

Current Research

Supported by The Alfred P. Sloan Foundation, Electric Power Research Institute, U.S. National Science Foundation, U.S. Environmental Protection Agency, U.S. Department of Energy, Tennessee Valley Authority, the U.S. Office of Naval Research, McDermott Technology, the ABB Group, Alliant Energy, the National Rural Electrical Cooperative Association, the Commonwealth of Pennsylvania Office of Energy and Technology Development, and Customized Energy Solutions, Ltd..

Markets and Investment

Market Power: We have shown that traditional indicators of oligopoly and market power are inapplicable to electricity markets. We developed a game-theoretic model of generators bidding their supply in uniform price auctions. In California, as few as three firms could have jointly set the market price of power more than 90% of the time in 2000. The PJM and New York systems appear to have much more competitive market structures.. Dmitri Perekhodstev, Seth Blumsack, Lester Lave

Autonomous Agents that Learn in Power Markets: We have developed a Java-based simulation facility modeling a distributed environment with different clearing mechanisms and different learning algorithms. We find that even “dumb” agents drive the market to monopolistic pricing in a few auctions. We study software agents as traders, including learning, strategies, demand response, and tests for market failures. Kong-Wei Lye, Sarosh Talukdar

Transmission Investment Incentives: We have argued that Locational Marginal Pricing (LMP) does not provide proper incentives for transmission investment, although LMPs do provide incentives to not wheel power over the most congested lines. Instead of relying on LMPs alone, we find that a two-part tariff for transmission, with a megawatt-hour-mile charge and an LMP charge provides more optimum incentives. Lester Lave, Jay Apt, Dmitri Perekhodstev

Valuation of Ancillary Services: We show that the value of ancillary services from hydro facilities can be quantified and is substantial, and we have developed a method of setting internal pricing for ancillary services. Dmitri Perekhodstev, Lester Lave

Generation Portfolio Optimization: We have developed a decision support framework for strategic investment decision-making for generation assets based on efficient frontier portfolio theory. David Rode, Paul Fischbeck, Jay Apt, Lester Lave

Risk Analysis and Electricity Project Capital Structures: We have shown that the ability to tie operational risks (such as fuel prices, maintenance expenses, regulatory compliance costs, *etc.*) directly to impacts on capital structure provides a unifying mechanism for understanding firm value and provides insight into areas in which nonintuitive negative consequences may arise from well-intentioned actions. David Rode, Paul Lewis, Paul Fischbeck

Monte Carlo Methods for Appraisal and Valuation as applied to Nuclear

Power Plants: For large-scale, technically unique projects, such as chemical and power plants, and old industrial practices, the four standard appraisal methods are insufficient. To include political, technical, and economic risks in an appraisal, we have developed a Monte Carlo simulation method. Probability distributions are used to model the appropriate uncertainty. The use of Monte Carlo methods and the modeling of future decisions decreased the worth of a nuclear generation plant by 28% as compared to a standard income capitalization method. David Rode, Paul Fischbeck, Steven Dean

Risk Management in Electricity Markets: We examine risk management for power suppliers, bidding strategies of power suppliers with the application of game theory, analysis of markets power, and evaluation of alternative market models ranging from totally centralized dispatch to decentralized bidding. We have constructed complex dynamic models of the electric power system in a restructured environment based upon the principles of control theory, and having information, technical, and policy loops. The control system uses performance metrics as inputs, and disturbances are introduced into the system. Zhiyoung Wu, Marija Ilic

Distributed Energy Resources

Distributed Decision-Making: We are examining the use of economic theory and autonomous agents to decentralize decision making in complex systems, such as transmission grids and micro-grids, to increase efficiency and reliability. Sarosh Talukdar, Lester Lave

Regulatory and Economic Assessment of Micro-grids: We assess the current regulatory framework, suggest new arrangements, and evaluate the likely economic performance of micro-grids. Doug King, Granger Morgan

Stability and Distributed Generation: We have examined dynamic stability of distributed generators in power systems, finding that a small load disturbance is capable of causing frequency instability in the primary dynamics of the distributed generators. We have developed a method of regaining system stability. Judith Cardell and Marija Ilic

Improving Reliability with Distributed Resources: (see entry under Reliability and Security).

