Introducing Electric Power Into a Multidisciplinary Curriculum for Network Industries

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***Abstract*—A qualitatively different graduate level curriculum for teaching electric power systems is needed. The motivation for such a new curriculum is outlined, and a specific program, now being implemented at Carnegie Mellon University, is described. The new curriculum: 1) provides students with a multidisciplinary introduction to the changing problems of the industry; 2) stresses the need for teaching systematic approaches to formulating power system problems; and 3) integrates teaching of the fundamentals for power systems with the fundamentals for other network industries. The program, referred to as the MS in Electric Power Systems (MSEPS) Program, is being developed as a special power-focused track within Carnegie Mellon's existing multidisciplinary Information Networking Institute (INI).**

***Index Terms*—Business, complex infrastructures, curriculum, electric power systems, information, multidisciplinary program, network systems, policy, technology.**

I. INTRODUCTION

WE begin with a brief description of how and why we believe the basic problems faced by the electric power industry have changed. In Section III, we stress the overall importance of systematic problem formulation. In Section IV, we outline one example of new ways to view the power system which are enabled by a new curriculum: viewing the electric power system as a large-scale distributed network. In Section V, we describe in some detail a new multidisciplinary curriculum designed to serve the needs of the changing electric power industry. We rely on the system theoretic problem formulation and its decomposition into subproblems to identify major subdisciplines underlying this curriculum design. Section VI briefly contrasts this educational approach with the more conventional ways of teaching electric power systems engineering. We argue that there are similarities between the education needed for future electric power leaders and those who will address problems in other areas involving networked systems. Finally, Section VII provides several illustrative examples of projects that have been successfully completed at Carnegie Mellon using the multidisciplinary approach advocated here.

II. WHAT CHALLENGES WILL ENGINEERS FACE?

The engineers of the future will have to be able to do everything that engineers do today—and much more. They will have to design, build, and operate generators, transmission and distribution lines, manage the networks for reliable operation, and do all of this safely and with security against attack designed in from the outset. They will have to do this within an environment that is much less friendly and forgiving than the environment their predecessors faced. Emissions regulations will be more stringent, fuel prices are likely to be more variable, and most important, there is likely to be intense market competition. In addition, each decision on new capacity and operations will have to be made with a view to its costs and its expected revenues.

Greater generation efficiency and system reliability can be achieved only if the additional costs are offset by additional revenues—only if they generate profit. This puts a focus on what customers want and what they are willing to pay for. For example, customers in Japan receive much more reliable service than in the U.S.; some customers are willing to pay the costs of greater reliability while most are not.

Advances in technology and competitive markets will produce qualitatively new challenges. For example, future capacity additions are likely to include significant numbers of decentralized generating units of 2 kW to 5 MW. Designing, maintaining, and dispatching these units poses qualitatively new challenges in a grid with thousands of generators and millions of buses. Knowledge limited to operating a 1000-MW generator and 700-kV transmission line will be incomplete in a world with much of the power coming from distributed generation. In the regulated world, almost all customers purchased their electricity at a fixed price, despite the high cost of generating peak power. A future world of real-time pricing could pose challenges to dispatching generation and maintaining stability in the grid. Perhaps the greatest challenge for future engineers will be keeping pace with the technology and economic challenges. Some technologies are evolutionary, such as going from 276-kV ac transmission lines to 900-kV dc lines. Other changes will be revolutionary, such as high-temperature superconducting lines and coal plants with carbon separation and storage.

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Since there is hardly enough time in the current undergraduate curriculum to educate power engineers today, how will we be able to educate power engineers in this new world? There is much to be learned from the education of physicists over the past two centuries. Undergraduates have spent approximately four years studying physics, despite the fact that there is so much more to learn now. The answer is to teach students theory with selective deep exploration of a subject area or experiment. Many "details" are sacrificed since there is not sufficient time to cover all of physics at this level. Instead, the assumption is that a student with a good understanding of the theory can learn the details in an area when required.

The analogy for power engineers is that they will have to focus on learning the theory with some deep explorations into particular areas and experiments. Except for the deep explorations, they will learn little about institutional details or the details of some power system components. The curriculum will provide them with examples from which they learn to apply the theory to a particular problem. Important problems should be chosen for the examples, but the focus of the exercise is to show the student how to apply the theory, not just to learn this particular example. Over their careers, they will have to learn the details of many designs and operations. They must be prepared to translate this theory into design and operation, rather than having the luxury of classroom instruction on the details of a technology. They will also have to know how to incorporate into their design the economics of the market as naturally as today's power engineers incorporate economic dispatch.

