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The Competitive Electric Power Industry: Making Decisions in an Uncertain Environment

The competitive electric power industry is not evolving as hoped. Prices are high and changeable; supply is sometimes inadequate; buyers, sellers, and system operators have trouble planning for the future; and perhaps worst of all, nobody is looking out for the welfare of the power system as a whole. MIT experts led by Dr. Marija Ilić have performed a series of studies that should help. They have identified various industry participants, the roles they play, the markets through which they interact, and regulations that will ensure that their actions are fair and supportive of power system performance. By simulating participant behavior and the impacts on power system operation, the researchers have demonstrated that their proposed structure leads to a well-run, efficient, reliable power system and effective customer service. Practical techniques based on the researchers' methodologies

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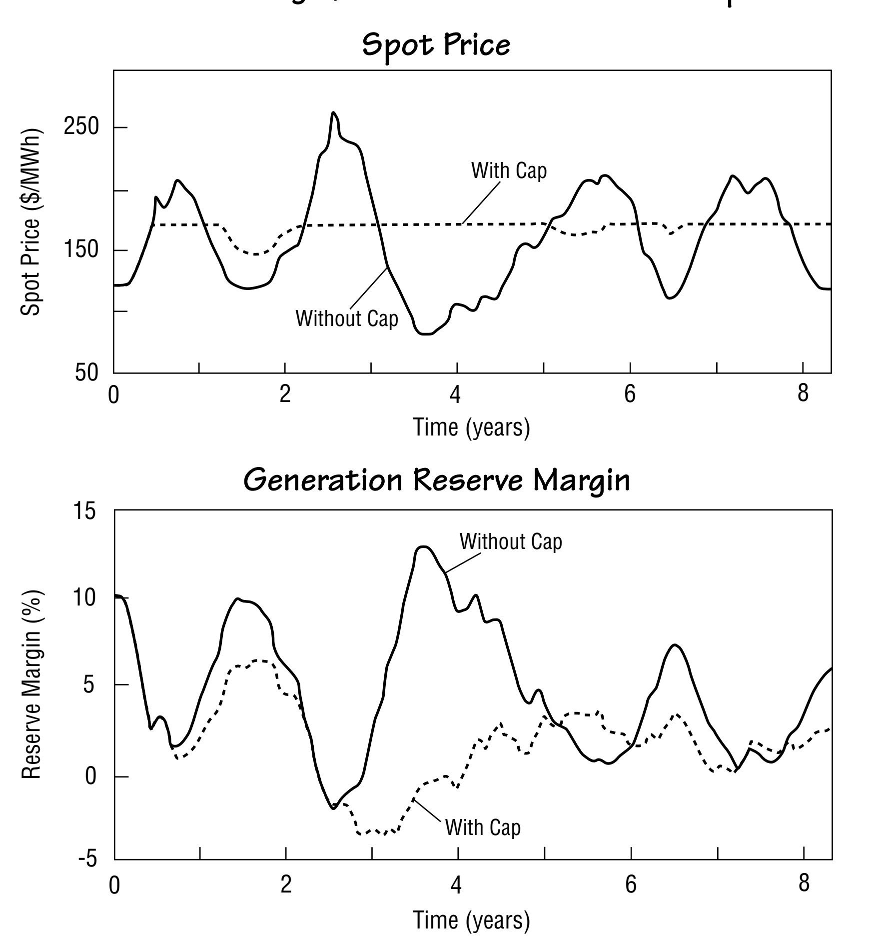


Relationship Between Spot Price and Generation Reserve Margin, With and Without Price Caps

MIT analyses examined the relationship between electricity prices on the spot market, generators' decisions to invest in new generating capacity, and reserve margins—the extra generating capacity available on a power system after demand is met. The solid curves show the outcome when spot prices are unregulated. Price spikes that appear in the top figure lead to the increases in reserve margins that appear in the bottom figure. When spot prices are capped (the dashed curves), as they were in California, the price spikes disappear, but so do the large increases in reserve margins. The artificially low prices do not stimulate investment, so shortages persist and prices remain relatively high—at times, higher than the unregulated price. **(See article on page 4.)**

could change the look of the power industry. Buyers and sellers of electricity and transmission services could use new techniques to project spot electricity prices and to quantify the potential benefits and risks associated with long-term contracts. System operators could disseminate information on prices and system conditions via the Internet so all participants could know what their options are. Companies could identify investments in new generation and transmission equipment that would be profitable and also beneficial to system operation. Customers might choose less-reliable service at a lower price, permitting system operators to curtail service when demand peaks and thus reduce the idle generating capacity they maintain. Regulators could use new methods to measure the potential for companies to drive up prices during shortages—a potential that the researchers' analyses show is far greater than traditional measures suggest. Regulators could then calculate price caps low enough to protect consumers but high enough to encourage needed investment. New profit-making organizations could expedite critical transfers of electricity from one region to another. Finally, "mini-grids" could arise—self-sufficient, stand-alone systems of interconnected small generating units that would operate with high reliability, deliver different levels of service to individual consumers, and provide a niche market for demonstrating small, flexible, environmentally friendly technologies that are undervalued on traditional power systems.

Buying and Selling Electricity: Getting the Best Deal

One of the most intriguing aspects of the new competitive industry is how electricity is bought and sold. Many deals between electricity generators—remnants of the traditional utilities and new profit-making companies—and their potential customers take place in a centralized "spot" market. Generators and customers submit bids specifying how much they will sell or buy at various price levels at a given hour on the following day. (In most regions, demand is simply estimated; at present, individual consumers generally cannot or do not respond to price.) The system operator then informs generators whether they can run in a given time slot (the lowest-priced generators are chosen first) and how much electricity they should produce. The system operator also tells customers how much electricity they will receive and—after the transaction is completed—the price they must pay for the electricity generated plus transmission service.