Advanced Generation, Transmission, and Environmental Issues

Large-Scale Wind Generation: The intermittency and geographic distribution of wind resources add significantly to the real cost of electricity from wind. In power systems where wind turbines represent a significant fraction of the generation capacity, the spatial correlation of intermittent wind resources forces an intrinsic tradeoff between installing dispatchable storage/backup capacity and distributing the wind turbines over a larger geographical area. We explore the role of long-distance transmission and dispatchable backup capacity in determining the economic viability of large scale wind systems. We explore how transmission can be used to mitigate the problem of intermittent supply. Joe DeCarolis, David Keith

Climate Impacts of Large-Scale Wind Generation: Large scale use of wind power can alter local and global climate by extracting kinetic energy and by modifying turbulent transport in the atmospheric boundary layer. We explored the climatic impacts of extracting 3-20 TW of electricity with a suite of numerical experiments using two independent atmospheric General Circulation Models (GCMs) and two parameterizations of the wind-turbine arrays. David Keith, Joe DeCarolis

Animal Waste to Power: We are performing a broad technical, economic and social assessment of the feasibility of animal-waste-to-power technology, including potential positive and negative interactions between this technology and other small scale technologies. Kyle Meisterling, Granger Morgan

Amine and Selexol-based CO₂ Capture for IGCC Plants: We have developed performance and cost models of Amine scrubbing of conventional coal plants and for a Selexol-based CO₂ absorption system for capturing CO₂ from IGCC plants. The analysis shows that based on commercially available technology, the cost of CO₂ avoided for an IGCC power plant is half that for a conventional

combustion plant with a chemical absorption process. For IGCC systems, the uncertainty associated with CO₂ transport and storage has the largest impact on the cost of CO₂ avoided. Anand Rao, Chao Chen, Ed Rubin

Metrics for Understanding Transmission Line Siting: We are quantifying siting difficulty at the state level, identifying siting constraints, and developing a model for predicting siting difficulty. Early work includes analyses of variations in market prices and cost of production data associated with transmission congestion, analysis of proposed and actual transmission miles constructed, and the development of a survey of industry regulators and siting experts to construct a measure of siting difficulty. The goal of this work is to develop comprehensive siting analysis that provides a framework for regulators and utilities to anticipate the demand for transmission construction, predict siting problems, and coordinate siting solutions. Shalini Vajjhala, Paul Fischbeck

Life Cycle Assessment: Carnegie Mellon University has developed a tool for lifecycle analysis that is quick and cheap (see www.eiolca.net). We are disaggregating the U.S. input-output matrix to separate the electricity sector by fuel type. This model enables us to perform lifecycle analyses for each fuel and technology used to generate electricity. We use a hybrid approach that embodies the process details of each fuel/technology in the more aggregate input-output analysis. Joe Marriott, Scott Matthews

The Cost of Regulatory Uncertainty in Air Emissions for a Coal-fired Power Plant Uncertainty about the extent and timing of changes in environmental regulations for coal fired power plants makes the difficult problem of selecting a compliance strategy even harder. Using a Multi-Period Decision Model (MPDM) that captures the decisions (both capital investment and operating) that a power plant owner must make each year, our framework employs a Stochastic Optimization Model (SOM), nested in the MPDM to find the strategy that minimizes the expected net present value (ENPV) of plant operations over a fixed planning horizon. By comparing model runs under different uncertainty conditions, the cost of regulatory uncertainty are calculated. Dalia Patiño Echeverri, Paul Fishbeck, Benoit Morel, Alex Farrell

Is It Better to Ship Coal or Electricity? We have built a model that examines the energy efficiency, economic, and environmental implications of shipping coal versus electricity depending on the distance, investment needed, and other factors. Shipments of Powder River Basin Coal to Texas were the first example. Joule Bergerson, Chris Hendrickson, Lester Lave

Studies of Particulate Air Pollution: We measure and model particulate air pollution on local, regional and global scales. Cliff Davidson, Allen Robinson, Peter Adams

Modeling Environmental Implications of Electricity Generation to 2050: we are working with the US EPA on a model of environmental discharges from electricity over a 50 year time horizon. Using MARKAL software, we specify the inputs, cost, and environmental discharges of each fuel-technology combination. The model then allows us to explore a range of scenarios concerning the price/availability of fuels, stringency of environmental regulations, and availability of advanced technologies. Joule Bergerson and Lester Lave

Reliability and Security

Survival of Essential Missions: Measures can be taken to reduce the number of large-scale power losses due to failures of the generation and high voltage transmission grid. However, such failures cannot be eliminated. The survival of essential missions is a more tractable problem than the prevention of all large cascading failures, and its solutions are verifiable. We have outlined a program to lower the social

costs of power failures through successful preservation of those essential missions. Jay Apt, Marija Ilic, Lester Lave, Granger Morgan, Sarosh Talukdar

Autonomous Agents for Power System Control: We examine the extent to which power systems can be controlled with distributed autonomous agents. Sarosh Talukdar

