A Strategic Framework for Electric Energy: Technology and Institutional Factors and IT in a Deregulated Environment [1]

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Abstract:

It is clear that deregulation has begun to arrive in the electric power industry. What is far less clear is what this means, how it will affect the current players, and how to even think about the diverse, complicated factors coming together in what is, for policy makers, users and managers, and energy providers, a witches' brew of potentially important, yet poorly understood factors. Such "wicked problems" demand more inclusive perspectives for understanding the context within which problems must be identified and decisions made about them. This paper proposes a template for analysis of "wicked problems" in the electric energy industry, adapting well-established tools from Industrial Economics and Analysis to suggest novel perspectives for assessing the current competitive environment, identifying potential points of high leverage for attention, and examining some compelling interactions among the factors affecting the electric power industry. Our ultimate interest is in identifying the R&D agenda – in technology, in regulation and in strategic terms -- essential for successful electric power industry.

[1] Views and conclusions expressed in this paper are those of the authors, and not necessarily those of the National Science Foundation. Responsibility for any errors or omissions also rests with the authors.

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The Challenge of Deregulating Electric Energy:

There is a problem facing the electric power industry, one that will become worse over time and generate huge difficulties if it is not solved. Yet the specifics of the problem are unclear because by its very nature, it is suffused with ambiguity, with multiple different definitions of "the problem," and with numerous insistent stakeholders, each pushing a particular viewpoint. In fact, the industry faces a "wicked problem" (or perhaps better, a "wicked environment") that is simultaneously:

- More complex than the existing technical paradigm can manage or understand;
- More complex than the existing regulatory regime can comprehend; and
- Within which many former externalities must now be embraced.

"Externalities" in this usage refer to factors formerly ignored or excluded from the paradigm-in-use by which those concerned with the industry made sense of their environment. Among the former externalities that can no longer be simply ignored are questions such as capacity levels and growth plans, energy use and environmental sustainability, allocation of resources to use, environmental pollution concerns, and the temporal and locational questions of power supply, to name but a few.

Externalities rise into prominence but rarely in an industry, typically in the context of some crisis (such as a major disaster like Three Mile Island, or the coming of deregulation) that forces a shift in attention[2]. Deregulation unfixes the rigid barriers or requirements of the past, undercutting the dominance of long stable technologies and analytical techniques. Political forces or technologies once safely ignored rise to critical salience, and new potential competitors come into view. Because they were "external" to prior understanding of the relevant factors affecting industry, such externalities often act as huge and unexpected surprises, throwing the industry and its long-held assumptions into disarray and obsoleting formerly unexceptionable "best practices" for understanding, analysis and effective response.

In short, the old ways of looking at problems and responding to them no longer work here. To understand the "wicked problems" (Linstone and Mitroff 1994) of the changing regulatory environment of electric energy requires more complex and sophisticated perspectives that include what was formerly ignored. Without this understanding there will be no systematic innovations in this industry. Further, individual actors concerned with only their portions of a much larger system, sub-optimize. However, it is

[2] Three Mile Island drove nuclear accident risks into dramatic prominence, as did Chernobyl, some years later. The net result of these incidents was a solidification of resistance to nuclear power in the United States. Note that the issue is political, environmental and perceptual, not purely technical.

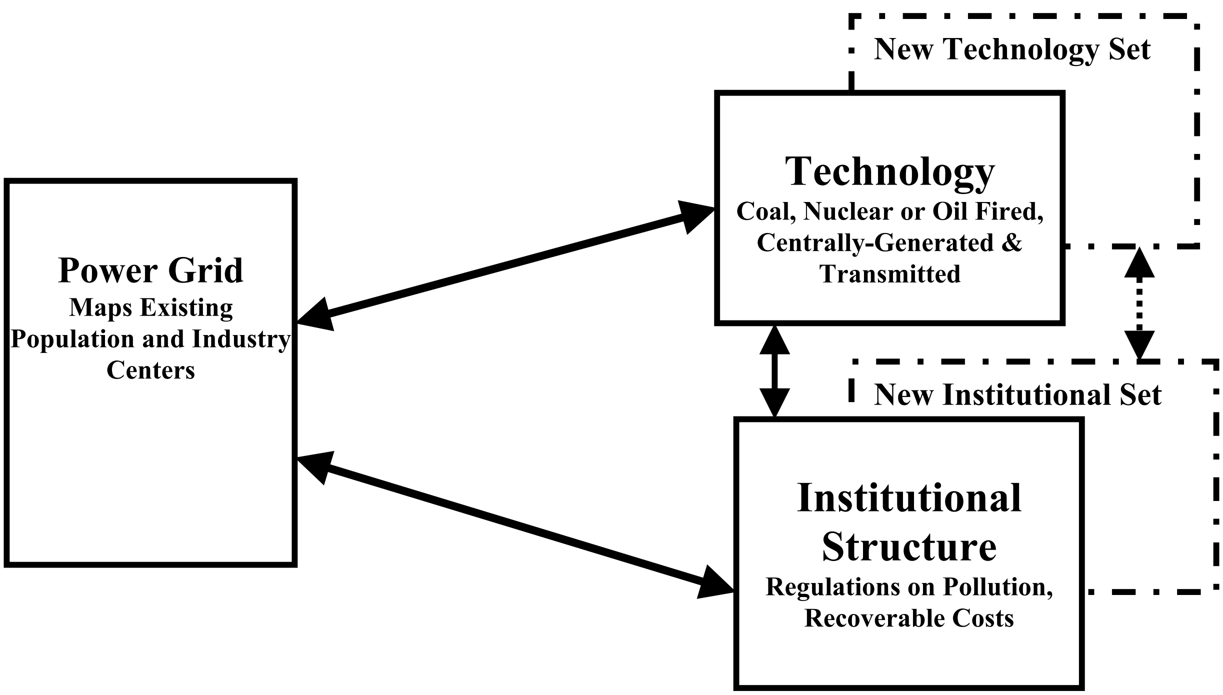
the evolution of the system itself that is of interest to us here. We see potential for system evolution from a rigid, hierarchically controlled entity (dominated by what we shall call the N-1 prevention paradigm) to a far more dynamic, real-time optimized and information-driven entity of greater long-term robustness and efficiency.

This paper will first sketch the nature of the original, regulated industry and its challenges. Next, we will touch upon new challenges and opportunities already visible in the transitional energy system. Finally, we will profile the new dynamic system whose outlines can already be discerned. Its characteristics are a function of changes in technology, regulations, and system interconnectedness, and their financial implications, as we shall demonstrate. It is also an IT-enabled system, where information rules.

A Template for Industry Analysis: The Regulated Industry

Take a snapshot of an industry: at any instant, the industry's configuration reflects the existing technology and institutional structure. Over time, this arrangement favors some industry structures, while at the same time impeding others. What is practical or what is economically feasible are governed by this structure, and choices embodied at any point in time do not always exhaust the set of what is possible. Changes in any of a number of factors can affect the balance, making feasible or profitable what formerly did not make economic sense. So it is with the electric energy industry. Fig. 1 outlines an overview of some factors affecting the electric energy industry, with selected illustrations.

Figure 1: An Overview of Factors Affecting the Electric Energy Industry



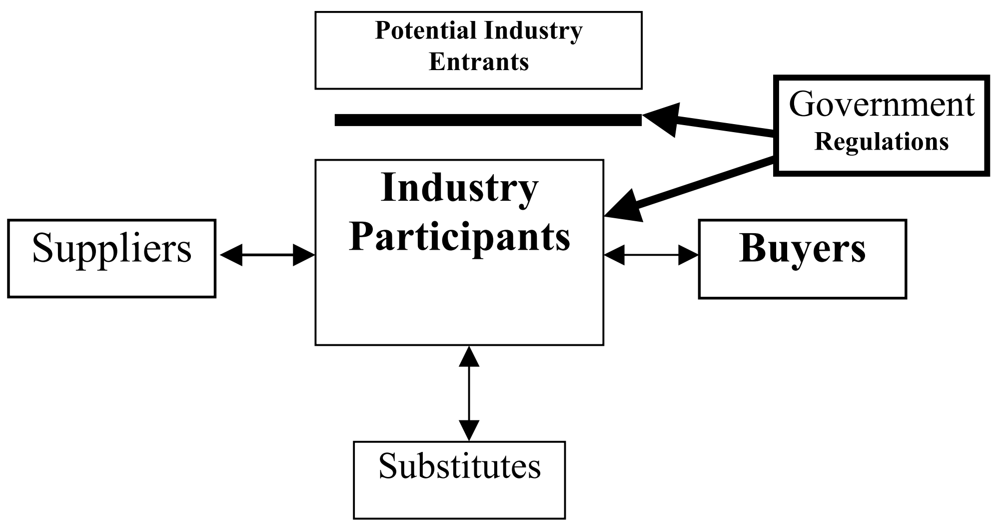
Available technology and the institutional structure, including regulation, rules regarding pollution and clean-up and recoverable costs clearly are factors behind the rise of the U.S. power grid in the particular shape it has taken. Characterized as it is by central, relatively large generating facilities connected into a network by transmission lines connecting major population centers, this structure embodies assumptions and economic decisions based on technology and institutions at a point in time. Investments in large-scale capital facilities such as generating capacity are not readily shifted overnight. Technology choices, once made, are exceedingly difficult to remake, as utility company experience with nuclear power underlines. Regulations are set up to facilitate a particular vision of what is needed, and to protect against the hazards envisioned at any one moment. But which technologies and which institutions matter? New technologies can call for new institutions; new institutions can favor different technologies than those favored in the past. What seems relevant is considered; what seems more distant is dismissed from the equation. Past experience and long-enduring trends seem appropriate guides for the future. Yet even longstanding trends can disappear.