The financial risk to all participants in the spot electricity market is enormous. One cannot buy electricity now and use it later because practical methods of storing electricity are not yet available. As a result, generators' incomes and customers' expenditures are constantly at the mercy of fluctuating spot market prices. However, participants can "hedge" their risk by buying long-term contracts on the "forward" market. The generator agrees to provide a certain amount of electricity at a set price at a defined time in the future, and the customer pays a fee to retain the right to exercise that deal when the time comes.

Generators and customers can thus lock in a deal for the future. But there is a new risk. How will the contracted price compare with the spot price that prevails when delivery time comes? If the contracted price (plus the fee) is lower than the spot price, the contract makes the customer better off and the generator worse off. If the spot price is lower than the contracted price, the opposite is true.

Graduate students Petter Skantze, Andrej Gubina, and Michael Wagner, supervised by Dr. Ilić, have developed techniques that will enable individual customers and generators to determine whether a proposed long-term contract is likely to be a good deal. Making that determination requires predicting electricity prices—a difficult task. Techniques are available for forecasting prices of most commodities. But those techniques do not suit electricity because it is not like most commodities. Gold or coal is easy to store; electricity is not. And for most commodities, tomorrow's prices bear some relationship to today's. In contrast, electricity prices are highly variable. The value of electricity varies with conditions on the power system, so a spike in demand or a plant outage can bring an abrupt change in price.

The MIT team has therefore developed a new method of forecasting the spot price of electricity for a given regional market. The price of a commodity is determined by the combined forces of supply and demand. Therefore, the researchers look at the behavior of electricity supply and demand independently and then combine the outcomes to infer price. They have developed a "physical" model that simulates the operation of an electric power system. To determine how supply and demand will move on the system, they use physical "drivers" that are more easily predicted or have been characterized by abundant historical data. Drivers for supply are prices of fuels (oil, coal, natural gas), rainfall (which affects hydro capacity), generation outages (unexpected and planned), and the availability of emissions rights contracts. Demand is driven by temperature (estimated using historical data) and economic growth (a long-term effect). Finally, the researchers draw on models of other regional power systems to track the impact of imports and exports on supply and demand, hence on price.

The supply and demand estimates generated by the physical model run a pricing model that forecasts electricity price over the short and long term. Any price spike that occurs can be traced to one of the physical drivers. As a result, the model can determine how quickly price will revert to "normal" levels—a critical factor in assessing the value of a long-term contract.

Armed with those price forecasts, generators and customers need to know what long-term contracts—prices, quantities, and dates for delivery—will give them the best financial outcome. That dilemma is standard fare for traders of options for stocks and commodities; techniques exist for valuing traded options. But again the researchers had to adapt the traditional financial techniques to suit the idiosyncrasies of electricity. Taken together, the pricing model and the options-based decisionmaking tool enable a market participant—either generator or customer—to define optimal strategies for using long-term contracts to hedge the risk involved in electricity sales and purchases.

A case study demonstrates the power of the new MIT tools. The study focuses on a utility company that has sold off its generating units (as recommended by regulators) but still has an obligation to serve its customers. The company is in a precarious position. If it loses more than $100 million in the coming year, it will go bankrupt. Depending solely on the spot market is unacceptably risky, so the company is considering buying a set of contracts for the next twelve months. Company managers have decided on an acceptable level of risk: the company's "portfolio" of monthly contracts must have less than a 5% chance of incurring a loss of $100 million. What portfolios of monthly contracts will meet that criterion?

To perform the analysis, the MIT researchers calibrate the spot pricing model for this generator's electricity market using historical data for the relevant drivers. They then define a single set of possible monthly contracts for the coming year and, using the options-based tool, calculate the profit (or loss) for the year under that set of contracts. Since demand and spot price are uncertain, they allow those inputs to vary randomly and re-analyze the same set of contracts repeatedly. By similarly analyzing hundreds of sets of possible monthly contracts, they define a group of portfolios that have less than a 5% probability of losing the company more than $100 million. Thus, the MIT decisionmaking tools can help generators minimize their loss—or with luck maximize their profits—from their electricity generating equipment.

The researchers are now working with other MIT investigators to find "smarter," less computer-intensive methods of implementing their analytical techniques. In addition, they are adapting their tools for use in "dynamic hedging." In real life, forecasts of fuel prices, rainfall, economic growth, and other drivers of supply and demand continually change. The adapted tools are intended to help decision-makers constantly adjust their portfolio of contracts in response to such changes, thereby maintaining an optimal portfolio over time and increasing the probability of investment recovery.

Marija Ilić is a senior research scientist in the Department of Electrical Engineering and Computer Science. Petter Skantze is a PhD candidate in the same department. Andrej Gubina is a Fulbright visiting scholar at the Energy Laboratory. Michael Wagner is a master's degree candidate in the Department of Electrical Engineering and Computer Science. *This research was supported by the MIT Energy Laboratory's Consortium on New Concepts and Software for Competitive Power Systems: Operations and Management. Consortium members include ABB Power T&D Company, Inc.; Constellation Power Source, Inc.; Electricité de France (EdF); and TransÉnergie US Ltd. (a subsidiary of Hydro Québec). Futher information can be found in references 1A–5A.*

Investing in New Generation Capacity and Measuring the Impacts of Price Caps

Knowing how to maximize profits from existing generation equipment is just one challenge that electric power generators face. An equally important challenge is making wise investments in expanded generating capacity for the future. Because future electricity demand and prices are unknown, decisionmakers have difficulty knowing how much, where, and what kind of additional generating capacity will give a good—let alone the best—payback and help meet growing demand efficiently. And the number of electricity-generating options now available is daunting. They range from traditional electric power plants to various innovative technologies with widely varying costs and characteristics.

