). These are power electronics that physically control the flow of power, instead of relying on uncontrolled physics driven by differences in potential (voltage). With FACTS, one could divert power based on both technical needs as well as commercial agreements.

However, much of the smart grid focus in a power system is at the distribution level. For starters, this is where consumption occurs (not to mention payments are made). Demand is also what drives supply, so managing consumption helps the overall system. It is also the space requiring most effort given the vast distribution of customers and the highly heterogeneous systems typically in place.

One subset of smart grids is *smart metering*. Here, again, there is no one definition of a smart meter. The earlier incarnations of smart meters were ones that allowed automated meter reading (AMR). This has since grown into advanced metering infrastructure (AMI) where the meter not only measures, stores, and communicates loads and other power statistics in (near) real time, but it can also be a point for control (through connect/disconnect capabilities) and signaling to consumers and their devices for load control.

## Designing a Smart Grid: Stages of capabilities

Not only are the technologies within a smart grid evolving, even using today’s technologies there can be a number of designs for a smart grid based on business case, legacy needs, regulatory guidance, etc. Across this continuum, we can identify a number of capabilities, with some that are linear (like below) and some capabilities that can be deployed independent of others. Some of these functionalities are typically not even considered part of a smart grid, rather, are part of modern grid operations and management.

**Accounting** → **Auditing** → **Monitoring** → **Control**

- 1) *Accounting* involves measurements to know what is flowing where and when – in a smart grid one can measure in small time increments, taking measurements beyond just energy consumption (kWh) such as peak load, power factor, etc. In India, a strong driver is to cut down theft and other losses, which can be tens of percent!
- 2) *Auditing* goes beyond accounting by reconciling power flows across different locations. This requires integration of what could be disparate measurement systems. However, auditing is historical in nature, and the analysis and reconciliation might be done, say, once per month. This is only partially useful for theft control.
- 3) With *monitoring*, measurements are undertaken in real-time or close to real-time. Such a system allows signaling in case of a problem, e.g., the loss of a line due to bad weather. Power systems often have Supervisory Control And Data Acquisition (SCADA) systems for monitoring, but these have typically only been deployed at higher voltages.

- 4) *Control* is a general term for making operational changes in a power system, e.g., opening or closing a circuit, capacitor bank switching, feeder switching etc. Control combines ICT with physical power system equipment. One change in a smart grid beyond traditional power engineering technology is the integration of data across various points to allow system level analysis and decision-making. Decisions could even be automated, or at least semi-automated. Such distributed intelligence is one feature of a smart grid that is not present today.

### *Interconnectivity – a Key Requirement*

In a smart grid, all the various nodes need to interconnect to share data as and where needed. This leads to a number of issues, beyond the costs of building out such a large communications network. First and foremost is the issue of defining boundaries, ownership, and responsibilities. Is the power utility to build out its own network, or rely on the third party telecommunications providers? Will a third party be reliable enough for emergency and control needs? Is wide enough coverage available for universal deployment (if that is a goal)?

Most designs typically end at the consumer premise, given utilities typically do not want to become involved with activities inside the consumer home or office. Here, the meter or alternative gateway becomes the interface and boundary. However, it's unclear as to the best design for signaling appliances or devices directly. Some signals might need to be broadcast, while others customized. The good news is that the connectivity bandwidth is modest. One doesn't need broadband for such applications.

It is worth clarifying any potential use of the Internet. The Internet is the public, global, interconnected network comprising of multiple smaller networks owned and operated by a number of entities. It has no owner or controller. Most ICT designs for a smart grid do not advocate directly using the public internet given security, control, and predictability concerns (the Internet as of today is designed for "best effort" data communications). "Broadband" is merely end-user high-speed connectivity to the public Internet. It can be used for many functionalities, but there are challenges when it comes to predictability, control, etc. given it ties back to the Internet.

A "smart home" also requires interconnectivity such that the meter (or gateway) can signal appliances, devices, etc. Here, management and security are the key concerns, combined with ease of deployment. Each home might have dozens of nodes to be controlled, from appliances, heating/ventilation/air conditioning (HVAC), solar panels, electric vehicles, etc. Plug-in electric or hybrid vehicles require a smart grid because one needs to ensure they use off-peak power for charging, and one would like flexibility of location for charging a vehicle.