Architecture of a Survivable Power Grid: We explore communication architectures for the electric power grid which are survivable against coordinated disruption. By using hybrid models of grid information technology, power dynamics, cyber-attacks, policy and markets we examine the survivability characteristics of candidate architectures, including distributed agent systems for fast, autonomous control. Benoit Morel, Sarosh Talukdar, Marija Ilic, Jay Apt

Advanced Protocols for Grid Reliability: We develop improved protocols for communication and control to enhance grid reliability. Marija Ilic

Improving Reliability with Distributed Resources: We use stochastic simulation to determine the extent to which distributed resource can improve reliability. Hisham Zerriffi, Alex Farrell, Granger Morgan, Hadi Dowlatabadi

Demand Estimation

Estimating Electricity Demand: Utilities need to know: 1. What incentives are effective in shifting demand from peak to off peak, 2. the short and long term responsiveness of demand to price changes, and 3. how to forecast long term electricity demand based on changes in income, demographics, and other factors. We constructed a large review of the extant literature. We are now examining a detailed data base of small industrial and commercial customers in California during a period of significant price change. Other aspects of demand to be examined include how users behave when they are offered a choice of different suppliers and contracts, and to see if this changes load patterns. Chantal Brandon, Lester Lave

Costs and Benefits of Thermal Energy Storage: We are studying the load-shifting provided by thermal energy storage systems (TES) – technologies designed to store heat or cold energy for later use. We find that cool storage provides great benefit for electric utilities. Cool TES shifts the customer's electricity demand from the peak to the off-peak hours, greatly benefiting the utility. Little TES has been installed because the full benefits are not shared with the customer. We examine the conditions under which TES lowers social costs. Dmitri Perekhodstev, Lester Lave

Publications

Apt, J., L. B. Lave, S. Talukdar, G. M. Morgan and M. Ilic. (2004) "Electrical Blackouts: A Systemic Problem." Issues in Science & Technology Summer 2004.

Apt, J. and L. B. Lave (2003). "Electric Gridlock: A National Solution." *Public Utilities Fortnightly* **141**(18): 14-16.

Bergerson, J. and L. B. Lave (2004). *Life Cycle Analysis: Power Generation Systems*. The Encyclopedia of Energy, C. Cleveland. New York, Academic Press.

Bergerson, J., L. B. Lave and H. MacLean (Submitted). "Electricity Generation: Can It be Sufficient and Green? Steps to Make Electricity more Sustainable." *Environmental Science and Technology*.

Blumsack, S., D. Perekhodtsev and L. B. Lave (2002). "Market Power in Deregulated Wholesale Electricity Markets: Issues in Measurement and the Cost of Mitigation." *The Electricity Journal* **15**(9): 11-24.

DeCarolis, J. and D. W. Keith (2002). *Is the Answer to Climate Change Blowing in the Wind? Proceedings of the first International Doctoral Consortium on Technology, Policy, and Management*, Delft, The Netherlands, Delft University.

Farrell, A. (2002). *Trading Expands, Increasingly Affects Gas and Power*. *Natural Gas & Electric Power Industries Analysis*. Houston, Financial Communications Company: pp. 101-113.

Farrell, A. (2003). *Environmental Impacts of Electricity*. The Encyclopedia of Energy (Forthcoming 2003-2004). C. Cleveland. New York, Academic Press.

Farrell, A. (2003). *Clean Air Markets*. The Encyclopedia of Energy (Forthcoming 2003- 2004). C. Cleveland. New York, Academic Press.

Farrell, A., H. Zerriffi, M. Ilic and S. Talukdar (2002). *White Paper on R&D for Security and Survivability in the Electricity Industry*. Washington, U.S. Department of Energy.

Farrell, A., M.G. Morgan and L. B. Lave (2002). "Bolstering the Security of the Electric Power System." *Issues in Science and Technology*: 49-56.

Farrell, A. and G. Morgan (2003). *Multi-lateral emission trading: Heterogeneity in domestic and international common pool resource management*. *The Commons in the New Millennium: Challenges and Adaptation*. N. Dolsak and E. Ostrom, MIT Press: 169-217.

Farrell, A. and M. G. Morgan (2003). *Multi-lateral emissions trading: Lessons from Inter-State NO Pollution*. *The Commons in the New Millennium: Challenges and Adaptation*. N. Dolšak and e. Elinor Ostrom. Cambridge, MIT Press.

Farrell, A. and H. Zerriffi (2003). *Electric Power: Critical Infrastructure Protection*. The Encyclopedia of Energy (Forthcoming 2003-2004). C. Cleveland. New York, Academic Press.