The pricing model and decision-making tool described in the previous article can help such decisionmakers identify good investments for the future. Indeed, unlike most investment analysis techniques, the MIT methodology can tell generating companies not only how much but what type of generating capacity to invest in. Because the methodology includes a physical model of the power system, it can recognize important aspects of operating different types of generating units, for example, the time and cost involved in starting up and shutting down the unit. Thus, it can recognize the special value of units such as microturbines and fuel cells, which are small but highly flexible. The methodology can assess a generator's potential long-term cash flow from building a microturbine versus a nuclear plant, and it can determine which of those technologies would best match the typical level and pattern of the demand in the region.

With further development, the MIT technique could be commercialized into software that industrial decisionmakers can use to assess their investment options. But already the methodology is helping the MIT researchers understand the evolving electric power industry, in particular, how market prices influence generator investment and thus the capacity available on a power system. In any commodity market, when growing demand leads to scarcity of supply, suppliers respond by expanding their production capacity. On an electric power system, this process is critical: it is the key to avoiding capacity shortages that may lead to blackouts.

In recent work, Dr. Ilić, Mr. Skantze, and graduate student Poonsaeng Visudhiphan simulated the investment behavior of generators in order to investigate two questions. How might changes in spot prices affect generators' investment decisions and ultimately systemwide generating capacity over time? And what happens to investment and systemwide capacity when regulators put caps on prices on the spot market, as they did in California?

To address those questions, the researchers used their pricing model and decisionmaking tools to simulate the investment decisions of generators and calculate the resulting effect on systemwide capacity as spot prices change over time. The two figures on page 1 present sample results for a hypothetical power system. The top figure shows the variation in spot price over time, with and without price caps. The bottom figure shows the changing reserve margin, defined as excess available capacity as a fraction of total demand at a given time.

The link between high prices and increased reserve margins is evident in the curves representing the uncapped situation. High spot prices signal growing demand and dwindling supply; generators invest in additional generating capacity; and the reserve margin grows. However, there is a considerable time lag between the high prices and increases in the reserve margin.

When market prices are capped, both prices and reserve margins behave differently. The cap does eliminate price spikes. But keeping prices artificially low when supply is scarce removes the signal and a primary incentive—greater earnings—for generators to invest in new generating capacity. As a result, the estimated reserve margin is generally far lower than in the uncapped situation, and at times it goes well below zero—a situation in which the system operator has to invoke rolling blackouts to prevent the collapse of the entire system. Interestingly, at times the capped price is higher than the uncapped price. The explanation lies in the investment response. With prices capped, an economic signal for generators to build new plants is removed. The supply scarcity continues, so prices do not drop.

Based on their analysis, the researchers point out a trap that regulators must avoid. Using price caps to flatten out spot prices will lead to periods of underinvestment, capacity shortages, and very likely a higher average price of electricity over a several-year period. Regulators may then be tempted to force down the average price by further reducing the level of the price cap—a move that will further reduce investment. Over the long term, investment will not keep up with demand growth; and capacity shortages and service cutbacks are almost inevitable.

The MIT researchers recognize that imposing price caps can be an important means of keeping generators from driving up prices during shortages. But regulators must choose their caps carefully. A cap must be sufficiently high that prices can still stimulate investment as needed for system reliability. Among the products from the MIT team is a formula for calculating price caps that are low enough to protect customers from artificial spikes but high enough to send appropriate investment signals.

The MIT analysis also suggests that using long-term contracts not only enables customers to protect themselves from spikes in the spot price but also plays a critical role in stabilizing power systems by providing information on likely demand and prices in the future. That information would give generators an early warning of impending supply shortages. Their prompt investment response could eliminate the delay in capacity expansion observed by the researchers and thus reduce the likelihood of generation shortages and blackouts. The MIT researchers are now using the decisionmaking tools described in the next section to see how the early availability of price and demand information would influence individual generator behavior.

Poonsaeng Visudhiphan is a PhD candidate in the Department of Electrical Engineering and Computer Science. This research was supported by the MIT Energy Laboratory's Consortium on New Concepts and Software for Competitive Power Systems: Operations and Management and by the MIT Department of Electrical Engineering and Computer Science. Further information can be found in references 6B–7B.

Can Generators Manipulate the Market?

An important question in the newly competitive electric industry is whether individual generation companies can exert "market power," that is, push prices above competitive levels without losing customers. Regardless of their actual bids on the spot market, all generators operating on a regional system at a given time receive the "market-clearing" price, defined as the price bid by the last generator to be scheduled. In theory, the market-clearing price should be the marginal cost, that is, the cost of generating the last and therefore most expensive unit of electricity required. But under some circumstances the last generator scheduled can bid a price higher than his actual cost. In addition, generators can occasionally cut back the amount of generating capacity they bid into the market. As in any commodity market, a reduction in supply brings an increase in price (for the same level of demand). What are the conditions under which generators can exert such market power? And how often do those conditions prevail on the electricity spot market?

To tackle those questions, Ms. Visudhiphan and Dr. Ilić are taking a novel approach to modeling the spot market. The traditional approach involves tracking systemwide (aggregated) supply and demand information when supply and demand are in balance (equilibrium conditions). A picture of the market's overall behavior emerges, but understanding what individual participants are doing and how the market behaves over time is difficult. The MIT researchers are instead simulating market behavior by starting with individual generators as they decide how much supply to offer at what price. (The effect of transmission constraints on market power is being addressed by researchers in the Center for Energy and Environmental Policy Research, led by Professor Paul Joskow, Elizabeth and James Killian Professor in the Department of Economics.)