Deregulation, driven in part by changing technology and in part by a changing political environment, changes the sets that matter, destroying old trends. By changing what may be done and by whom, deregulation creates possibilities and opportunities hitherto nonexistent, or only now practical because of technological changes, or perhaps simply invisible in the past. At the same time, technological evolution also affects what is possible – even whether or not deregulation itself makes sense. Any snapshot of "what is" captures a time-anchored complex – one that will become inadequate to a changing environment over time. Thus, population growth in general, accelerating computer technology and its demands for "cleaner" power, new "must have" appliances, and population growth in particular new places all contribute to a growing misfit between today's needs and yesterday's arrangements. Capacity needs offer a case in point.

Capacity for years was added according to a rough rule of expectation that around 20% buffer capacity above usual peak needs was required. In the regulated environment of the past, such a rule governed building new plants, and was generally predictable against well-understood characteristics of usage, usage growth and population growth projections. From energy company's perspective, capacity needs were a function of peak usage, storage capacity, and options for buying additional peak-load capacity. Centrally generated power, the range of viable alternative energy sources (e.g., petroleum, coal, nuclear), transmission structure and the economics of the existing power grid constitute a paradigm. It is embodied on the ground; widely shared within the industry, where experience verifies its standing; and privileged by the previously existing regulatory structure. But such a paradigm is by no means inevitable, or permanent.

What happens when we include new sources of power, new maps for locus of generation versus use? Updated generator technology, photovoltaic shingles, solar power, wind power, geothermal power and temperature differentials (heat pumps) create different possibilities. Information technology applied to point-of-use monitoring and switching also affects what may be technically possible; perhaps facilitating distributed generation, or some hybrid of central-distributed generation. A host of possibilities begin to emerge. A modified form of Michael Porter's competitive forces map (1980) will help to organize this variety.

Figure 2: Competitive Forces Map for the Regulated Electric Energy Industry



In the regulated industry, government rules preclude or limit new entrants into the industry, dramatically affect participants, and structure competition. Essentially, industry participants hold regional monopolies, while technical considerations control the degree to which a given generating plant can access alternative fuel supplies (for instance), as well as the degree of competition among participants, if any. Industry structure evolves – for example, in a particular infrastructure of transmission, a particular locus of power generating facilities (perhaps dependent upon proximity to an energy source, such as hydro power) – in response to the regulatory environment as well as the technology first established as the industry standard. Clearly, regulations must reflect what a given technology makes possible. Costs are passed through to buyers, with limits on the profit potential for industry participants, and for suppliers.

Because of high capital costs and the difficulty of retooling an extensive network of in-place capital equipment (such as the existing electrical power grid in the United States), once in place, an industry configuration endures. Consequently, as change accumulates in the environment, or as the pace of change intensifies, the degree of "fit" between existing industry structure and demands of the environment around it erodes over time. Change can come from any element in the picture – change in power generation technology, for instance, or transmission technology, in the physical location of industry, or in industry or consumer demands for power (whether amount or character). Regardless of where change comes from, as fit diminishes, problems arise: different demands are likely, but their source and nature are uncertain. Where factors from the environment, hitherto ignored, come into salience, the problem becomes "wicked," because the very models for understanding are inadequate, and "what we've always known" may no longer be true, or even relevant.

Deregulation, one potential response to such misfit, creates dramatic revisions in the relative power of the players diagramed in Fig. 2, putting substantial pressure on prices and costs as new claims for portions of available margin arise. Consumers want lower prices – yet suppliers may demand higher prices, while substitute products may undercut the industry's position. Ideally, the hoped-for outcome is increased competition among rivals in the interests of lower prices for customers. That is not always the case. A brief look at the US airline industry's experience with deregulation will help to illustrate.

Potential Consequences in the Electric Power Industry

There are many similarities between the airline industry and the electric power industry as phased transition from the fully regulated state evolves. As in the airline industry, for electric power too the transition is difficult and slow. In much the same way as in the airlines industry, technology costs in the regulated industry were characterized by large economies of scale, with a very few large, fuel-efficient power plants. The same swings and mismatches in supply-demand balance can be seen, and the electric energy industry and its customers have likewise been vulnerable to the major shifts in fuel costs.

Utilities have also been wrong in the past in forecasting much larger load demand growth than has actually occurred. This has resulted in over design, and consequently in over capacity of the system characterized by very large power plants and strong transmission network (and overly high costs), in some areas at least. More recently, forecasts have erred in predicting less demand than was actually experienced – in Southern California, for instance. As computer usage has grown – particularly for high-reliability, high-capital cost applications like computer controlled manufacturing – complaints about "dirty power" and unreliability have grown. Where population and demand have surged, prices have soared and supplies have been tight. Meanwhile, technology has progressed to offer new choices for fuel-efficient and sustainable, but smaller generating options. Such new energy resources are not necessarily "traditional" competitors, but they can provide partial substitutes for mainstream power.

These changes have triggered a first phase of electric power industry restructuring. Typically transmission-related barriers to new entrants have resulted in rather slow integration of new energy sources into the existing power industry. Even in utilities where the functional or corporate separation of the energy supply business from the power delivery entities (the transmission and distribution companies) has taken place, much remains to be done. The old paradigm of structure around existing, traditional-source power continues to dominate. Thus far, deregulation is partial at best.

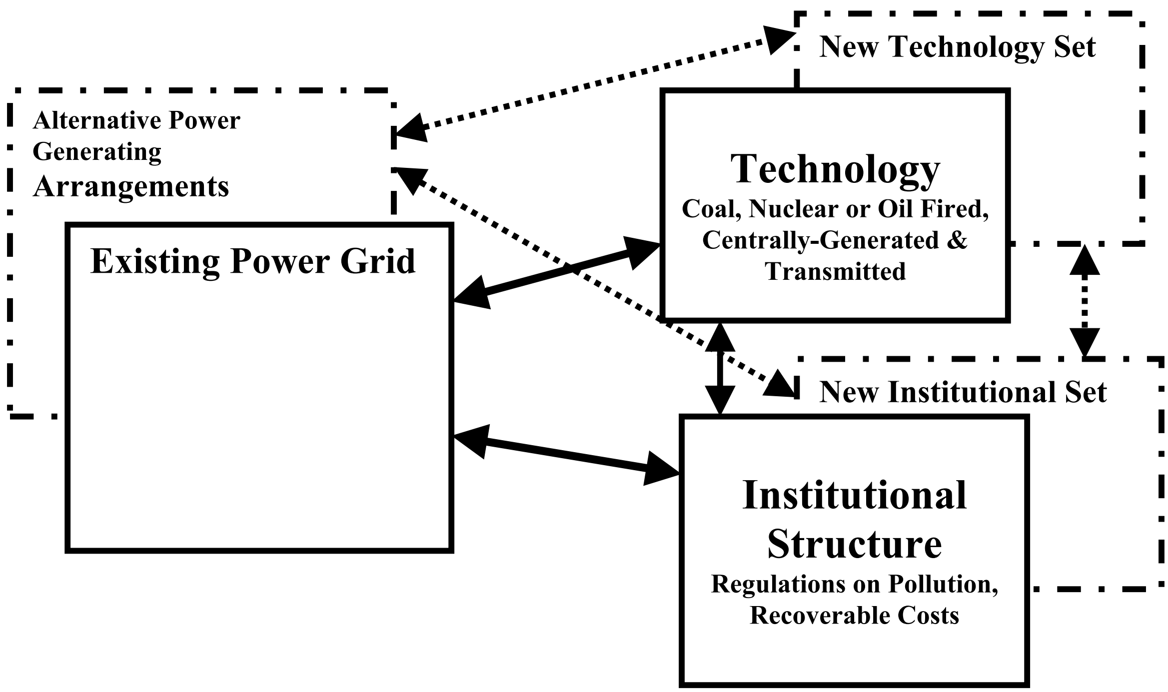
Separation of vertically integrated utilities into competitive power supply businesses has begun, but transmission and distribution businesses are still fully regulated. Managing the interface between these different worlds requires much re-thinking. Among the issues are change of technical standards, new regulations and incentives to these newly formed businesses to promote most effective solutions on customers' behalf. The recent California power shortages have witnessed massive outflows from still-regulated downstream companies whose revenues are capped, while deregulated power generating entities and brokers have profited mightily.

