Diversity Article

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The Intellectual Challenge

Behind Bundling Diverse Energy Systems of the Future

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In just a few decades there will be insufficient energy to meet increased worldwide demand. The obvious solutions include scavenging remaining resources while seeking new energy sources. Determining the true potential and effects of new and unknown energy resources will take some time. Moreover, use of existing resources and discovery of new ones bring high economic and environmental costs that are often difficult to fully assess. Furthermore, a significant increase in these costs may have far-reaching economic and societal consequences.

I suggest that it is wrong to assume that more energy will be accessible without determining how to most effectively use what is already available in a sustainable fashion. While this view is not new, and has been expressed by numerous individuals and organizations, it has been given relatively little attention. Even top institutions fail to recognize that making the most out of what's available is a huge technological and regulatory policy problem.

Arriving at the best solution is equally as challenging as discovering new energy sources. A better solution is to maximize what is available by approaching the problem of providing and pricing energy with a full consideration and understanding of the contextually, spatially, and temporally complex interdependencies among energy production, delivery, and consumption.

The answers are sensitive to existing industry structures; the most effective are those offering strong economic and regulatory incentives for the most effective solutions. The same problem becomes harder by order of magnitude when viewed at the international level.

Novel solutions are needed to catalyze defining and meeting energy users' needs. I suggest that there are currently no ready-to-use engineering methodologies for providing much-needed solutions of predictable performance for such complex systems.

The basic challenge begins with the strong distinctions in current approaches to characterizing energy problems among:

1. Availability and type of energy resources
2. Customer demand
3. Delivery challenges

Various research and educational activities are generally clustered around the themes of energy availability and delivery. Customer demand, despite its fundamental relevance, is hardly ever posed as the central problem. Moreover, to date, the interdependencies among the aforementioned challenges have not been formally studied anywhere. In addition, interdependencies within each category are studied only up to a certain degree, primarily in the area of energy resources. If this trend continues, many opportunities will be missed as technologies evolve in all three areas.

Such a piecemeal approach to providing energy cannot lead to the most effective technological or economic policy solutions. Many predictions of energy needs and associated economic impact suffer from two problems:

1. Not capturing the level of detail necessary to obtain even semi-realistic conclusions
2. Making strong, implied assumptions about aspects of the problem that have not been modeled

The solutions are often seemingly too complex and not easy to communicate. In particular, the question of modeling "externalities" quickly becomes an overwhelming issue. Initially, everything affects everything else. For example, production affects delivery, which in turn, affects demand, environment, and pricing. Therefore, if one studies production while assuming delivery to be an externality, much can be missed.

There are several examples of various sub-problems and the role of what one may be tempted to declare an externality.

I suggest that one must begin with posing the basic problem of energy systems of the future. Solving this problem requires that we approach it with an eye toward addressing previously unexplored energy alternatives. The main goal is to steer the United States away from over-reliance on *more* energy resources toward a more systematic use of overall existing energy resources. This requires significant advances in both developing technological solutions and in designing systematic signals for value-based incentives across various and diverse subsets of the energy industry.

My limited experience working in the electric power industry and electricity markets clearly indicates that possible savings could run in trillions of dollars per year in the United States. Estimates of environmental impact are harder to assess, but are also likely to be huge.

Basic Problems of Diverse Energy Systems of the Future
Given today's diverse energy systems, and their wide range of customers and delivery methods, I suggest we view the problem of Energy Systems Design (EnSD)/Energy Systems Operations (EnSO) as a **complex network system problem** in which objectives are to:

- Meet desired technical, economic, and regulatory constraints in a sustainable way.
- Catalyze the dynamic evolution of existing systems as these attributes change in order to manage demand growth uncertainties accordingly.

This very broad problem formulation requires extremely carefully posed modeling to capture critical interdependencies and attributes. Once this is conceptualized, formal methods for dynamic model aggregation (spatial, temporal, and contextual) need to be introduced to facilitate quantifiable decision making and, ultimately, partial automation.

The temporal, spatial, and contextual model simplifications must be carried out with full understanding of quantifiable inaccuracies and loss of initial attributes, as reduced-order models are derived and used. For example, given the very complex starting model, different model classes must be developed for assessing spatial effects of delivery on the needed new energy resources, more so than classes of models for assessing effects of environmental constraints on the need for new resources.