The first step in simulating the decisionmaking process is to define the characteristics of a single generation company. What types of generating units does it own? How big are they, and how much does it cost to run them? How risk averse is the firm? Based on such information, the researchers simulate the decisionmaking process of the firm as it develops its bids. They then perform similar analyses of additional generators with other characteristics. On the demand side, the researchers assume a forecasted load that is fairly unresponsive to price (a reflection of conditions on most current spot markets). Based on the individual supply bids and assumed demand, the researchers simulate the bidding process used on spot markets, thereby calculating the changing price of electricity over time.

In an initial series of case studies, Ms. Visudhiphan and Dr. Ilić demonstrated how the assumed "bidding strategies" of individual generators influence estimated market prices. In their analysis, each generator decides first how much capacity to sell and then the price it will charge if it is scheduled to operate. If the opportunity arises, the generator may withhold capacity to push up market prices. Three bidding strategies are assumed. In the first, all generators simply increase their bids each time by a prespecified amount. In the second, each generator changes his new bid based on how successful he was in the previous bid. (If the bid was successful, he submits the same price. If the bid was unsuccessful, he submits a lower new price.) In the third, each generator chooses as his new bid the highest market price seen over the past 15 bidding samples. The different bidding strategies generate market prices that display differing trends over time. The first strategy leads to a persistent increase in price, while the second and third strategies result in prices that are fairly stable. Clearly, the ability to predict bidding behavior can provide insights into the dynamics of market prices.

Using their new approach, the researchers examined which types of firms would be able to exert market power and under what conditions. They analyzed the behavior of 13 hypothetical generators with differing capabilities, constraints, and objectives. They concluded that the key measure of a generator's potential for exerting market power is the generator's capacity relative to excess capacity at a given time.

An example will demonstrate. Assume that New England has a total capacity of 15,000 MW, and tomorrow's demand is expected to be 14,000 MW. Excess capacity for tomorrow is therefore 1,000 MW. Under those conditions, a generator that owns 2,000 MW of capacity is critical. If that generator chooses not to operate, demand cannot be met. If he offers 1,000 MW at an extremely high price, the system operator will have to take the offer and that high price will prevail. Significantly, the generator's 2,000 MW of capacity is just as critical if New England's total capacity were 30,000 MW and tomorrow's demand were 28,000 MW. Thus, the important measure is how a generator's capacity compares to excess capacity; and when excess capacity is low, more generators will be in a position to push up prices.

Once again, the performance of the electric industry cannot be measured using standard techniques. The US Department of Justice usually judges the market-power potential of a company based on its "market share," that is, the amount of a commodity that the company controls relative to the total amount of that commodity traded. However, according to the researchers' analyses, an electricity-generating company with a relatively small market share may be able to exert market power. Demand for electricity is much less responsive to prices than is demand for other commodities, so generators can more easily push up prices without losing customers. As a result, opportunities for exerting market power are more prevalent in the electric industry than standard analyses suggest. For example, analyses based on the standard Department of Justice index suggest that generators in New England have little opportunity to exert market power. But an analysis using the new MIT index shows that the potential for firms to exert market power is substantial. It varies dramatically from day to day and season to season and is particularly high during the summer.

Thus far, the simulations involve generators developing their bidding strategies based only on past market prices and forecasted demand. How would their strategies change if they had information on future plant outages, maintenance schedules, or the bidding behavior of other generators? How would bidding change if generators had the option of selling long-term contracts? And what would happen if demand actually responded to price? The ability of customers to reduce their demand when prices rise profoundly changes the spot market. Indeed, generators' ability to manipulate electricity prices might simply disappear.

This research was supported by the MIT Energy Laboratory's Consortium on New Concepts and Software for Competitive Power Systems: Operations and Management and by the MIT Department of Electrical Engineering and Computer Science. Further information can be found in references 8C–11C.

Running the Power System and Delivering Power

The traditional approach to operating electric power systems has emphasized avoiding problems in order to ensure reliability. Thus, for decades, utilities built excess generating capacity, kept power flows on transmission lines well below their physical limits, ran devices that would automatically fix or disconnect components that were starting to malfunction, and in general tried to ensure that the system would hum along with little intervention required.

With the demise of the single utility, a regional system operator is now responsible for scheduling generating units, arranging transmission capacity, and providing other services needed to implement the deals made by generators and customers. But the old-fashioned conservative approach to power system operation is no longer an option because investment *and* use of power system components must occur for market participants to get paid. Therefore, competitive pressure is on to run the power system closer to its physical limits, notably by increasing electricity flow on the transmission lines.