The potential for substantial new investment needs – in new, more-efficient and cleaner generating capacity, and in transmission infrastructure as well – promises potential for substantial restructuring within the industry, and possibly for significant new entry, perhaps with new technology. Yet where will the money come from? California's power companies, Southern California Edison and Pacific Gas and Electric, like the deregulated airline industry of the old days, are losing billions. Asymmetric deregulation will eventually come back into balance – but whether soon enough to rescue existing firms is not certain.

Not surprisingly, in the midst of this experiment in deregulation, many companies have consolidated through mergers and acquisitions. Yet few of these appear to be analyzing the technological threats and opportunities broadly. As a consequence, the current energy markets are more like loose oligopolies than truly competitive businesses. This situation, like that of the airline industry at a comparable stage of deregulation, may constitute a significant entry opportunity – if an alternative business model based on the new technological possibilities can be developed.

Other changes in practice reflect the uncertainties and opportunities. More and more small power plants are being built closer to the customers in order to avoid the cost and uncertainties related to power delivery. This change shifts the electric power industry's longstanding geographic paradigm, while the economics reflecting the relative geography of power plants, customers and their sizes is played out. Similar to airline industry experience, IT is beginning to play a much larger role. Broadly distributed and more readily available IT may support much more dynamic response to demand, invisibly reconfiguring the industry. Like airline yield management, electricity rate management on a real time basis may improve margins for those able to take advantage of it. The trading of electricity is likely to become more widespread, and more actively supported by distributed IT. Depending on the dominant changes in regulatory, technical and pricing mechanisms, the electric power industry is likely to evolve into qualitatively different architectures from those of today. In what follows, we briefly describe three such possible new industry paradigms, emphasizing how IT may drive new industry configurations.

Figure 3: Opportunities for Alternative Architectures for the Electrical Power Industry



Some Architectures for Electric Energy in the Future:

Opportunities exist to make strides in all areas affecting the electric power industry, as shown in Figures 3 and 4. On the technological dimension, serious R&D (into to the new types of energy sources, energy storage, technologies for cost effective customer choice) to support systematic understanding of the role of transmission providers offers potential. So, too, does the promise of flexibility in power delivery to facilitate the needs of the competitive supply/demand markets. IT deployment affects all these forces, by offering new ways of providing products and services under competition, reacting to information instantaneously. Temporal and locational aspects of demand and supply make this effort particularly challenging. In what follows we highlight both such challenges and some emerging alternative solutions.

Before we do so, however, a summary of the shortcomings of the existing technologically based paradigm of today's power industry is in order. The existing paradigm fails when

a) The new environment is more complex and more complexly linked than in the past;

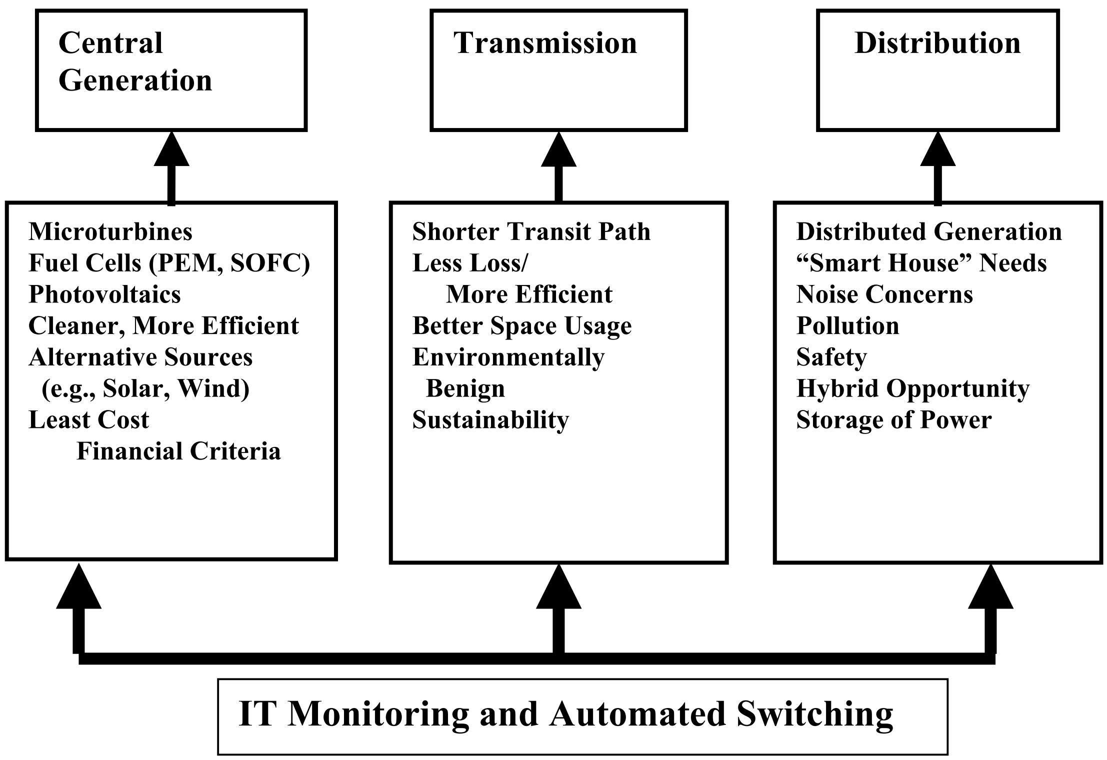
b) The old regulatory regime fails to address urgent questions that arise;

c) Technological possibilities not hitherto envisioned undercut the old regime; and

d) Former externalities demand attention.

We argue that all of these conditions hold today. Such a constellation translates the electric power industry's environment from benign to "wicked." How "wicked"? Figure 4 outlines a few of the potential sources for change, noting potential shifts against a contemporary schematic value chain for the electric energy industry. Changes to smaller, cleaner and more efficient generation, for instance, or alternative (distributed sources), and most especially automated management of hybrid systems all pose substantial potential threats to the existing industry configuration.

Figure 4: Points of Potential Change in the Existing Energy Value Chain



Widespread IT capability -- for system management and automated switching -- enormously enhances the potential of hybrid arrangements. IT creates the potential for substituting many smaller alternatives for any single element that may be out of service for scheduled maintenance – or for hot-swapping in real-time, as the alternative grid's elements are put into place over time. In short, it offers an emerging migration path from the current industry configuration and paradigm to a vastly different one.

The Electric Power Industry's New Environment

The electric power industry's environment has traditionally been defined in purely technical terms, with little acknowledged need to attend to external factors. In the past – like the airline industry -- the regulated energy industry was guaranteed pass-through on any increase in costs. Capacity decisions were tied to economic growth in what decades of (regulated) experience said was a virtually immutable algorithm: add capacity when peak demand approaches within 20% of total available capacity. Now, a new environment insists on taking into account not only the fairly evident factors of business, economic growth and engineering technology, but also a host of new factors. “NIMBY” (“Not in My Back Yard”) and growing public resistance to dams, no less than outright intransigence on nuclear power and even its clean up and shut down costs have foreclosed that option – and dramatically shifted financial risk.

But the complexities don’t stop with political fallout. New technologies, potential new entrants and externalities not hitherto considered important all play potentially disruptive roles. “New entrants” can be new companies – including substantial rivals created by mergers and acquisitions among hitherto non-competing firms – but also new sources of energy from alternative generation sources, like photovoltaic shingles, distributed generators, wind or solar power. None were considered “rivals” to mainstream generation in the past, and even now are difficult to assess, since they don’t generally substitute for “all” power needs. Still, the potential for IT to knit these elements into new “virtual power grids” cannot be dismissed (Awerback et al., 1997).

Of particular interest here is the emerging reality of complex computer-controlled hybrid systems. Thus partial systems that could easily be dismissed as inadequate not long ago[3], can now be managed in concert to substitute for much or even all of a consumer’s needs, at least some of the time. Similarly, energy storage capacity has been evolving, making partial solutions more attractive for some customers at least, while consumer-size generation equipment has substantially improved in quality while dropping in cost. Thus it was long believed that electricity could essentially not be stored, particularly for consumer use. Yet advances in battery technology have made many consumers familiar with uninterruptible power supplies for their computers – and a few with the potential for battery storage as a bridge to automatically started home generation. Commercial installations are already in use.