### *Capabilities of a Smart Grid*

There is a spectrum of functionality a smart grid can enable, with limits placed not just by technology but regulation. Renewables and storage of energy would both benefit from a smart grid such that power is both appropriately controlled and paid for (rewarded) as per the grid conditions. Feeding in power from end-users into the grid can cause operating issues at the local level, and potential safety issues as well. Other capabilities a smart grid could enable include rapid detection of faults and even adaptation based on available options (such as alternate supply or routing of power).

One of the main capabilities of a smart grid is the ability to manage or reduce loads based on operating and load conditions. Part of this involves reducing consumption through efficiency and optimal control, perhaps through sensor networks. When load control is done in response to dynamic grid conditions is termed "demand response" else it is simply demand side management. The first question is whether load control should be direct or indirect, i.e., in response to pricing

signals. The latter assumes some level of price elasticity, but prior elasticity studies are limited given many of the smart (responsive) loads haven't been built out yet – “smart appliances” from an energy perspective are still under development.

The simplest modification of prices is Time of Use (ToU) pricing. Here, the schedules are known to consumers in advance, keeping things relatively simple, but there are some limitations. For starters, loads may shift in response, obviating many of the benefits (indeed, in India, there are portions of the system where the peak load is at 1 AM, when the so-called off-peak was meant to power irrigation pumpsets). Second, such a system cannot respond to unpredictable or emergency conditions.

Real-time pricing involves continuously varying prices, or, more realistically (to keep things manageable), prices that vary in time blocks. How is a consumer to be made aware of his or her prices? Various options have been considered, from a home gateway to using mobile phones for messaging to simple color coded lamps that signal hi-med-lo pricing. Any solution chosen must be as simple as possible, and we may have to enable intermediaries to absorb the price risks and load variance for consumers who don't want to undertake the uncertainty of a real time system.

Given we cannot expect individuals to wait for pricing signals and then manually modify their loads, an ultimate smart grid deployment should incorporate smart appliances which can automatically adjust their load based on end-user (or, if desired, utility) preferences. Refrigerators are a classic example of loads ripe for becoming smart. Such loads are several percent of the overall load, and there is no reason the compressor should come on at 5 PM. Worse than the compressor is the defrost cycle, which is literally a heater in the freezer that comes on briefly at random times in the day to prevent ice build-up. Beyond HVAC loads, white appliances (like washers and dryers), and other large loads, even lighting can be modulated in response to a signal.

It remains to be determined to what extent the utility can or even should have visibility or control into consumers' premises. One option for managing emergency conditions is not to interface with the appliances but for the utility to limit consumers' total consumptions. Thus, modern load-shedding would no longer need to be at the feeder or sub-station (if not city!) level, but could allow for 2 or 5 or some number of amps of power supply per home. If a consumer tried to use more, then their meter would disconnect (or they could choose to pay heavily premium rates). Such a smart system could allow for uninterrupted power for uses like schools, hospitals, traffic lights, etc. It is worth mentioning that the total level of load control required to avert most blackouts is modest (a few percent of the total grid in many cases), and one usually has enough time (recall the Aug. 2003 US blackout) to gradually and fairly control the load.

## **Smart Grid Challenges**

### Costs

If a smart grid made easy business sense, it would have been the norm everywhere. Cost is clearly one of the biggest hurdles for smart grids. The investments per node average some hundred-plus if not two hundred dollars per consumer, depending on design and functionality. Thus, for most utilities, we're talking billions of dollars. Will this be worthwhile? Merely saving money over physical meter readings will not justify a smart metering system (or smart grid). Other savings come from improved operations (e.g., reducing equipment failures or the need to over-engineer), avoiding additional capacity, etc. Beyond such savings, typically seen by the utility under Return on Investment (RoI) calculations, there are a number of benefits enjoyed by consumers and broader society, which are not appropriated by the investing utility. E.g., power quality and predictability may improve, or there may be more use of “green” supply. It takes careful societal cost-benefit analysis beyond RoI calculations to properly justify a smart grid.