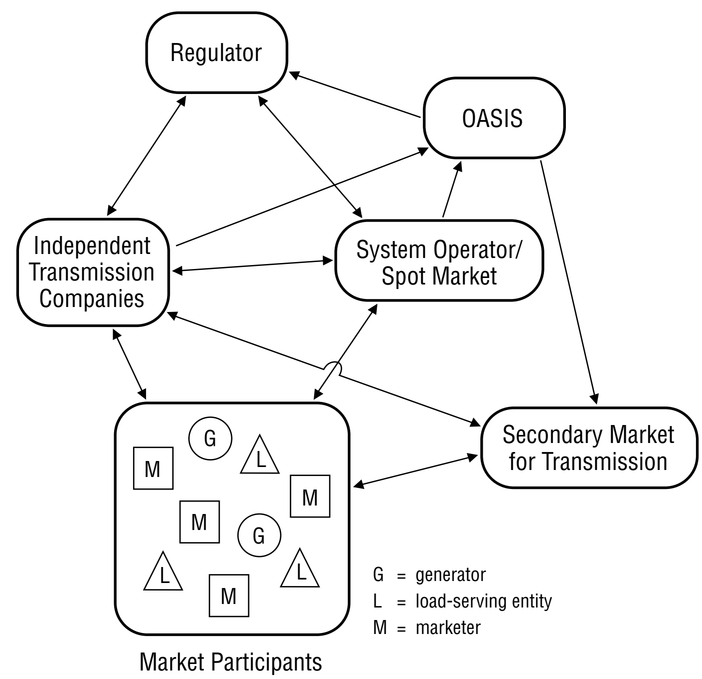
This less-conservative operation can theoretically bring dramatic reductions in cost. However, today's system operator remains closely regulated and has no financial incentive to operate the system closer to its physical limits, thereby running the risk of delivering less-than-reliable service. Moreover, in many regions, the system operator does not own the transmission system and thus is not in a position to either maintain or improve it. In addition, maintenance on today's transmission lines has been targeted at reduced levels of utilization, not at close-to-the-edge limits where market participants now want to use them.

According to graduate student Yong Yoon and Dr. Ilić, the solution to those problems is the establishment of independent, for-profit transmission companies. Today's non-profit system operator assigns transmission rights and bundles the price of transmission in with electricity price, charging customers after transactions are completed. Instead, transmission should become a commodity that can be bought and sold. And the owners of transmission lines should be permitted to make a profit. Transmission companies would then have an incentive to maximize the service they provide, to operate as efficiently as possible, and to maintain and expand the transmission system as needed to meet potential demand.

In late 2000, the Federal Energy Regulatory Commission (FERC) formally recognized the need for a more active transmission provider. FERC issued an order calling for the creation of "regional transmission organizations" that can provide transmission service to customers. The order calls for regions to submit proposals describing the structure and functioning of an organization that could provide efficient, reliable service, given the characteristics and needs of the region being served.

In January 2001, Dr. Ilić and Mr. Yoon responded to that request. In their comments, they state that optimizing regional transmission systems and services requires participation by a number of entities that perform different functions. Some are regulated, some are not; but when the individual businesses operate to meet their own objectives, their actions must work together to improve the long-term social welfare of all market participants.

Electric Power Industry Structure Proposed by MIT Researchers



The industry structure that the MIT researchers propose is shown in the figure above. At the lower left appears the market where generators, "load-serving entities" (new for-profit companies that serve groups of customers), and marketers interact, buying and selling electricity. The system operator (SO) oversees the spot market and takes responsibility for the short-term operation of the system. The independent transmission companies (ITCs) own the transmission lines and sell transmission services. The ITCs cooperate closely with the SO to implement all contracts for transmission delivery. The regulator oversees activities of the ITCs and the SO.

To expedite the buying and selling of transmission, Dr. Ilić and Mr. Yoon include in their plan a secondary market for transmission—a financial market for the trading of long-term contracts for transmission rights. Instead of the SO auctioning off long-term contracts

(FERC's assumption), sellers and buyers would go to the secondary market to make deals that would reflect the real value of transmission to them. Thus, some customers would continue to get reliable transmission service by paying a higher price, while others might choose to pay less and get interruptible service. The final entity in the structure is the Open Access Same-Time Information System (OASIS), an on-line system run by ITCs and the SO where market participants can get information on the availability and value of transmission, line by line, so they can make informed trading decisions.

Under this structure, the ITC has both the incentive and the ability to maintain its lines and to operate as efficiently as possible. To maximize its profit, it can sell more rights, push its capacity limits, and expand its transmission system where congestion is apt to occur, thus where transmission capacity is most valuable. However, an ITC is typically still a natural monopoly, so it could in theory push up the price of transmission capacity by limiting the capacity it makes available. The MIT researchers therefore recommend that the ITC be subject to price-cap regulation, which limits the price charged for service on a specific transmission line to the market value (the market-clearing price) of that service. Under price-cap regulation, the ITC can increase its profits only if it lowers prices to attract more customers and increases capacity, either by building more transmission lines or by investing in software and instrumentation to identify and manage transmission constraints more carefully.

Economic theory suggests that price-cap regulation will give better incentives than will traditional cost-plus regulation (which gives a fixed rate of return on actual operating costs and capital investment). However, the techniques usually used to calculate price caps are not directly applicable to transmission; and no physical model of the power system has been available for use in analyzing the impacts of transmission price caps.

Mr. Yoon and Dr. Ilić have now created a model that can calculate price-caps for a given transmission line and the investment in new transmission capacity that they would stimulate. Using their physical model of the electric power system, they have performed case studies in which they determined what transmission lines would be built, first assuming traditional cost-plus regulation and then assuming the proposed price-cap regulation. The analytical results show that the hypothetical ITC makes better investments under carefully structured price-cap regulation, building transmission lines that bring the overall power system closer to optimal performance.

Using their new models, the MIT researchers have shown the increases in efficiency that come with their proposed industry structure. In collaborative work, graduate students Ozge Gozum, Bruce Tsuchida, and José Arce have produced computer-based tools that will help in its implementation. Included are methods of achieving system control, techniques for accomplishing transfers of information, new approaches to measuring and ensuring reliability, and a design for an information company to support the OASIS.