Similarly, wind and solar power can be used as available, even where neither alone might be a viable alternative to traditionally distributed power, if IT manages shifts between the different power sources. Photovoltaics, fuel cells, and micro-turbines are already nearing the kilowatt-hour cost of industrial gas turbines, for much smaller-output units (2000). Still newer technologies, like flywheels for energy storage, are also under development, with initial commercial installations for uninterruptable power supplies.[4]

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[3] Because they could not substitute for **all** a household’s power needs during a lengthy spell of cold, cloudy weather, for instance, or because manufacturing costs were too high. See also: Dunn, S. (2000). Micropower: The Next Electrical Era. Washington, D.C., Worldwatch Institute**:** 94; and (2000). The dawn of micropower. Economist**:** 75-77.

[4] Platt, C. (2000). Re-Energizer. Wired. **8**.05.

In strategic terms, the threat here is that what was formerly dismissed as irrelevant can emerge as a viable substitute for the existing arrangements. Thus industrial customers, or even homeowners, can become self-supplying, wholly or partially. Further, with legislation requiring buy-back, such self-suppliers can in effect integrate backwards. The significance of such possibilities is by no means entirely clear; such customers may be threats to existing suppliers of electric energy, or they may be potential allies in the effort to create a more robust, survivable electric power network. “Threats” may be opportunities in disguise. It is to these possibilities that we turn next.

A New Paradigm and a Possible Framework for solving Energy’s Wicked Problems

We briefly describe the industry of the past, its transition and one potential future. The existing industry paradigm is generally characterized as a fully centralized, large-scale system – a century-old model. The transitional industry is seeing aggregation across non-traditional boundaries: unlikely partnerships, participants who neither own generation nor transmission facilities and vastly different groupings of power sources are among the new factors. Finally, the likely end-state industry architecture will become very much more distributed, with a large number of relatively small actors – as is already the case in some developing countries.

The evolution process is slow, inconsistent, and heavily dependent on regulatory uncertainties, pricing mechanisms and on the actual technology transfer process. As in the airline industry, regulators are often tempted to introduce temporary price fixes, such as guaranteed pricing for some transitional period, or price caps under competition. Major questions remain concerning the technology transfer of fuel-efficient and environmentally acceptable energy resources (distributed generation), the evolution of appropriately distributed architectures, and the development of technology (especially IT) to support customer choice. The interplay and interdependencies among these factors is also at present uncertain.

The late Professor Schweppe through a concept of homeostatic control predicted one likely end-state-paradigm for the electric power industry in 1978. Homeostatic control is based on distributed, automatic usage adjustments by individual users in response to local frequency and voltage changes (Schweppe et al., 1980). The technology and regulatory setup of 1978 was not ready to support his vision, but contemporary developments render his ideas once again relevant. Only very recently have commercially cost-effective distributed technologies at both customer and generation side, as well as flexible control of wires, begun to emerge. Only with the coming of micro power, described recently in (2000; Dunn 2000), has Schweppe’s vision at last beginning to materialize.

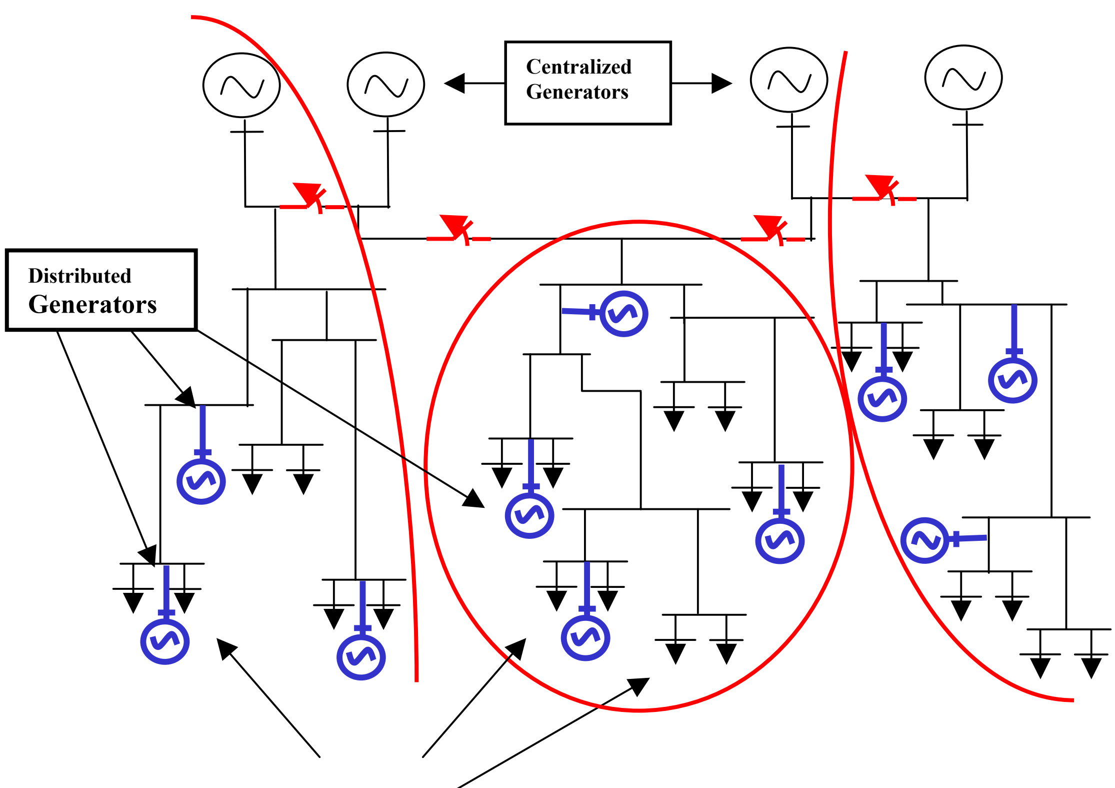
The R&D achievements needed to support the evolution of the electric power industry into these new architectures are substantial. Yet what is necessary is not so much “one silver bullet” as removal of a series of related bottlenecks. Moreover, as the system evolves, the value of each component will change, revealing new possibilities for the whole. Thus even now micro-turbines, or fast switching, create alternatives that were impractical not long ago. Small-scale, stand-alone generating capacity for home use has little apparent value in a contemporary urban setting. Yet if a reliable switching system permitted many such small generators to respond to partial system outages elsewhere or sudden demands, the system as a whole could acquire valuable surge capacity.

A given technology may have completely different value, depending on the overall industry paradigm and the state of evolution of other elements in the system. Moreover, managers need to develop operating, maintenance and planning tools for various paradigms. Even the old industry is no longer the same, since deregulation has introduced competition in the supply business.

Electric Power Industry as It Has Been and Its Transition

A typical schematic for an electric power system as it has been is shown in Figure 5. Contemporary systems are generally characterized as having very large power plants, often distant from the load centers being served. Power delivery from these plants to the control centers is carried out by means of an EHV transmission system designed by utilities or groups of utilities within each region. Moreover, the regional grids are interconnected via even higher voltage transmission lines, so-called tie lines. The longer the transmission lines, the greater the power loss between transmission point and eventual delivery to customers. Up until very recently each region planned enough generation to serve its "native" load; the inter-regional (inter-state) level planned to supply native customers and share the burden of reliable service among the regions when any very large component fails. Both achieved reliability by anticipating likely failures or service outages equivalent to the largest component of their own systems.

Figure 5: Hybrid Paradigm



Users/ Load

Present-day systems operation relies on passive additional capacity. There is little attention to flexible decision making; a far more robust response that would be possible if available reserves could be used most effectively. To start with, present-day knowledge of various system parameters, whether equipment or wires, including the settings of protective relays (switches) used in different software, is quite unreliable. Because such data is recorded, database update and error become problems. The software tools in place (such as state estimation, load flow studies, contingency ranking methods and alike) are used as ancillary information for a system operator assumed to be intimately familiar with his/her own system. This has led to the industry-wide approach of preventive, rather than corrective systems operation. That is, the system is normally operated in a sufficiently conservative way so that if any of the single critical equipment outage occurs, customers are unaffected, at least for some reasonable time. Conservative assumptions and rigid forecasts are used in place of “real” information about the system.

At the EHV transmission level, this so-called N-1 contingency criterion calls for the system provider to have operating generation reserve equivalent to the largest power plant in the area, typically around 20% of total generation. Utilities have over time become more interconnected in order to share the burden of this reserve. Tie line dimensioning of the connections between different utilities has been done primarily with this in mind. However, these tie lines have not been designed for economical active transfers under normal conditions, but for emergency sharing. Yet over time, the divide between the economy transfers and reliability has become less pronounced. The utilities have cooperated in a bilateral way to schedule energy imports/exports in and out of their areas without affecting inter-regional reliability. For example, there is a pre-agreed upon limit on how much one could import from Canada into New England in order not to affect the reliable service in Pennsylvania. These limits are derived from studies generally done off-line for most likely outage scenarios; no on-line coordination exists for ensuring that as these schedules vary, the interconnection operates reliably.