A regulator also needs to manage the inevitable disruption a smart grid may create. Modifying tariffs, e.g., Time of Use or Real-Time Pricing, will lead to some winners and some losers. In addition, there are transaction costs. So, why bother if this is worse than a zero-sum game? The loads should shift, allowing changes in fuel as well, so that the overall average costs should fall with proper pricing incentives. The regulator (and, perhaps, policy-makers) must spell out how the smart grid should be deployed. Is full (universal) deployment mandatory? Given many of the benefits will accrue from targeted deployment, what are the fairness implications if such a design were chosen?

### Fears of Transformation

Ultimately, a smart grid must lead to a fundamental transformation of the power sector beyond a technical re-design. Most distribution utilities world-wide are regulated, and many operate on a costs-plus mechanism. Thus, the more they sell, the more money they make. Such profit mechanisms must be re-engineered to incentivize saving energy. What fraction of investment costs can be passed through to consumers must also be clarified.

In the long run, one change advocated by analysts and planners is the shift from energy and electricity as a commodity to one as a service. Thus, the need in India is not electricity for powering pumpsets (some 30% of the total load) but water. One needs light, not electricity per se. One advantage of such a model is that regulatory and business boundaries can be broken down more easily. A smart grid could also interface with other utilities (gas, water, etc.). New services such as home monitoring, healthcare monitoring, etc. could be unleashed, which could provide new revenue streams to utilities as well as enhance consumer convenience. A power utility with its own network could become an Internet Service Provider, either directly or through a partnership or subsidiary. However, such changes are not only resisted (because of the creation of winners and losers) but also because there is vast uncertainty in how these will evolve.

If we consider the vast complexity in ICT and other systems in a smart grid, one has to remember that power utilities have historically been conservative in technology choices, and also have not invested much on R&D (historically a fraction of a percent, reportedly lower than the pet food industry). Thus, their ability to innovate, experiment, and foster radical innovation will take time. Utilities have often considered ICT as a *product*, to be dropped in by ICT specialists. ICT, and, in particular, a Smart Grid, is more a *process*, which requires active participation and engagement by the utility at all phases of the process: needs assessment, design, prototyping, business case analysis, deployment, integration, and scaling. In addition, such steps are not sequential, but require iterative learning and experimenting.

### Design Challenges

There are a number of technical design issues for which there are no easy answers – each utility will be slightly different based on existing architecture, legacy equipment, topology, demographics, etc. Utilities often span different geographies, consumer mixes, etc., not to mention often incorporate assets decades apart in technology (sometimes made more complex through acquisitions or restructuring). What would work well in one case may not be optimal in another.

As an example, the US power grid typically has relatively small distribution transformers serving 4-7 homes. In Asia or Europe, the consumer voltage is 220 or 240 volts instead of 110 volts, and a distribution transformer typically serves 100-200 homes. This could dramatically impact the choice of wide area communications technologies, e.g., enhancing the value of and increasing the bandwidth requirements of an aggregation point or concentrator for data flows.

Beyond issues of complexity and scale, there are several broad technology issues all utilities will have to face. ICT evolves very rapidly, while power systems have much longer lives. It is tough to

design for something that should last 20 years. This requires modularity and upgradeability, which raises costs. ICT can be made cheaper by integration on-chip, but this reduces the flexibility. A balance must be struck.

Security of the system is paramount given the vast financial and safety implications of a smart grid. This is one reason that most people do not advocate using the Internet per se, though they may use Internet Protocols on a private network. Security cannot be added on but must be designed in from the start. A worst case scenario would be for a hacker to turn on our stove!

A subset of security is privacy. At the very least, the power company will know when you are or aren't home. More sophisticated analysis could lead to much more information, including consumption patterns (a proxy for wealth), how many people are home, etc. There have already been cases of law enforcement using power data for investigatory needs. This space needs integrated legal, regulatory, and technical planning, keeping in mind the needs of the citizens.