Different classes of models will be needed for inducing efficiencies from managing temporal interdependencies than for other purposes. Similarly, computer-aided tools for decision making will require the right model classes to meet predictable performance requirements.

Following is a brief overview of some major intellectual challenges concerning energy resources, delivery and demand sub-problems, and managing their interdependencies.

Energy Resources
The sub-problem of energy resources has been extensively studied. Many believe it is the major challenge for meeting future energy needs. Studies have focused primarily on future types of energy sources, and to a lesser extent on their spatial and temporal characteristics.

We are entering a cycle of seeking energy sources from outer space and creating acceptable forms of nuclear energy. In addition, novel ideas such as hydrogen and micro-, nano- and bio-energy resources are beginning to be considered. Matching these largely unknown resources with the needs of millions of energy consumers dispersed geographically and across different time zones will determine these new resources' ultimate impact. Therefore a fundamental understanding is needed.

A major intellectual challenge concerns shifting from economies of scale to economies of scope. Economies of scope come from the ability to meet more than one objective with the same resource. In energy systems with little or overly expensive storage, economies of scope are measurable in terms of efficiency and sustainability that can be gained by the right temporal and spatial aggregation of available resources.

The best possible use of resources will require optimal temporal use given various technical constraints. For instance, a nuclear power plant is “natural” for serving a large average load. A smaller coal plant serves medium-sized loads well. A large number of many flexible power plants could serve highly varying loads. Production of some attractive energy sources, such as wind and solar cannot be controlled. In order to match use of such energy with the customer needs some form of storage is needed.

However, planning and operations for a combined mixture of resources remains a serious challenge. This has become more pronounced in light of revisiting nuclear power issues, as well as in attempting to develop the futuristic hydrogen economy. The most immediate challenge is to understand the role of natural gas, including LNG, and the real potential of small-scale renewable energy resources, such as wind, solar, geothermal, and tidal power.

The question of scaling is also critical. Is it possible to simply see the ideal world as one in which many magical technology micro-/nano-resources replace huge energy resources, if they were available? For example, how many tiny energy resources would be needed in order to avoid building one new conventional combustion power plant? What would be their cumulative environmental impact and how adaptable would they be to users’ needs?

The technological problem of cost-effective energy storage remains a major
unsolved problem, too. It is striking to realize that we still do not have long-lasting laptop batteries. Given this simple observation, I believe that a huge gap exists between what may be the dream for future storage technologies and what is practical and achievable now.

Storage economics have not been carefully studied and clarified either. It may be that with doing very little of something else on the system, such as demand-side response or using natural storage such as hydro, the need for solving large-scale storage problems would be eliminated altogether.

A significant problem of regulatory economics concerns incentives for efficient energy production. It is much more common to pay only for energy used and “piggy-back” on others for economic effects of temporal and spatial differentiation. Some of these problems are beginning to be posed as game theoretic problems, but it has been recognized that they pose serious intellectual challenges to current knowledge in game theory because they don’t lend themselves to the assumptions typically made.

The final challenge involves managing risks associated with long-term investments using regulatory and/or market-based mechanisms. The non-uniformity of market signals for various forms of energy sources is puzzling: Electricity restructuring has been dominated by strictly short-term market design, while the fuel markets tend to have longer-term forward markets as well. It is important to research what may be an adequate combination of diverse energy markets and for what purposes.

Customer Energy Needs

Customers' energy needs are a critical problem because understanding demand greatly determines what needs to be done. Often, a highly accurate forecast of long-term demand does not address, let alone solve, the problem at the utility, regional, or state levels.

There is a much better understanding of the characteristics of customer classes, but these are not straightforward enough to map into spatial, temporal, and energy systems characteristics. For example, while one knows in considerable detail the characteristics of individual air-conditioners, or even light bulbs, the characteristics of households they are in are not known after aggregating all appliances within the household. Further aggregation to the medium/high voltage level of utilities (such as cities, counties) leads to even poorer characterization. Daniel McFadden's early work clearly provides much food for thought in this area, especially the characterization of price-responsive loads.

Next comes the rich problem of customers' roles in balancing energy supply and demand. The work of Fred Schweppe put forward the vision of homeostatic control, which basically says that energy users adjust locally, and that this leads to a fully adjusted system as a whole. These were the first ideas signaling the major role in customers' active adjustments to energy shortages and prices. The time has come now for working out the details of homeostatic control, since automation and its cost make this a truly viable concept. This represents a huge opportunity for using distributed sensors and controls.