Nor is there much coordination between the distribution systems and the EHV transmission grid. Historically, most failures have occurred at the distribution level; therefore meeting the (N-1) criteria at the EHV transmission level is by no means a guarantee that continuity of service will be as expected at the user’s level (Illic et al., 2000). This turns out to be a very critical disjuncture when it comes to incentives for small power sources at the distribution level, customer choice and the re-enforcement of the distribution grid as a survivable system.

Similarly, planning is done quite conservatively for assumed load growth. Most of the transmission and generation redundancy comes from the anticipated need to cope with critical equipment outages. These are very low probability, high impact events, which are hard to guard against using deterministic decision making, such as the (N-1) security criterion. Some argue that the industry has consequently opted for over-design under the old regulatory setup. (Others, pointing to California, would note the systematic under-design in the face of dramatic growth in demand.)

Current industry transition is characterized by at least four distinct new processes: 1) Energy supply has now been made competitive, at least at a wholesale level. 2) At least functional if not corporate unbundling of the transmission, distribution and generation businesses is under way, but far from complete. 3) In some states, retail competition at the customer level has already begun. And 4) wire companies are required to allow power delivery to all suppliers. Each of these processes creates new opportunities, multiple sources of business uncertainty – and calls for different technology development for its full exploitation. Meanwhile, residual regulation based on the older configuration endures to affect expectations and financial outcomes. The parallels to earlier deregulation of telecommunication is striking; once AT&T was required to allow others to attach equipment to its lines, substantial competition followed rapidly.

The electric energy industry is caught in a hybrid system, in more than one sense of the word. The system is partly regulated (transmission and distribution), partly competitive (supply). There is still much large-scale generation, although this is gradually being supplemented by smaller, more numerous power plants. Yet the technology (most particularly, an integrated IT management system) to exploit this potential is not yet in place. Some customers (industrial and commercial) are price responsive, while others (smaller industrial/commercial, residential) are not yet actively choosing services on price. While the physical processes of balancing supply and demand are continuous, at present various switching and decision-making signals are discrete time signals (switches in Figure 5). Today's system is exposed to an inconsistent mix of regulatory and technical constraints, and the regulatory constraints do not reflect either technical possibility or desirable technical development path.

System users are likely to begin to respond to market signals, when they have genuine choices at a retail level – much as with telecom services, or the airline industry. This process is likely to be facilitated through the Energy Service Providers (ESPs), Load Serving Entities (LSEs) and alike-load aggregators who might enter into different longer-term agreements with the users to provide them electricity at mutually agreeable terms. Yet the process of effective load aggregation, including creation of consumer syndicates, is vulnerable to the regulatory rules relating to wholesale electricity markets and transmission provision, particularly with respect to reliability-related risks. Who bears responsibility – and thus financial liability – for system reliability at any given point?

Today, for example, costs for massive system outages for weather or overload are borne by users, while the utility repairs its equipment. No account is taken for losses or damage to consumers – frozen pipes, for instance, or loss of foodstuffs in refrigerators. The price of electricity is generally high to assure extra capacity in generation and stronger transmission lines, in case some equipment fails or goes out of operation for scheduled maintenance[5]. The regulatory and market rules will have to be designed to carefully support unbundling of reliability-related risks under open access. Potentially, some customers could opt for a contractually determined level of outage risk – an hour per week or month – for a given price, or for a much higher (or lower) outage risk for another price. Most of the hedging instruments address regional transmission uncertainties (such as transmission congestion contracts or TCCs (Hogan, 1990), or flowgate-based approaches (Cazelet, 2000), etc.) and seek effectively to make the owner of these instruments risk-neutral: shifting the risk to the transmission provider and ultimately the load carrying entity. Yet the system as presently configured has not been structured for maximum survivability or dynamic robustness.

R&D Challenge for the Industry in Transition: Sustaining vs. Disruptive Technological and Regulatory Methods

Hardware: Major advances in various components in the recent past offer potential for new systems reconfiguration and dramatically improved robustness. Most notably, there has been significant progress in the development of a variety of near-cost effective new power sources, ranging from smaller scale combined cycle GAC turbines (CCGTs) through micro diesel engines, micro-turbines, wind power, solar power, and very small hydro, to mention just a few. Similarly, there has been significant movement toward technologies for consumer choice and price-responsive use of electricity, ranging from automatic meter readings (AMR), through one- and two-ways wireless communications between the users and providers of electricity. A variety of household automatic controllers have appeared to help implement price-elastic demand use (Black, 2000). Moreover, at both transmission and distribution levels, there have been major theoretical breakthroughs in the area of direct power flow control, ranging from electronically switched reactive devices through efficient DC transmission (Hingorani, 1995).

Some of these technologies are primarily sustaining in their intended impact, facilitating existing industry operating and planning methods. Others are more disruptive of the current practices and strategies. Thus widespread economical distributed generation could obsolete existing large-scale generating and transmission facilities. Generally, methods supporting an active customer response to the price of electricity over various time horizons as well as small scale distributed generation (negative, varying load) are likely to be disruptive to existing industry paradigms (and perhaps to existing participants).

Systems: One of the major R&D challenges for the electric power industry comes from the system-wide interactions of various components, at various levels of hierarchies and varying degrees of aggregation, through a variety of technical, regulatory and price feed-forward and feedback signals. The time horizons over which these signals feed the actual physical process range from seconds (primary feedback on generators, FACTS), through minutes (automatic generation and voltage feedback schemes at each control area level). Their form ranges further, including open-loop (feed-forward signal) scheduling

[5] Rolling blackouts in California and soaring wholesale energy costs on the West Coast in early 2001

for the anticipated system level demand so that technical constraints are not violated (constrained economic dispatch, optimal power flow, unit commitment). Various much slower planning and system design approaches to facilitate the long-term load growth trends have been typical in the existing industry.

These feedback and feed-forward signals are designed in today's industry keeping present-day economics in mind. However, actual price feedback is not a precise signal, although contemporary planning approaches often assume it is. Instead, the price has been averaged over all customers within each utility, both temporally and spatially. Potential consumer choice creates potential for differentiating prices. Similarly, the regulatory signal is very straightforward and parametric, reflected only through the rate at which return is ensured, yet such a metric ignores quality of service as well as potential differentiation.

Actual progress in systems research has been much harder, slower to show results, and less focussed in comparison to the progress in research and new technologies for individual component designs, despite much effort over the past three decades. Systems research literally started following the power grid blackouts in the Northeastern U.S. in the 1960's and 1970's, and accelerated whenever this type of problem re-occurred, as most recently in California.

The power systems research community has done much detailed system modeling and analysis for short-term operations, assuming coordinated (centralized) decision-making. Models range from methods for stationary analysis, through understanding system dynamics under small perturbations and, to a lesser extent, transient dynamics in response to large equipment outages. Decision making tools for facilitating system operation in near real-time range from state estimators, through static deterministic scheduling of generation, to minimizing operating costs for the estimated demand, and so on.

Given the complexity of large-scale power systems dynamics, most of the approaches for operating under large equipment outages have been based on off-line scenario analyses of one kind or the other (Ilic & Zaborszky, 2000). This area remains heavy in the theoretical challenges seen in any complex dynamical systems, as typical models are high order Differential Algebraic Equations (DAEs) rich in phenomena hard to simulate in an on-line environment. Nevertheless, progress has been made toward so-called dynamic security assessment, which would mean near on-line stability analysis as operating conditions change, by exploiting unique structural properties of power systems dynamics. Much less work has been done toward systematic control design methods for individual components, utility or interconnection levels (Ilic & Zaborszky. 2000.

The situation is much worse when it comes to modeling, analysis and decision-making for planning under uncertainties. Typically, tools are entirely static; very few, close to no, effective stochastic methods exist for dynamic decision making to optimize long-term actions, such as investments into generation or transmission capacity, in response unforeseeable uncertainties. Yet clearly such dynamic modeling capability is increasingly needed, because long-term commitments must necessarily be taken in the face of

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underline the issues, as does the consequent slowdown in the California economy, the world's sixth largest.

uncertainties. Particularly in an era characterized by rapid technological development, like our own, long-established technology configurations seem almost certain to be beset by substantial change.

The underlying theoretical problems are those of complex, large-scale dynamic systems, which exhibit many nonlinear phenomena under large equipment outages, including from chaos and bifurcations, etc (Ilic & Zaborszky, 2000). In contrast, the available decision-making tools are hierarchical and coordinated at various levels of the existing hierarchies. The technical ``standards'' (NERC 1997) supporting the system operations and planning are closely dependent on these underlying hierarchies. In short, the tools we have are compromises intended to approximate acceptable responses to mathematically intractable problems, even though we know that complex non-linear systems are not predictable by deterministic methods. Generally, the research efforts have been stronger in the analysis and less in the decision making/design aspects for the electric power industry.