## **Status of Smart Grids**

Various utilities around the world have taken steps towards deploying a smart grid. A number of nations also have regulations and legislation towards smart metering if not smart grids. Perhaps the largest deployment to date has been Enel, in Italy, where all 27+ million consumers have smart, bi-directionally communication, controllable meters. However, with continuous improvements in technology, new deployments (e.g., Boulder, Colorado, or Southern California) are “smarter” in their capabilities. Smart grids remain a work in progress, and there are other projects ongoing around the world.

In developing countries, smart grids have not been the focus of the utilities given the other challenges they face, including supply shortfall, theft, financial losses, etc. However, given their small base of present deployment, it is possible that they could leapfrog to smart grids, while at the same time using them as a means to improve their operating and financial sustainability.

## **Moving Ahead with Smart Grids**

While there are uncertainties if not fears about costs of a smart grid, amplified because the benefits will accrue over a long time, the benefits likely will improve as deployments increase and costs fall. Most regulators agree that with or without a smart grid, consumer costs are likely to rise, sometimes drastically, given the constraints of fuel supply, environment, sustainability, etc.

Today, we have the chicken-and-egg issue of low-volumes/high-costs, which need to be converted into low-costs/high-volumes (almost like commodities). How can we achieve this? One solution involves the use of government funds or other external support. This is to help early adopters who face higher costs than others, who then help the industry move along a positive learning curve.

Another solution involves more experimentation and innovation. This is in not only underlying technologies (where many ingredients exist but there may be space for breakthrough technologies) but also in operating and business models. The latter is especially the case given consumer behavior and response is a key component of realizing benefits. Beyond pilot deployments, which are in the field, some researchers advocate for more controlled testbeds where more radical and unknown innovations can be researched, developed and deployed, in addition to simply testing the existing state-of-the-art.

Possibly the most important step for smart grids is the creation of standards, so that not only will production costs fall through competition but also utilities will not face a lock-in into proprietary solutions. Ideally, such standards should be open standards not controlled by any one entity. Rather, a collaborative or open process should lead to the respective stakeholders coming up with the right standards, combining industry, government, regulators, etc. There are already a number of

industry bodies and consortia creating standards for aspects of smart grids. This work will continue, including efforts by IEEE, EPRI, and the US National Inst. of Standards and Technology (NIST).

The case of WiFi (“wireless Ethernet”) is a good example of ICT innovation, commoditization, and standards. WiFi is the standard by the WiFi Alliance, an industry-driven consortium, which adds standards for inter-operability and security. This sits on top of technical standards by IEEE (IEEE802.11). WiFi began as IEEE 802.11, and in just a decade the speed has increased from 2 Mbps to hundreds of Mbps (802.11n standard). At the same time, the costs have fallen from over \$1,000 per node to a few dollars per node (with WiFi now embedded in personal computer chips by manufacturers). While we cannot claim similar advances are likely in smart grids, there is still room for substantial improvements in price points with increase in volumes and standardization.

The stimulus money from President Obama for smart grids (roughly \$4.3 billion) or the Indian Government program on Revised Accelerated Power Development and Reform Program (R-APDRP, \$10 billion, of which some 20% is for ICT) are just small steps towards the total effort required in this space. Utilities or planners should not rush into Smart Grids without due analysis and discussion, but, at the same time, should not wait indefinitely for the solutions to “mature.” Varying levels of smart grids are already under way – the challenge is to try and reach the virtuous circle of technology improvements, standardization, and scale deployments as rapidly and as cost-effectively as possible.

For further information

US Dept. of Energy: <http://www.oe.energy.gov/smartgrid.htm>

Natl. Inst. of Standards and Technology: <http://www.nist.gov/smartgrid/>

PSERC: <http://www.pserc.wisc.edu/ecow/get/generalinf/presentati/smartgride/>

*India-specific*

Min. of Power (Report by CSTEP and Infosys): [http://www.cstep.in/docs/Power\\_Sector\\_Report.pdf](http://www.cstep.in/docs/Power_Sector_Report.pdf)