Perhaps the most important attribute for current and future engineers is the ability to reduce a complicated situation to a properly formulated model. The real world does not present us with formulae to solve. Rather, we have to examine a complicated situation, decide what is irrelevant detail, and then translate the important features into a model that we can solve. That is a highly demanding skill that we give students too little opportunity to develop and practice in present power system curricula.

III. IMPORTANCE OF PROBLEM FORMULATION

Engineering, like medicine, management, and other professions, is part science, part craft. By "science" and "craft" we mean bodies of experimentally testable information. The differences are in their forms. In a science, the information is explicit, general, and has been distilled into compact expressions, such as laws and theorems. In a craft, the information is more diffuse, may even be tacit, and is often transferable only through apprenticeships and narrow, time-consuming projects.

The ratio of science and analytical methods to craft in engineering curricula has been steadily increasing. Several events have contributed to that evolution at Carnegie Mellon University.

- In 1930, in his inaugural address as president of MIT, Karl Taylor Compton, called for more fundamental sciences in engineering curricula. MIT and most other universities, including Carnegie Mellon, were enthusiastic in heeding this call.
- In 1939–1940, the Carnegie Plan was devised. One of its goals was to develop the science of problem-solving and spread it among engineering students. The result is graduates who are better problem-solvers.
- In 1990, a radical change was made in the structure of the curriculum of the Electrical and Computer Engineering (ECE) Department [1]. The goals were to improve dramatically both breadth and access by flattening the hierarchy of courses, increasing the lateral relations among courses, and providing multiple routes through the elementary courses to each advanced course.

As a result of these and lesser events, engineering curricula at Carnegie Mellon University (CMU) are rich in problem-solving science. Problem-formulation, however, is still very much a craft that is not covered adequately.

Problem-formulation is important because:

- The best possible solution to the wrong problem is the wrong solution.
- Much of the innovation and difficulty in design processes is in the problem formulation.
- Engineers tend to acquire their problem-formulation skills after they have graduated. But in electric power systems, we have become so used to dealing with the same familiar problems that there is no base of problem-formulation expertise on which fresh graduates can draw when they enter industry.

The fundamental components of a well-posed problem are a set of explicit, precisely specified goals, a set of decision variables, and a computable mapping of the decision variables into the goals (that is, practical ways to test any solution or element of decision-space to see if it meets the goals). In 1993, an Engineering Design course (39-405), was instituted at Carnegie Mellon to teach techniques for integrating these three components. The course has been offered every year since, and the fraction of science increases slightly with each offering. In the next offering, we will begin another trend—to introduce more material from power systems into the case studies and projects through which the course's main ideas are conveyed.

IV. ELECTRIC POWER SYSTEMS AS LARGE-SCALE DISTRIBUTED SYSTEMS

Major advances in small-scale distributed sensors, actuators, and information technology (IT) are making distributed intelligence a real possibility by developing data-based models, by verifying these models and updating them in an online setting. The early concepts from generalized systems theory for self-organizing and flexibility and the more recent concepts from computer science on distributed learning for control and multiagent decision making must be combined to achieve highly distributed flexible management for robustness. This is a qualitative departure from the static coordination and conservative design for robustness in all major older infrastructures. We see combining systematic model-based approaches to managing risk in a complex system with various IT intelligence and distributed hardware options as a real opportunity to provide a framework for flexible dynamic robustness in complex electric power systems.

Also, the software-based methods needed to induce system evolution from the current state into a highly decentralized state involving active end users are far behind what is needed and what is possible. Markets, users, and groups can be reaggregated and reconfigured "virtually," via IT, depending on the patterns of use or demand, and the quality required defined in terms of characteristics such as reliability, noninterruptibility, and amount of power, among others. Given multiple sources for power and multiple dynamically reconfigurable markets, a viable new industry structure might center on brokers, owning no assets for generation or transmission themselves, but servicing the IT/reconfigured demand. Such brokers are already present in the industry under transition, but often with poorly defined market rules, particularly in relation to the reliability risks. This is an example of how technology would affect change of policy state.