As with the individual component hardware (at component level), systems related approaches and challenges can be identified. Some approaches aim to improve the performance of the system in order to sustain the industry architecture as it is, while other disruptive technologies would instead facilitate the transition of the industry into what it might become. As with componentry, disruptive systems approaches do not necessarily favor existing configurations, older technology or incumbent participants.

Software: IT tools play an increasing role in the present industry, but they need much improvement to make the system as a whole more efficient and flexible. There are some obvious values to IT tools in moving the industry from its current passive prevention perspective to corrective on-line decision-making. If done right, IT tools could ensure more robust operation with less generation and transmission reserve while maintaining the same or even higher levels of reliability. Such robustness in the face of perturbation is derived from real-time response to outages or demand surges, and by virtue of active creation of virtual networks (working around outages, or calling up additional supplies) on the fly.

Yet long before such a real-time emerges, IT tools can play an important role. Thinking in terms of decision making as a switching process within a hybrid system, switches will have to be very smart and act upon much on-line information to achieve their coordination. Research on this subject is very worthwhile even if one assumes that the industry will stay as it is. IT offers the promise of substituting information and response capability for capacity to achieve dynamic response to uncertainty. The ultimate benefit would be more efficiency obtained through clever IT tools. Customers could benefit from guarantees standards of technical performance and price differential choices. Such systems appear essential for genuine customer choice in a deregulated environment.

Regulation and Economics of the Electric Power Industry

By definition, the regulated power industry has until recently been based entirely on a guaranteed rate of return (ROR). In return, the utility has been obliged to serve all customers in its geographical area (Circle in Figure 5). The regulatory performance standards for checking whether the service has been provided accordingly are averaged over time and geographically, and generally relate to the allowable number of interruptions in the electricity service as seen by a customer. The price of electricity has, therefore, been a result of lumped costs encountered for operations, maintenance and capital investments; all averaged within any given utility. Utilities have managed to negotiate the actual rate of return, depreciation rates, and so on, and currently have non-uniform rates of return.

This type of regulation does not allow for differentiated quality of service, or any customer choice of quality. It is a macro approach in which all that utility does over the entire year and all of its customers get averaged out. More specifically, there are no temporal or special distinctions in regulatory rules for today's industry, although it is fairly straightforward to show the locational and temporal cost differences when meeting the same quality of service to different groups of customers. (This hiatus in regulations reflects older technology – where differentiation was difficult or impossible; see Figure 1.) A second critical aspect of guaranteed ROR regulation is its lack of effective incentives for the most adequate technologies, particularly in an environment of technological change. Transfer of new technology from the lab to commercial use has been slow, particularly in the area of systems software and control designs.

Some exceptions to these limitations are visible in special arrangements for larger users. Industrial users with special needs for reliability may pay lower prices depending on continuity of service, the amount of energy and the time of use agreed upon. Of course, larger users can often credibly threaten to self-generate, strengthening their bargaining power with energy providers. Emerging technology, particularly IT for active switching combined with distributed small-scale generation, suggests the potential for democratizing this adjusted bargaining power. However, it is apparent that new regulations, such as buy-back provisions, affect it.

R&D Challenges for the Emerging Industry:

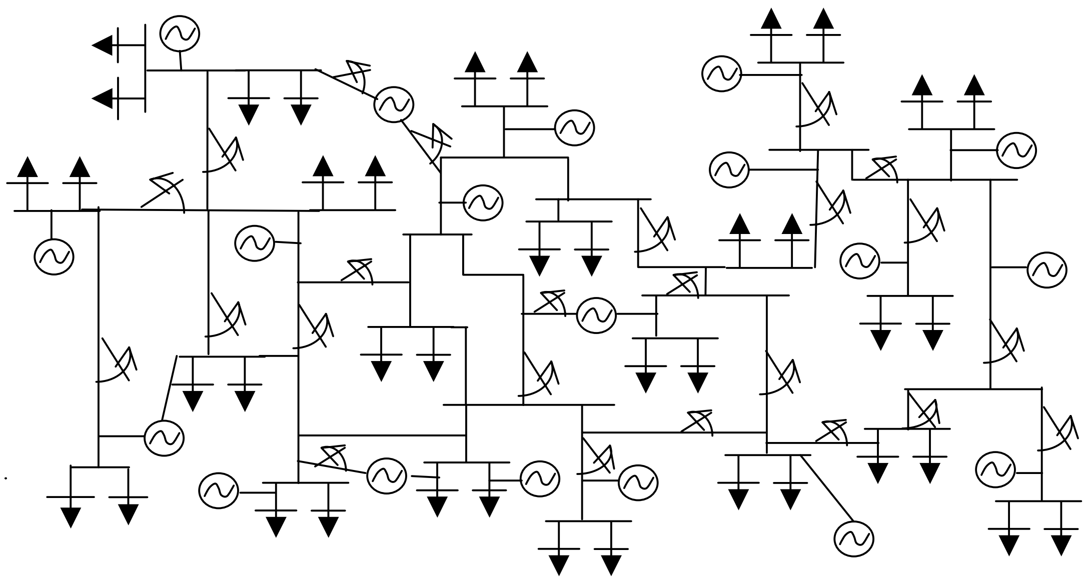
In sharp contrast to the present operating paradigm of the electric power industry described above, a likely end-state and a new paradigm for the electric power industry as it might be have begun to emerge. The new technologies shaping the very structure of the industry are here; many of these technologies are disruptive to the current practices. The most profound and disruptive change is likely to occur in moving from a few very large power plants to literally thousands of much smaller power sources, amounting to the same (or, more likely, greater) total capacity. These new smaller sources could be new commercial or domestic usage plants, in addition to existing private power plants supplying some larger industrial users. Buy-back power arrangements are likely to be routinely available for self-generating users, and will impact the remaining demand and technological needs.

Similarly, there are many new technologies in the making which would make even small users of electricity much more responsive to their actual needs; these range from long-available set-back thermostats, through automatically balanced demand and adjustable-speed motors, all supported by various metering and switching devices. Some users may desire to have a choice of more environmentally sustainable "green" power than currently provided by existing power plants. Others may prefer lower cost, or greater control over power availability, or the potential for lowering pay out by selling cheaply-generated solar or wind power back into the grid.

On the wire side, we can predict a huge number of often independently controlled switches, many of these being located closer to users. More localized storage of energy, particularly of locally-generated solar or wind power, also appears likely. Such storage will have the fundamental value of enabling the users to acquire energy at lower price, for use it when it is more expensive. (At present, storage is large, heavy and expensive, and generally used to assure uninterruptible power, as for critical users like hospitals or computer systems.) With more effective, lower cost devices, storage could become routine, and potentially very widely distributed. The old belief that electric power systems are without storage is likely to crumble soon.

IT has clear potential for changing use patterns (when everyone is away, use less power) as well as for changing the locus of generation, as noted above. IT can, in addition, promote changing work and residence patterns toward broader distribution. Telecommuting, including very long distance telecommuting from remote/rural locations, is one possibility. All these technologies, if adopted, would lead toward the new electric power industry paradigm depicted in Figure 6. The implications of such change in usage, generation, work and residence patterns on R&D needs are huge.

Figure 6: The Industry of the Future



On-going Challenges: Possibly the biggest technological challenge facing the industry is actual implementation of supply/demand entities based on homeostatic control. Such implementation would be decentralized at least to the level of coalitions of users or electricity providers. Systemic formation of sufficiently adaptive coalitions for customer choice, portfolios of distributed generation to sell electricity, and mini grids within the existing interconnected system to serve groups of customers requires research to establish clear objectives for these entities and for their optimization. The optimization criteria of interest are typically long-term benefits to customer coalitions, long-term profits for the portfolios of producers of electricity, and profits for the designers of mini grids. Other criteria may also be desirable – such as system robustness.

In addition, manufacturers will have to develop adequate hardware to support flexible response of these coalitions to changes in operating conditions as well as to electricity prices, such as automatic meter reading, or to changes in fuel prices (which would shift the prices offered by different providers). Internet links with embedded software are likely, but carry with them the need for hacker-resistance, anti-virus and worm programs and the like. Switching at various locations in any such system will again utilize embedded IT for simplicity, in comparison to the existing switching in today's power system architecture. Embedded IT switching creates also results in a highly re-configurable network architecture. The higher number of (automated) decision-makers, the simpler switching logic is likely to become. Consequently, involved control, such as sliding mode control, is likely to be replaced with a swarm-type distributed intelligence, embodied in various simple decision-makers. Swarm decision-makers adopt over time by learning by means of a distributed or hybrid Internet.