In addition, Mr. Yoon, Dr. Ilić, and graduate students Santosh Raikar and Kenneth Collison have developed tools that will help regulators implement price caps. A single regional system may contain thousands of transmission lines and system users. However, the MIT team points out that on uncongested lines, the value of transmission—hence the appropriate price cap—will not change much with time. Therefore, regulators need monitor only those that are prone to congestion. The team has developed an analytical model that can identify the critical lines and clusters of primary users that contribute to that congestion. The regulator can thus monitor those lines, set price caps as required, and post the prices, the transmission lines, and the associated customer clusters on the OASIS. All market participants can quickly see weak areas of the system—areas where investment in additional generating or transmission capacity would most pay off.

Yong Yoon is a PhD candidate and Ozge Gozum is a master's degree candidate, both in the Department of Electrical Engineering and Computer Science. Bruce Tsuchida is a master's degree candidate in the Engineering Systems Division. José Arce is a visiting PhD student at the Energy Laboratory from the Instituto de Energia Electrica, Universidad Nacional de San Juan, San Juan, Argentina. Santosh Raikar is a master's degree candidate in the Engineering Systems Division. Kenneth Collison is a master's degree candidate in the Sloan School of Management. *This research was supported by the MIT Energy Laboratory's Consortium on New Concepts and Software for Competitive Power Systems: Operations and Management and jointly by the Electric Power Research Institute and the US Department of Energy's Energy Information Administration.* *Further information can be found in references 12D–32D.*

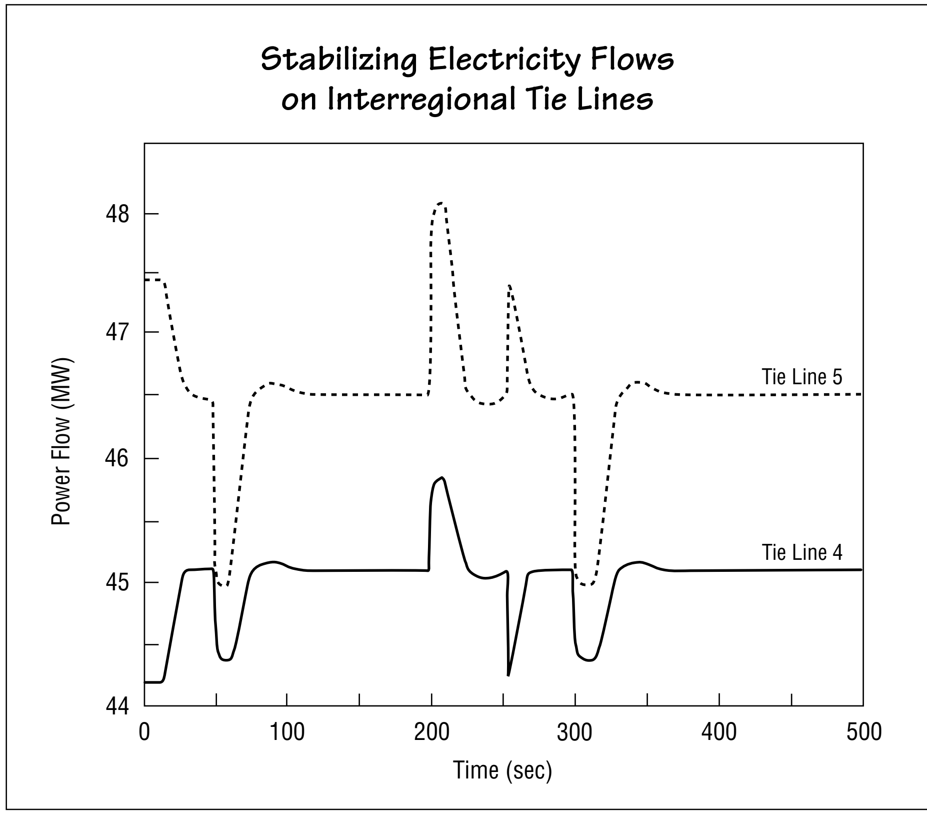
Expediting Interregional Transfers of Electricity

As the electric industry becomes increasingly competitive, customers and their representatives are looking for inexpensive power from any source they can find. As a result, more and more electricity is being sent from one regional power system to another. For example, New England, New York, and PJM (serving Pennsylvania, New Jersey, and Maryland) all now import electricity from Canada. With power systems running more efficiently, thus with less excess transmission capacity, those transfers can be critical. On a regular basis, for instance, both New England and California require electricity imported from Canada to meet their systemwide demand.

For system operators, those transfers create new headaches. Conditions on a regional power system can be directly affected by transfers of electricity among other regional power systems. When, for example, New England imports electricity from Canada, flows on the New York system change. As system operators plan, they generally make assumptions about the flows on their "tie lines"—the transmission lines that connect neighboring systems. If those flows become too disruptive, a system operator can complain to the interregional "security coordinator," who oversees interregional flows. The security coordinator identifies the transfer causing the problem and takes steps to curtail that electricity flow by denying access to specific transactions. In the new competitive industry, however, interregional deals disrupt the tie lines so frequently that the security coordinator cannot keep up.

A new concept developed by Dr. Ilić and Mr. Yoon should solve that problem. Their patented design and supporting modeling tools describe the market mechanisms needed to make interregional transmission work better. Central to their approach is having the security coordinator replaced by a more active marketer who can make a profit while allowing the regional transmission providers to make decisions about their own participation in tie-line flow control. This coordinator, called the Interregional Transmission Organization (IRTO), operates physical control devices that ensure that flows on the tie lines remain stable and predictable. When disruption occurs, the control devices take action to correct the fault and return electricity flows on the tie lines to the desired levels. The IRTO then computes the cost of making the correction and charges that cost to whoever caused the problem.

