"Smart Grid": R&D for an Intelligent 21st Century Electrical Energy Distribution Infrastructure

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Today's energy infrastructure is a relic. The "grid" has expensive, centralized generation via large plants, and a massive, centrally controlled transmission and distribution system. It delivers high quality power to all subscribers simultaneously and is sized to the peak aggregate demand at each distribution point. Power is transmitted via high voltage lines over long distances, with associated inefficiencies, power losses, and right-of-way costs. Local distribution, via step-down transformers, is expensive in cost and efficiency, and is a single point of failure for an entire neighborhood. The system demands end-to-end synchronization, and lacks a mechanism for storing ("buffering") energy, thus complicating sharing among grids or independent operation during an "upstream" outage. Recent blackouts demonstrate the existing grid's problems — failures are rare, but spectacular. Utilities mitigate energy consumption because of the expense of deploying new infrastructure to meet growing demands. Average demand/consumer is a small fraction of the peak — a 25 kWhr/day home draws on average less than 5% of its 100 amp service. Consumption correlations, e.g., air conditioners on a hot day, drive demand beyond estimated aggregates, which can result in huge spikes in supply cost, and may trigger blackouts.

Technology Opportunities: The Smart Grid, Pushing Intelligence to the Edges, to Integrate a Diversity of Energy Sources and Loads

There is much that can be done near-term to exploit information technology to improve the reliability, visibility, and controllability of the existing grid and to support loads that reduce their energy demand in response to price signals, through such technologies as synchronized phasors and intelligent metering. Longer-term and more transforming, the Internet suggests alternative organizing principles for a 21st Century Smart Grid. It succeeded by pushing intelligence to the edges while hiding the diversity of underlying technologies through a well-defined interface. Any device can be a source or sink of routable traffic and intelligent endpoints adapt their behavior to what the infrastructure can deliver in accordance with localized utility functions.

Radical proposals to replace existing infrastructures, given their wide deployment, high capital costs, and well-understood technologies, are unlikely to succeed. Here, too, the Internet offers a model — of infrastructural *co-existence* and *service displacement*. The early network was deployed on top of the telephone network. It provided a more resilient set of organizing principles, became its own infrastructure, and eventually the roles reversed: services such Voice over IP (VoIP) telephony are recent additions, having been added over time. The same approach can yield a new architecture for local energy generation and distribution that leverages the existing energy grid, but achieves new levels of efficiency and robustness, similar to how the Internet has improved the phone network.

[1] For the most current version of this essay, as well as related essays, visit http://www.cra.org/ccc/initiatives

Imagine a system built on *packetized energy*: store energy where it is generated, "route" it to where it is needed. The existing infrastructure is generally unable to store energy for later use, yielding a centralized system with crude mechanisms to adapt load (e.g., regional exchanges, peaker plants, curtailment) and provisioned so that users lack the means to present an easier-to-manage load to the infrastructure. New environmentally friendly energy storage technologies are needed, with capacity/cost metrics suitable for deployment in homes, buildings, and throughout the transmission and generation system, including renewable/intermittent energy sources. Combining intelligent communication protocols with energy transmission in a common architecture makes possible distributed control and demand response to pricing signals.

Such an infrastructure design would permit a shift from peak/worst case to the average case "with sufficient headroom," analogous to statistical multiplexing in packet networks. The key is to use this headroom as an input for controlling generation, storage, and loads. Standardized intelligent "interfaces," at the level of homes or even individual appliances, allow independent powered operation, distributed generation, and energy exchange. The architecture should allow aggregation to plug into the regional grid, the neighborhood peer-to-peer grid, or the facility grid to use localized storage and control to smooth load, adapt demand, and engage in exchange.

Leadership

With the deregulation of the energy industry, no entity exists in the United States able to undertake the research and development of a new energy infrastructure. EPRI, funded by the Utilities, is not incentivized to investigate radical alternatives. Numerous industry-driven "smart grid" initiatives have been undertaken recently, yet none has yielded a comprehensive system architecture for the future grid. This is one area where it makes sense for the Federal government to fund research and the development of proof-of-concept prototypes, to organize testbeds and partnerships between the information technology and energy technology industries, and to develop new research communities at the intersection of distributed and energy systems.

Recommendations

NSF is a key agency to fund foundational research in this area, but the area falls in the cracks between the CISE and the Engineering Directorates. A comprehensive interdisciplinary cross-foundation thrust in this and other critical infrastructures should be undertaken.

DOE is the lead agency supporting energy research. In the smart grid area, DOE should integrate its research activities with the best research groups outside its own laboratories, to play a critical role in bringing emerging technologies into testbeds to demonstrate the viability of alternative architectures and technologies to the energy industry.

The DoD has interests in rapidly deployable, easily transportable energy infrastructure. DARPA should undertake an aggressive research programs to investigate and demonstrate scalable intelligent energy infrastructure with application to military needs.

The Executive Branch should organize cross-agency coordination in this critical area.

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