Reliability in the new industry configuration becomes a differentiable factor, non-uniform and provided in response to the specific demands of individual users for a particular quality of service. Its management is effectively based on contractual agreements among the affected parties. This is fundamentally different paradigm from the paradigm under which the interconnection was built in response to the need to share large impact of equipment failures. In the new architecture with many small participants, the reserve needed in case any single piece of equipment fails, will be drastically reduced. Possibly the hardest technological implementation will be the last resort implementation by the remnants of today's utilities, for those who for one reason or the other do not have a chosen provider. This problem is very difficult because the entire interconnection must be operated as one despite various uncertainties created by network users who only use the network for backup service when their contracts are not met. This generally creates large disturbance to planning and operations of the interconnection. Differential reliability offers a pricing mechanism to allocate reliability, charge for perturbations created by unusual demand, and call on surge capacity to maintain system integrity.

R&D Challenges for Regulatory Solutions:

In order to implement differentiated reliability service many regulatory questions must be resolved. Some believe that electricity should remain a basic public good to which all are entitled, independent of their ability to pay. If certain level of socially acceptable service is to be provided, it is necessary to establish regulatory/pricing rules to enable this under competitive power production. Others prefer an end-state in which the entire industry rests on simple, value-based competitive incentives, possibly with very little regulation (and perhaps none in pricing).

Systemic regulatory and pricing mechanisms for minimizing problems during the transitional from current industry practices to whatever end-state is envisioned, create more major R&D challenges. These problems are further emphasized by the regulatory asymmetries between competitive supply and demand, and what has long been seen as a natural monopoly, the transmission industry. The wire business is characterized by lumpiness in investments, very long depreciation time, as well as both economies of scale and economies of scope. Temporal and geographical aspects of power delivery also make delivery pricing quite complex. Since the existing infrastructure is designed and operated according to " best effort," rather than guaranteed performance outcomes, it is highly unlikely that guaranteed reliability can be provided to all for quite some time to come. Systematic R&D is needed on performance–based regulation for socially acceptable service reliability and its valuation, under conditions of pronounced temporal and geographical differences in products. How, in such a system, should regulations be crafted to assure reliable service?

Decision making uncertainty -- and robustness-reliability risks under uncertainty – must be reflected in regulatory arrangements. Further, to be effective for the future, regulations must provide incentives for ongoing technology development and transfer into use. Supply side, wire and user-side technology, feedback and feedforward technology, and further IT development must all be encouraged to facilitate system robustness. Three types of uncertainty are involved:

- Long-term load growth trend uncertainty;
- Long-term substitution potential, which results from actors' independent discoveries and actions (e.g., independent decisions to add self-generation capacity affects the need for transmission lines);
- Contingencies and equipment status on a moment-by-moment basis.

Each requires a somewhat different regulatory perspective. How will "the system" know of user needs, growth potential and projected capacity? The old regulatory system centralized decisions in regional monopoly providers. A completely decentralized system, with no coordination, appears to be in place at present, if the California power crisis is any indication.

The Role of IT in the New Industry:

The technological, regulatory and pricing aspects of a new electric power are further complicated by the opportunities created through IT. A future decentralized system might provide coordination through information requirements – any device attached to the power grid might be required to "announce" itself and its characteristics (how much power it uses or might generate, for example). In any event, regulations will have to assure that the necessary information is provided as needed to coordinate the system, preferably in some automated, non-intrusive way.

Markets, users and groups can be re-aggregated and reconfigured "virtually," via IT, depending on (for example) patterns of use or demand, quality required (defined in terms of characteristics such as reliability, non- interruptibility, and amount of power, among others). Given multiple sources for power and multiple markets (re-configurable on the fly, at least potentially), a viable new industry structure might center on brokers who "wheel and deal," owning no assets for generation or transmission themselves, but servicing the IT/reconfiguration demand[6]. Such brokers are already present in the industry under transition, but often with poorly defined market rules, particularly in relation to the reliability risks.

IT also affects the electric power system's dynamic characteristics in another way. Information is not perfect (and externalities like weather intervene); information asymmetries are worth money. Pervasive IT creates the potential for profiting from such asymmetries. Simultaneously, however, the Internet and pervasive computer penetration raise the potential for a much more equal balance of information between users and energy vendors at all level, including both industry users and consumers. The ability to use information is not homogeneous, however, and the ability to change or reconfigure in response to demand shifts and opportunities is also worth money. Inter-temporal information and need asymmetries translate to non-coincidental peaks, thus can use information as a substitute for capacity, convenience, demand and time.

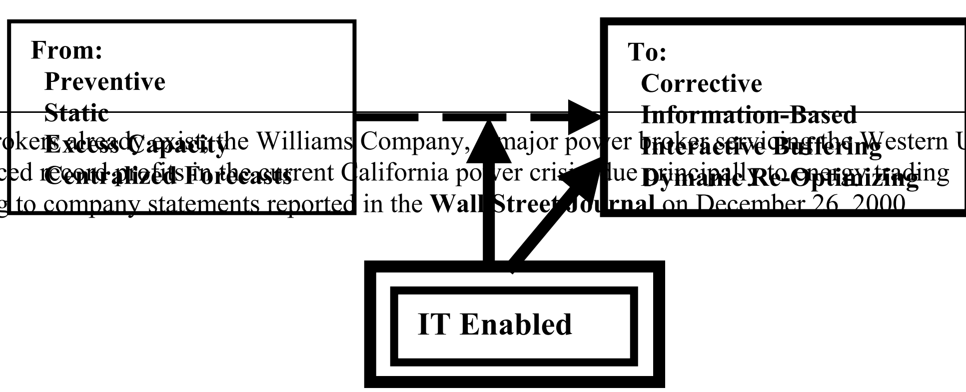
IT's impact on the structure of the system as a whole, no less than on possible configurations of the system that may emerge over time, can scarcely be overstated. Indeed, real-time information offers the single most powerful response to systemic "wickedness:" response capability can respond to what **is**, at any given moment, rather than seeking to forecast a complex, non-linear system. By operating on fact and rapidly readjusting, rather than on forecasts which must surely be wrong, dynamic IT-enabled system response will surely diminish the perception of wickedness. But how?

Transcending ``Wickedness'' -- A Speculative View

The R&D challenges outlined above, both for the industry in transition and for an emergent industry as it might be, do not instantly offer us a well-defined approach. As we have suggested in Figures 3, 4 and 6 in particular, successful solutions toward dealing with the wicked problems in hand must recognize the interdependence of technological, regulatory and pricing elements to any eventual solutions, if overall industry's performance is to approach socially optimal performance – or even economically sustainable performance. Also, under competition, it is important to shape these incentives through signals from the environment. Signals must come from other parts of the context, including regulators, customers, suppliers, and society at large, so that the overall performance is best for the society as a whole. This is a very difficult task. Only systemic R&D can generate the fuller understanding of interdependencies and designs, the technical, regulatory and pricing signals needed, and the system-level modeling to help identify where major payoff may reside. It is already quite obvious from difficult transitional experiences that lack of such a ``full picture'' is disruptive to a smooth transition from the current practices to an effectively deregulated industry.

A key element in transcending "wickedness" is comprehending the character of the shift in paradigm. It is not simple. In sharp distinction to analytical models and approaches, the needed new paradigm is synthetic. Figure 7 highlights the nature of the change– from a predominantly static perspective, in which excess capacity and centralized planning seek to forecast needs; to a predominantly dynamic perspective, in which information serves effective interaction and buffering in dynamic, real-time re-optimization of the system, moment by moment.

Figure 7: System Paradigm Change



[6] Such brokers already exist: the Williams Company, a major power broker servicing the Western U.S., has experienced record profits in the current California power crisis due principally to energy trading according to company statements reported in the **Wall Street Journal** on December 26, 2000.

Both the transition and the end-state of a dynamic system are IT-enabled, as Figure 8 suggests. There will be system-level challenges whether or not major developments occur in components or regulations. IT will be critical even in such a case. However, it is equally clear that without substantial further development in IT penetration and integration at the system level, neither incumbent industry participants nor the system as a whole will achieve the flexibility and survivability needed for the future. Figure 8 highlights the desired direction of system evolution: towards greater dynamism, flexibility and responsiveness, along with greater robustness and capability for "self-healing" from various perturbations.

Competition brings changed incentives – some negative, some positive, from incumbents' points of view. Individual actors may find profit in R&D servicing their specific, individual needs. Yet address to the system itself must not be ignored: this is the major role for government R&D, to assure those dynamic signals are generated to guide system-level benefits. Laying out the desiderata – dynamism, flexibility, information-enabled system robustness and survivability – the need is evident.

The barriers to progress are many. To start with, current US academic structure is not well positioned to support aggressive progress on the R&D agenda outlined above. Primarily because of strict divisions between engineering, policy, and business and economics research, much academic research is simply too narrow in scope. The R&D needed here involves the active collaboration of experts in these multiple areas. Only interdisciplinary perspectives can provide the progress essential for overcoming the current status quo and transcending the "wickedness" inherent in disruptive developments that cross disciplinary boundaries.