IT also affects electric power system dynamics because information is not perfect, and the information symmetries are valuable. The ability to use information is not homogeneous and the ability to change or reconfigure in response to demand shifts and opportunities is also valuable. Intertemporal information and asymmetry translate to noncoincidental peaks, thus the use of information can substitute for capacity, convenience, demand, and time.

The impact of IT on the system structure as a whole can scarcely be overstated. Real-time information offers the single most powerful response capability to adjust to system conditions; this is more powerful and important than seeking to forecast a complex nonlinear system. By operating on fact and rapidly readjusting, rather than operating on forecasts that might be wrong, dynamic IT-enabled system response will surely diminish its vulnerability, and transform the system into a highly flexible responsive mechanism.

The IT-based systems engineering for complex network infrastructures is potentially very straightforward. It naturally lends itself to homeostatic control, swarm intelligence, and multiagent reinforcement learning and the like. Dynamic, or virtual, aggregation of many small decision makers to extract the remaining benefits from the economies of scope is a very important challenge. Here, in particular, we see a real opportunity to enhance the use of the interaction variables introduced for dynamic aggregation of the complex system into different layers, as these get formed in response to policy, economic, and technological feedback. Portfolio building by the suppliers or coalitions of consumers becomes a very important mechanism of adjusting the size of decision makers to the technology of interest and its value to the group as a whole. The interdependence of portfolio and coalitions building dynamics and the policy state feedback needs major innovations.

V. A NEW MS PROGRAM IN ELECTRIC POWER SYSTEMS (MSEPS) AT CARNEGIE MELLON UNIVERSITY

In this section, we summarize a new Power Systems Master's Program at Carnegie Mellon University. The program is launched as an inherent part of the Information Networking Institute (INI) educational programs already in place. Like the INI Educational Program, Masters of Science in Electrical Power Systems (MSEPS) was initiated as a cooperative endeavor between the Department of Electrical and Computer Engineering (ECE), the Graduate School of Industrial Administration (GSIA), and the Department of Engineering and Public Policy (EPP). The program emphasizes networks and systems and their business applications, at an advanced level.

MSEPS, the Electric Power Systems track now being developed in the INI Master's Program, fits well into this existing Educational Program at Carnegie Mellon. The INI Educational Program is based on the premise that the future leaders in network systems of various kinds must acquire broad knowledge which goes beyond strictly technological. In particular, the INI program stresses the business/managerial and the policy cores, in addition to the technology core. Moreover, the emphasis of the INI educational programs is on the information systems and the role these play in facilitating performance of particular classes of physical network systems. Given these features of the program already in place, the new MSEPS Program will provide an organized program for those interested in learning about: new challenges in the evolving electric power sector; how to formulate these problems; and how to model them at as high a conceptual level as possible. Once these skills are acquired, the students will be able to chose to concentrate on subproblems involving the technology, business/economics, or policy. The point is that the students will start from the very complex problem and will use systematic methods for identifying assumptions under which only particular aspects of the full problem are studied.

A sample of a schedule for an MSEPS 16-month track is shown in Table I. The program is designed to be customized through electives, but to have a strong core of technology, management, and policy. We briefly describe these core courses below.

The electric power systems program at Carnegie Mellon starts by providing students with a broad introduction to both 1) business (Course 19-731/45-955) and 2) engineering challenges and opportunities in the changing electric power sector (Course 19-733/45-959). The first of these examines the regulated and deregulated power industry economics, including examination of corporate strategy case studies, demand, and generation economics. Students are required to complete a project examining one or more aspects of the power industry. Projects have included analyses of capacity markets, ancillary service pricing, dynamic price equilibrium, economics of demand reduction, and security implications of distributed generation. In the second of these courses, the emphasis is on modeling dynamics of the interconnected power system, and on viewing it as a process driven by technical, economic, and/or policy feedback and feedforward signals. Three distinct operating paradigms are modeled, analyzed, and compared: a) fully regulated, centrally managed power system, b) an electric power system in transition represented as a hybrid dynamic system, and c) fully distributed, highly adaptive power system represented as an entirely decentralized, multiagent driven dynamic system. The course identifies open questions concerning the interdependencies between system architecture, its control, and performance. Various technologies, such as distributed generation, load adaptation, and IT, are assessed in terms of their potential impact on performance.