Farrell, A. and H. Zerriffi (2003). *Improving Energy Infrastructure Security: Costs and Consequences*. 26th International Conference of the International Association of Energy Economists, Prague.

Gregory, R., B. Fischhoff, G. Butte and G. Thorne (2003). "A multi-channel stakeholder consultation process for energy deregulation." *Energy Policy* **31**(12): 1291-1299.

Ilic, M. (2003). *Electric Power Systems Engineering: Methods for Normal and Emergency Conditions*. The Encyclopedia of Energy (Forthcoming 2003-2004). C. Cleveland. New York, Academic Press.

Ilic, M., E. Hsieh and P. Ramanan (2003). "Transmission Pricing of Distributed Multilateral Energy Transactions to Ensure System Security and Guide Economic Dispatch." *IEEE Transactions on Power Systems*, **18**(2): 428-434.

Ilic, M., J. Apt, P. Khosla, L. Lave, G. Morgan and S. Talukdar (2003). "Designing an Interdisciplinary Curriculum for the Changing Electric Power Industry." *IEEE Power Engineering Society Transaction on Power Systems*. Forthcoming.

Keith, D. and M. G. Morgan (2002). *Industrial Carbon Management: A review of the technology and its implications for climate policy*. Elements of Change 2000, Aspen Global Change Institute, Aspen, CO.

Keith, D. W., J. F. DeCarolis, D. C. Denkenberger, D. H. Lenschow, S. L. Malyshev, S. Pacala and P. J. Rasch (Submitted). "The influence of large-scale wind-power on global climate." *Science*.

Morgan, M. G. and H. Zerriffi (2002). "The Regulatory Environment for Small Independent Micro-Grid Companies." *The Electricity Journal* **15**(9): 52-57.

Rode, D. C., P. S. Fischbeck and S. R. Dean (2001). "Monte Carlo Methods For Appraisal And Valuation: A Case Study Of A Nuclear Power Plant." *The Journal of Structured and Project Finance* **7**(3): 38-48.

Rode, D. C., P. Lewis and S. R. Dean (2003). "Probabilistic Risk Analysis and Project Capital Structures." *Journal of Structured and Project Finance* **9**(2).

Rode, D. C., P. S. Fischbeck and S. R. Dean (2002). "Residual Risk and the Valuation of Leases under Uncertainty and Limited Information." *Journal of Project Finance* **7**(4): 37-49.

Strachan, N. (2001). *Distributed Generation and Path Dependence*. 5th International Conference on Technology and Policy Innovation, The Hague, The Netherlands.

Strachan, N. (2003). *Overview of Distributed Energy*. The Encyclopedia of Energy. C. Cleveland. New York, Academic Press.

Strachan, N. and H. Dowlatabadi (2002). "Distributed generation and distribution utilities." *Energy Policy* **30**(8): 649-661.

Strachan, N. and H. Dowlatabadi (2003). *Supplier Strategies and Responses to Institutional Drivers for an Emerging Energy Technology*. International Energy Workshop, IIASA. Vienna.

Strachan, N. and A. Farrell (2002). *Emissions from Distributed Generation*. Utilities Environment Conference. Tucson, AZ.

Strachan, N., H. Zerriffi and H. Dowlatabadi (2003). *System Implications of Distributed Generation: Economics and Robustness*. Critical Infrastructures: State of the Art in Research and Application. P. Herder and W. Thissen. Dordrecht, Kluwer Academic Publishers. Forthcoming.

Strachan, N. D. and A. E. Farrell (Submitted). "Emissions from Distributed Generation." *The Journal of the Air & Waste Management Association*.

Talukdar, S., J. Apt, M. Ilic, L. Lave and G. M. Morgan (2003). "Cascading Failures: Survival vs. Prevention." *The Electricity Journal* **16**(9).

Zerriffi, H., H. Dowlatabadi and N. Strachan (2001). Electricity and Conflict: An Evaluation of Distributed Co-Generation as an Economic and Reliable Solution. 5th International Conference on Technology, Policy and Innovation (Critical Infrastructures), Hague, Netherlands.

Zerriffi, H., H. Dowlatabadi and N. Strachan (2002). System Implications of Distributed Generation: Economics and Robustness. International Energy Workshop. Stanford CA,.

Zerriffi, H., H. Dowlatabadi and N. Strachan (2002). "Electricity and Conflict: Reliability advantages of a distributed system." Cogeneration and On-Site Power Production **3**(1): 29-33.

Zerriffi, H., Hadi Dowlatabadi and N. Strachan (2002). "Electricity and Conflict: Advantages of a Distributed System." Electricity Journal **15**(1): 55-65.