Beyond these disciplinary boundaries, it is essential to comprehend the pervasive impact of IT in marrying technology to strategic potential. New businesses, as well as seismic shifts in existing industry standings, are likely as a result of information technology applications. Certainly the changing environment, technology and IT alone pose dramatic changes in information asymmetries long assumed immutable. Thus change will also occur in the power and dominance that formerly flowed from old asymmetries but are now called into question. Surely, too, this will call forth changes in the potentials and externalities with which managers must contend. Above all, here too it should be evident that not only are the pieces evolving – components, elements, rivals, and regulation – but also the system itself in its most fundamental dimensions will be changed. Smart switches, broadly distributed on the wire side and at the point of use, create feedback potential as a function of their embedded IT. IT thus serves as a connection mechanism to enable a dynamic adaptive system.

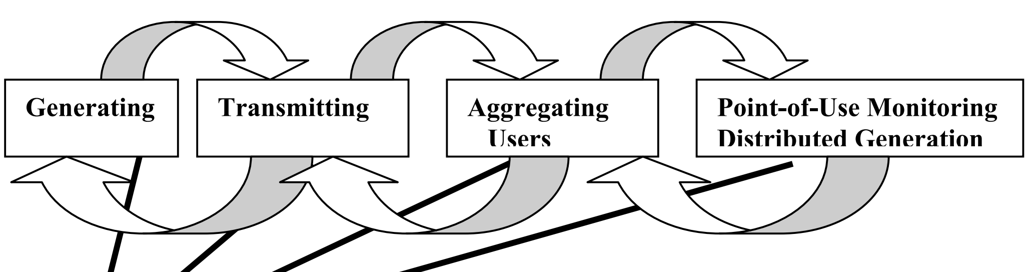
Contemporary IT tools require substantial development before they will be adequate to these needs, however. Financial analysis of the risks to system reliability require a far more dynamic understanding of how and where failures occur, and of how alternative configurations affect reliability at multiple levels, and in different aggregates. The information needed by users (and thus by their presumably automated decision-makers) will include dynamic price adjustments to reflect moment-by-moment power availability – so that equipment outages instantly raise prices to alert users. Dynamic, performance-based information is needed to recognize and facilitate the role of price spikes, whether instantaneous, as with equipment outages; or more enduring, as with fuel-cost adjustments. IT can create liquid forward markets, to support appropriate investment decisions. In the medium term, demand incentives to encourage use response (turning on self-generating capacity or improvements in efficiency of use) are also likely to be IT driven.

Yet at present, performance information for power providers is minimal and not provided in a form useful for consumers. Information to fuel forward markets or medium term demand responses is equally lacking, as is effective information on trends. Both hardware and software developments are needed to support these information challenges. All trend toward system flexibility, dynamism and robustness.

The biggest challenge is system reconfiguration. What kind of reconfiguration? The required new organization of the system will be a function of technology, especially IT, and of regulations, particularly those that foster new technologies (for generation, for transmission, for switching, monitoring or virtual aggregation. Because each of these factors drives profit dollars, each will presumably drive research dollars as well. But research on the system per se, and its best organization in light of accelerating IT capabilities, will very likely remain a government responsibility, for at present the system as a whole is "nobody's business," so no single actor takes responsibility, and no incentives to do so are in view.

The potential IT offers is nothing less than a new paradigm for robustness: at the system level, based upon dynamic optimization in real-time, and using active information exchange (on price, demand, and capacity) between multiple levels to substitute for the passive and centralized control of the past. Total system reliability must result despite changing virtual aggregates, mini-grids and even neighborhood associations for power generation, down to individual-level decisions to acquire generating capability (for example). Dynamic interconnections and system-wide links can potentially provide substantial equifinality across this range by creating potential additional generating capacity, available on a contract basis. From an information-based perspective, such equifinality – substituting aggregates of many smaller users' local generating capability to buffer the system from surges – suggests that information (about capacity and as a tool for calling it up) supports economies of scope in an electric power system. Both additional capacity and temporal and geographical distribution are dimensions of system scope.

Figure 8: IT's Role in the Emerging Dynamic Energy System:



NSF: Whose Agenda for Research?

Numerous NSF Directorates have a potential stake in the research agenda outlined here, including **CISE, MPS, SBE and ENG Directorates.** It is essential for NSF to take the lead in creating the environment for interdisciplinary research among these directorates in order to facilitate progress of the electric power industry from where it is to where it must go. The R&D agenda items described here are challenging; they require major effort and funding to focus attention on the critical problems. Yet the benefits to NSF's mandates are significant. In addition to being a real-life test bed for many new concepts underlying complex dynamical systems, the potential impact on societal well being from such an R&D agenda is huge. The benefits range from environmental to economic to social: a more efficient power system will be less costly and have less environmental impact. Energy is so essential to economic activity and development that improvements in the robustness and survivability of our national power system will provide critical improvements in national economic security.

While different entities in the evolving industries may develop tools to benefit their own businesses, the game here is larger. The complex interplay of the technological, regulatory and economic signals can only lead to the improved system-wide efficiency and ultimate benefits to customers and the public at large -- provided the wicked problem is understood, modeled and addressed with adequate tools for analysis, synthesis, policy and system design.

Public Benefit issues

The national electric energy system crosses many regulatory boundaries, so that policies affecting it are made in numerous different government agencies. An effective framework for analysis can facilitate coordination among these agencies. Agency coordination is but one aspect of a larger role for science, in advising policy makers in their regulatory (and de-regulatory) efforts. NSF is the logical agency to foster such a framework, and to provide leadership and advice on policy issues.

- Political solutions should be informed by our best knowledge, not merely our PAST knowledge

- Policy makers need to know how deregulation changes the play: market power, alternative perspectives, alliances and technology effects are all relevant.
- Evolving technology and economics create a new “wicked” environment for Government regulators, too.
- Electricity is central to economy, until and unless it is replaced by an alternative (of which there is no present sign).
- The “knowledge economy” in which economic growth is a function of information, demands adequate amounts of reliable power – and the current system’s failures here demand response.
- The electric energy industry can serve as a potential model for others, if deregulation is handled appropriately.

Conclusions:

The electric power grid at any moment is the outcome of complex interactions among existing technology, perceived needs and possibilities, regulations, and institutional structures. Any given configuration reflects best efforts and compromises among different interests, so that at best the grid is a function of assumptions, technology, and regulations of a moment. Over time, any configuration becomes less well suited to the demands placed on it as technology, needs and possibilities change. Both the in-place technical system and the institutional structure of regulations and economic profit endure, changing only slowly. Deregulation promises huge changes, yet the old framework of “what was” offers insufficient guidance for decisions. Decision makers -- in business, government, and environment – as well as consumers need a new framework for understanding what is possible, and for evaluating potentials.

The restructuring of the electric power industry creates change, and change new, strong incentives to form new companies, to create alternatives business models, and to exploit opportunities hitherto unseen. These incentives could be either good or bad; they can encourage more efficient technology, or create opportunities for huge individual profits along with exclusion or exploitation of others. Like deregulation in the airline industry, deregulating electric energy can give rise to unanticipated problems, unless a broad systems view is taken. Proactive R&D can help to deal with these problems prior to their occurrence.

The “wicked problems” described here for the Electric Energy industry are real, and arise out of the inadequacy of older paradigms-in-use that have long dominated industry thinking. Our description addresses them from the perspective of this industry. However, the phenomenon of wicked problems is far more general []. For example, it can be said today that there is no genuine long-term storage for electrical power. A broader perspective suggests that there may merely have been insufficient incentives to the present to develop appropriate technology. At present, both the incentives and the technical state of the art are rapidly changing: a recent issue of Wired magazine described a business actively developing flywheel technology for energy storage for various use contexts, including hybrid automobiles and private homes. Moreover, the notion that electric energy is uniquely ephemeral is not persuasive; the airline industry's seats on any given flight are capacity that exists and is available to sell ONLY until the plane takes off.

The case for research that is interdisciplinary has been made here because the issues comprising the "wicked problem" faced by the electric energy industry are themselves multidisciplinary. These issues simultaneously involve IT, organizational and managerial issues, social and political concerns, and of course industrial economics, no less than a broad array of relevant technologies (some of which have long been dismissed as irrelevant). Above all, the inter-related complex of technology, economics and finance, and regulatory policies is multidisciplinary. We argue that any uni-dimensional approach is necessarily partial, and thereby limited in its insight and potentially misleading or even dangerous in its advice.

Given this, multidisciplinary R&D is needed, which promotes innovations in institutional forms and also promotes competitive forces. NSF could play critical role in taking the lead by aggressively nurturing such R&D. Other agencies, the Department of Energy in particular, ought to be involved in creating an inter-agency agenda for forward looking R&D directed at the evolving electric power industry. Moreover, the regulatory bodies, both state and federal, can support the innovation through meaningful regulatory designs. The potential benefits from such R&D are higher than ever before in the past. On the other hand, if the wicked problems of the electric power industry are not addressed, society is likely to see major problems in the area of electricity use.

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