The question of most effective load aggregation as a function of attributes desired is completely open. It is not clear what measurements and communications are needed for which groups of customers in order to adequately manage inter-temporal dependencies, average shortages, and peak demand shortages. This design has direct implications on the risk and cost of not being served and on how flexibly customers can respond to overall changes in energy availability.

The overarching intellectual theme underlying demand management of the future is that one could use much filtering, learning, and the like to model and identify customer characteristics, then design ways to manage them to meet customers' specifications. Depending on how the aggregation is calculated, customers could be defined as either large individual loads with very specific power quality needs or groups of customers served by an entire utility. It could also include something in between, like a town served by a newly formed aggregator.

Without characterizing demand carefully, all other energy systems problems become meaningless. For example, recently Professor Ernie Moniz discussed a major problem – supplying energy to future “gigacities." This is a huge challenge. The gigacities need to be characterized for their energy and utilities demand before a design of energy resources and delivery can become useful.

Demand management also has a unique role in balancing system-wide supply and demand because it is one of the least expensive storage technologies known. Much energy consumption can be adjusted to availability using techniques such as time-of-use and its more advanced versions, such as real-time price response.

Energy Delivery Problem
Only recently has it become clear that there are many diverse, and far-reaching issues in energy delivery. These were exacerbated by the strong tendency to build gas-fired power plants and by recent ideas for hydrogen super-grids. Gas-powered plants could be located either close to gas tanks, and/or placed far away, where plants would produce electric power and delivery would be via electric wires. Or, gas could be delivered to closer power plants via pipelines. Similarly, ideas have recently been put in place to transport energy via hydrogen, instead of electrical wires.

While these ideas are in their infancy, they raise the major issue of finding adequate ways to deliver energy. Moreover, when one begins to examine multiple delivery media, the question of storage becomes potentially useful.

In order to move forward with comprehensive solutions, it is critical to model a heterogeneous, diverse network comprising gas/electricity/coal networks and their interdependencies in delivering well-defined source-sink nodes within this network. The question concerning hydrogen cannot even begin to be posed outside the context of other delivery means.

The delivery problem lends itself to the entire set of questions formally studied in other complex networks, such as Internet, electric power grids, gas/fuel delivery systems and healthcare. These involve routing for congestion, temporal and spatial (only harder, because there are no cost-effective electric switches on the electric power lines); relations between backbone, and local (distribution networks); top-down, vs. bottom-up network management; and management and cost of uncertainties.

Also, there are more recent questions concerning regulatory support for incentives to evolve the delivery system into the system with well-defined quantifiable attributes.

Interdependencies among Energy Resources, Delivery, and Consumption
It is fairly straightforward to demonstrate that as far as the customer is concerned, there is little, if any difference in providing inexpensive energy from distant suppliers or expensive energy from local ones. For providers, however, there are different implications.

Similarly, the customer needing heat is largely indifferent to the various types of energy sources providing it, as long as the cost is the same. That is, unless s/he cares about other attributes beyond cost, such as sustainability, flexibility, etc.

There are many examples of these substitutes in an energy system of the future. As the system evolves into new architectures and needs to meet new objectives, the possible number of options is huge.

Studying energy system architectures and operational paradigms of the future requires systematic modeling, analysis, and decision making tools that could capture attributes of interest. Significant overall dynamic (energy) efficiency could be achieved by assessing the problem as a complex, diverse engineering-economic-social network system for which analytic and software tools can be developed to drive it toward well-understood attributes. Ultimately, the system becomes a closed system in which attributes evolve in response to system performance. Our current knowledge of engineering systems does not yet offer tools for adequately managing a diverse energy system.

My very rough estimate of the benefits based on equipping our engineering-economic-social system to perform according to evolving attributes (including sustainability) is 20% to 30% higher overall dynamic (energy—not electric only) efficiency than in the current system. This would drastically modify numbers projecting future energy needs based only on resource analysis.

The challenge and the opportunity for MIT's ESD and CMU's EPP is to light the way for other universities and the United States. This is no longer a problem of finding only a single magical hardware or software technology that will make everything else fall into place. It is, instead, a serious challenge of modeling diverse, heterogeneous network systems, characterized by temporal, spatial, and contextual variety, and developing a means for quantifying performance and designing/operating to accomplish this. It is a huge undertaking, and will have many serious consequences if not undertaken.

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