To increase efficiency further, the new design allows market participants to make a profit by running the control devices (typically on generating units) that correct the tie-line flows when



New MIT methods can keep electricity flows on interregional tie lines from fluctuating unexpectedly—a situation that makes it difficult for regional transmission providers to ensure reliable service. In a small case study, researchers simulated the process whereby a hypothetical interregional transmission organization accepts bids to supply and use tie-line capacity and estimated the tie-line flows for a given period. In this figure, flows on tie lines 4 and 5 fluctuate from that estimated value due to variations in regional demand. But adjustments in generation dispatch repeatedly drive the tie-line flows back to the estimated value.

necessary. Suppose that New England is importing low-cost electricity from Canada, but that activity disturbs operation on the New York system. Instead of the IRTO's taking action to correct the problem, New York can invest in control devices that can restore its own system to its original condition. The IRTO then charges New England for the trouble it created and pays New York for having corrected it. Aided by New York, New England can take advantage of less-expensive electricity than it can produce itself; and the efficiency of the overall multi-region system increases.

In their patent, Dr. Ilić and Mr. Yoon present a formula for calculating how participants will bid, what deals will be made, and what market prices will be set. Based on those results, they then calculate the interregional transfers that will occur, their impact on the various interconnected power systems, and the control responses that will be taken.

A small case study performed by Mr. Collison demonstrates the success of this system in stabilizing tie-line flows. The curves in the figure on page 9 show flows on two tie lines—numbered 4 and 5—that interconnect two regions during a typical transaction period. At times, the tie-line flows deviate from their estimated base value, generally due to variations in regional demand. Any time such a deviation occurs, the responsible generator adjusts demand so as to drive the tie-line flows back to the estimated base values. With tie-line flows close to constant, regional transmission providers can maximize reliability on their own power systems.

To demonstrate the broader impact of their plan, the researchers performed an analysis of an IRTO for the Northeast region. The assumed IRTO auctions off interregional transactions, taking bids from system operators, transmission providers, marketers, and others. The IRTO then coordinates the activities of the market participants to maintain strict control of tie-line flows for the duration of the transactions. The results of the analysis suggest that the proposed market structure would minimize disruptions due to interregional transactions and maximize the benefits to all participants, namely, inexpensive supply and increased reliability. Implementing the market structure would require new regulations for the IRTO but few changes on existing regional markets and power systems. Indeed, the method appears to work, regardless of the market structures that prevail in the individual regions involved.

This research was supported by the MIT Energy Laboratory's Consortium on New Concepts and Software for Competitive Power Systems: Operations and Management and by the US Department of Energy's Energy Information Administration. Further information can be found in references 33E–34E.

Distributed Generation Systems: Mini-Grids and Consumer Choice

Most discussions of the competitive electric industry focus on the behavior of entities at the wholesale level—those that supply electricity, own transmission lines, operate the power system, and so on. Demand at the retail level is handled as an aggregate that is generally unresponsive to prices or system conditions. The behavior of the individual consumer is lost in the shuffle.

But competition is supposed to benefit the consumer, and one of the main benefits is meant to be the right to choose higher or lower reliability of service. Right now, all consumers pay to receive (generally) uninterrupted electricity service. But some people may be willing to accept less-reliable service in return for a reduction in price. If some consumers were flexible, system operators would no longer have to maintain the excess capacity and conservative operating practices that now ensure that electricity flow is uninterrupted.

The first step toward achieving consumer choice is to provide a means for consumers to make their wishes known. According to Dr. Ilić, a critical missing market participant in the current electric industry is the load-serving entity (LSE). The LSE would be a profit-making company (although until many competitive LSEs form, it would be subject to price-cap regulation). The LSE would sign long-term contracts with consumers to provide their electric service at specified levels of reliability and price. All contracts would include "reliability insurance"—an agreement that specifies a fee that the LSE will pay the consumer if the LSE fails to perform with the promised level of reliability. The LSE would thus be paid to remove consumers' uncertainty by promising to deliver electricity with a certain level of reliability regardless of any disturbances on the system.

What practical problems would be encountered in implementing the LSE-consumer contracts that specify different levels of reliability? Most electricity is still generated by large, central power plants serving big regions. The system operator's job of coordinating power flows while providing different levels of service for individual consumers would be difficult at best.

Analyses by Dr. Ilić and graduate students Elena Fumagalli, Jason Black, Charles Chalermkraivuth, and Jill Watz, with support from Professor Paul Kleindorfer of the Wharton School at the University of Pennsylvania, suggest that the solution may lie in a new type of power system—one based on distributed generation and many small decisions made by the actual users. Rather than having large power plants serving big regions, many small, local generating units would supply different neighborhoods. Numerous interconnected distributed generators could form a self-sufficient, stand-alone system called a mini-grid. High reliability would be achieved simply by having many small, interconnected suppliers and consumers. If one or two generating units on the mini-grid were to fail, other small generating units could easily fill the gap. And growing demand would be met by building additional local generating units rather than by building more transmission wires to a central plant.

A mini-grid of interconnected generating units and consumers could provide cost-effective consumer choice. A switch installed in each house would receive price signals via the Internet. When prices go up because the mini-grid is stressed, supply to a consumer who has chosen low reliability would automatically be reduced. Household demand would be adjusted accordingly, perhaps by lowering the house thermostat by a degree or two or by raising the refrigerator temperature slightly.

According to Dr. Ilić, several technological advances now make this arrangement commercially feasible. Various distributed generation and support technologies are now available and cost-effective; examples include fuel cells, microturbines, cogenerators, flywheel or battery energy storage, and devices for maintaining power quality. Most houses now have access to the Internet, the perfect source of real-time prices to which consumers can respond. And switching technology is available that can cut or reduce flows on low-voltage lines that carry electricity through neighborhoods.