Working Papers

"Electrical Blackouts: Repeating Our Mistakes" Jay Apt, Lester B. Lave, Sarosh Talukdar, M. Granger Morgan, and Marija Ilic

"A Current Study of Automatic Meter Reading Solutions via Power Line Communications" Chong Hock K Goh

"Guidance for Drafting State Legislation to Facilitate the Growth of Independent Electric Power Micro -Grids" Douglas King and M. Granger Morgan

"Market dynamics driven by the decision-making of both power producers and transmission owners" Anna Minoia, Damien Ernst, and Marija Ilic

"Market dynamics driven by the decision-making power producers" Damien Ernst, Anna Minoia, and Marija Ilic

"Maintaining Stability with Distributed Generation in a Restructured Industry" Judith Cardell and Marija Ilic

"Temporal Hotspots in Emission Trading Programs: Evidence From The Ozone Transport Commission's NOX Budget" Alexander E. Farrell

"Cascading Failures: Survival vs. Prevention" Sarosh N. Talukdar, Jay Apt, Marija Ilic, Lester B. Lave, and M. Granger Morgan

"Electric Gridlock: A National Solution" Jay Apt and Lester B. Lave

"Introducing Electric Power into a Multi-Disciplinary Curriculum for Network Industries" Marija Ilic, Jay Apt, Pradeep Khosla, Lester Lave, Granger Morgan, Sarosh Talukdar

"Risk Analysis and Project Capital Structures" David C. Rode, Peter R. Lewis, and Paul S. Fischbeck

"Distributed Power Generation: Rural India – A Case Study", Anshu Bharadwaj and Rahul Tongia

"Transmission Line Siting: A Quantitative Analysis of Transmission Demand and Siting Difficulty" Shalini Vajjhala and Paul Fischbeck

"A Life Cycle Analysis of Electricity Generation Technologies: Health and Environmental Implications of Alternative Fuels and Technologies" Joule Bergerson and Lester Lave

"Literature Review of Demand Elasticity Estimates" Chantal Brandon and Lester Lave

"Transport of Coal by Rail vs. Transmission for Electricity Generation: Application of Hybrid LCA Comparative Analysis" Joule Bergerson, Lester Lave, Chris Hendrickson

"The Cost of Regulatory Uncertainty in Air Emissions for a Coal-fired Power Plant" Dalia Patiño Echeverri, Paul Fishbeck, Benoit Morel, Alex Farrell

"A Technical and Economic Assessment of Selexol-based CO₂ Capture Technology for IGCC Power Plants" Chao Chen, Ed Rubin

"Fossil Electricity and CO₂ Sequestration: How Natural Gas Prices, Initial Conditions and Retrofits Determine the Cost of Controlling CO₂ Emissions" Timothy L. Johnson, David W. Keith

"Is the Answer to Climate Change Blowing In the Wind?" Joseph DeCarolis, David W. Keith

"A Power Quality Study of Carnegie Mellon University." Yinglan Tan.

"The Regulatory Environment for Small Independent Micro-grid Companies" M. Granger Morgan and Hisham Zerriffi

"The Model of Pivotal Oligopoly Applied to Electricity Markets" Dmitri Perekhodstev, Lester Lave, Seth Blumsack.

"Electricity and Conflict: Advantages Of A Distributed System." Hisham Zerriffi, Hadi Dowlatabadi, and Alex Farrell.

"Emissions From Distributed Generation." Neil D. Strachan and Alex Farrell.

"Modeling the Potential Savings of an Air Conditioner Reset Demand Response Program." Peter van der Heijden.

"Residual Risk and the Valuation of Leases under Uncertainty and Limited Information." David C. Rode, Paul S. Fischbeck, and Steve R. Dean.

"Monte Carlo Methods for Appraisal and Valuation: A Case Study of a Nuclear Power Plant." David C. Rode, Paul S. Fischbeck, and Steve R. Dean.

"The First Year of the NO_x budget." Alexander E. Farrell.

"Electricity and Conflict: An Evaluation of Distributed Co-Generation as an Economic and Reliable Solution." Hisham Zerriffi, Hadi Dowlatabadi, and Neil Strachan.

"Distributed Generation and Path Dependency." Neil Strachan.

"Multi-lateral emission trading: Implications for international efforts from two U.S. examples." Alexander E. Farrell and M. Granger Morgan.

"Capacity withholding equilibrium in wholesale electricity markets." Dmitri Perekhodstev and Lester Lave.



Graduate School of Industrial Administration
and
Department of Engineering and Public Policy
Carnegie Mellon University
Pittsburgh, Pennsylvania 15213-3890
www.cmu.edu/electricity