Simulations performed by the MIT researchers show that their proposed setup of LSE-consumer contracts plus mini-grids would lead to near-optimal system performance. Problems at generating units or on transmission lines would not lead to the "cascading reliability failures" that occur with large generators on a traditional power system. The logical and physical switches for reducing service to selected consumers are relatively simple because they need respond only to local measurements, not systemwide conditions. And the mini-grid should need little coordination because it can self-correct. If electricity is in short supply or transmission lines are congested, prices displayed on the Internet will rise. As prices go up, more and more consumers will have their demand lowered; and the system will once again stabilize. This self-adjustment concept was first proposed by the late MIT Professor Fred C. Schweppe and his Energy Laboratory colleagues in the 1970s. They called the scheme "Homeostatic Control," drawing on the word "homeostatis," a biological term that refers to the tendency toward equilibrium among associated but independent elements of an organism.

A small case study showed that the use of reliability insurance in contracts stimulates investment in performance-enhancing technology. The MIT researchers, in collaboration with economist Professor Ingo Vogelsang of Boston University, analyzed the investment behavior of participants in a hypothetical mini-grid, both with and without reliability-insurance contracts. As seen in the table above, implementing

Effect of Reliability Incentives on Outage Rate and Investment

Reliability Incentive	Total Investment ($)	Total Outages (hrs/yr)
None	0	679
Reliability Insurance	32,000	127
Penalty Fee	24,000	137

MIT researchers recommend that each contract between an electricity provider and a consumer include "reliability insurance"—a set fee that the provider pays the consumer if it fails to deliver electricity with the level of reliability defined in the contract. Simulation results shown in the table indicate that the use of reliability insurance increases total investment in power system improvements and decreases the outage rate significantly. Using reliability insurance also gives better outcomes than does using penalty fees, which award a set payment to all consumers for each outage, regardless of the level of reliability specified in their contracts.

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reliability insurance induces more investment and reduces outages relative to the case without explicit reliability incentives. For comparison, the researchers also examined the impact of a "penalty" fee, a more conventional scheme proposed by others wherein all consumers receive a set reimbursement for each outage, regardless of their selected reliability level. Again, reliability insurance elicits a better outcome.

One problem that arises with consumer choice is social welfare. Some consumers may not be able to afford reliable service; and others may be located in remote areas that make them hard to serve, thus less attractive to LSEs. Such issues need to be addressed, perhaps using government subsidies.

Once tailored for industrial users, the MIT simulation tools can help companies estimate the value of potential investments in distributed generation systems and transmission capacity. Investments aimed at creating mini-grids would encourage deployment of small generating technologies that may be undervalued on a traditional power system. While their generating capacity may be low, such technologies should receive credit for their ability to enhance reliability and for the environmental advantages they offer over conventional large-scale plants. Mini-grids can provide market niches for such technologies so that their real value can be demonstrated and they can play an increasing role in the competitive electric power industry.

Elena Fumagalli is a visiting scholar at the Energy Laboratory. Jason Black is a PhD candidate and Charles Chalermkraivuth and Jill Watz are master's degree candidates, all in the Engineering Systems Division. This research was supported by ABB Power T&D Company, Inc. Ms. Fumagalli's doctoral scholarship was financed by the Italian Ministry of University and of Scientific and Technological Research. Further information can be found in references 35F–41F.

On January 10–12, the **Joint Program on the Science and Policy of Global Change** held its **seventeenth Global Change Forum**, "**Designing Post-Kyoto Mechanisms**," in New Delhi, India. Topics included a review and analysis of the results of the sixth Conference of the Parties of the UN Framework Convention on Climate Change (COP-6); the future of Annex B commitments; the role of clean development mechanisms, with and without entry into force; greenhouse gas mitigation and urban/regional pollution control; regional climate projection and adaptation aid; and long-term issues relating to accession and convergence. The keynote address was given by Ambassador Arne Walther, Norwegian Ambassador to India, International Energy Agency. Meeting participants included about 70 representatives from industry, government, and academia, worldwide.

PUBLICATIONS AND REFERENCES

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Publications marked by an asterisk (*) can be found or are forthcoming on-line via the following addresses:

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Instructions for ordering paper copies of the reports and working papers are also available at the above-listed sites or by telephoning 617-258-0307 for Energy Laboratory publications, 617-253-3551 for Center publications, and 617-253-7492 for Joint Program publications.

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NEW AND RENEWED PROJECTS, JANUARY–MARCH 2001

Topic	**Donor or Sponsor**	**Investigators *(Department)***
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Center for Energy and Environmental Policy Research membership	Pennsylvania Power & Light Co.; Shell Oil Co. Foundation	
Joint Program on the Science and Policy of Global Change membership	Statoil	
Study of Electric Transmission Network	Leonard S. Hyman	M. Ilić *(Electrical Engineering and Computer Science)*
NEW PROJECTS		
Formation of Independent Transmission Company	National Grid USA	M. Ilić *(Electrical Engineering and Computer Science)*
Systematic Lead-Bismuth Corrosion Studies	Japan Nuclear Cycle Development Institute	M. Kazimi *(Nuclear Engineering)*
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Analysis of Homogeneous Charge Compression	BMW AG	J. Heywood *(Mechanical Engineering)*
Kinetics of Chemical Agents Destruction in Supercritical Water	US Army Research Office	J. Tester *(Energy Laboratory and Chemical Engineering)* W. Peters *(Energy Laboratory)*
A Collaborative Program of Research in Engineering	US Department of Energy (DOE)	D. Parks *(Mechanical Engineering)*
Scenarios for Carbon Sequestration	US DOE	H. Herzog *(Energy Laboratory)*

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