The required general core technology courses also include 3) broad methods for formulating these real-life problems using systematic approaches (Engineering Design: Creation of Prod-

TABLE I
RELATIONSHIP OF THE CORE, ELECTIVES, AND PROJECT/THESIS IN THE MSEPS INI TRACK

	Fall	Spring	Summer	Fall
Management Core	46-531 (Managerial Economics) or 46-510 (Business Management)	Elective	Thesis	Elective
Technology Core	19-731/45-931 (Challenges and Opportunities in the Electric Industry) and 19-733/45-933 (Modern Electric Power Systems: Operations, Decision-Making and Performance as a Function of Industry Structure)	39-405 (Problem Formulation Methods) and 18-879A (Large-Scale Dynamic Systems)	Thesis	Elective (18-842 (Distributed Systems) strongly recommended
Policy Core	19-701 (Theory and Practice of Policy Analysis)	Project Course	Thesis	Elective
Elective	Elective	Elective	Elective	Elective

ucts and Processes, Course 39-405); 4) generalized methods for modeling, analyzing, and decision making associated with the general problem of interest (Large-Scale Dynamic Systems Course 18-879A); and 5) distributed systems (Distributed Systems Course 18-842).

Students equipped with both the art and craft of formulating complex engineering problems and with the rigorous methods for modeling these problems are now in a position to assess the more specific business and engineering challenges and opportunities in the electric power sector. Using modeling tools acquired in large-scale dynamic systems (18-879A), in particular, the student becomes capable of modeling very complex technical, economic, and regulatory interactions over the various temporal and spatial ranges as a single quite complete model. The model reduction techniques introduced provide students with means of decomposing a complex dynamical model into submodels which are primarily intended for technical, economic, financial, and/or regulatory assessments and decision making.

This is one turning point in the curriculum at which the student realizes the relevance of the other two, nontechnology, core tracks in their educational curriculum. These are Management Core and Policy Core Tracks. The Management Core Track has one required course, Managerial Economics (46-531) or Business Management (46-510). The Managerial Economics course presents the basic concepts of microeconomics with an emphasis on business applications. The approach of microeconomics is understanding the effects of various forms of market structure on the behavior of firms and customers and on economic welfare. The Business Management course includes management functions such as accounting, finance, human relations, and marketing. The importance of information systems is emphasized across all management functions. The Policy Core Track requires taking a course on Theory and Practice of Policy Analysis (19-701). This course is a lecture and discussion course that reviews and critically examines a set of basic problems, assumptions, and analytical techniques that are common to research and policy analysis in technology and public policy. It begins with a rational actor utility maximization perspective, moves on to a behavioral decision analysis perspective, explores some issues in organizational behavior, and group decision processes, and, in light of the preceding, explores several issues in government science and technology policy. The objective is to look critically at the strengths, limitations, and underlying assumptions of policy research and analysis tools and in so doing to sensitize students to some of the critical issues of taste, professional responsibility, ethics, and values that are associated with policy analysis and research.

Each student will participate in one multidisciplinary problem formulation and problem solving power/policy project which deals with research and development of recommendations for solving actual and critical problems currently affecting the power industry. The students, faculty, and graduate student managers for projects will be drawn from Electrical and Computer Engineering, Engineering and Public Policy, the Graduate School of Industrial Administration, the Heinz School of Public Policy, and Humanities & Social Sciences, and, hence, bring different areas of expertise to the structuring and solution of the problem.

A good model for these projects is found in the multidisciplinary project courses now offered in EPP. Although a different topic is chosen for each project, every project has the same basic characteristics: 1) The problem is constrained by technology, politics, and economics. The students participate heavily in the formulation of the problem. 2) A client is defined to focus the framework within which the project is worked. Often, the client agency or institution interacts closely with the students in the project. 3) A set of external experts acts as a client for the project and composes a review panel which critiques class efforts during the semester. 4) Class organization is aimed at putting together a workable set of alternatives to the problem. Typically, small groups of students investigate subelements of the problem; group efforts are coordinated by student managers and faculty advisors; who revise objectives and reassign personnel during the semester. Three formal oral reports are given before the review panel during the semester; a written report is also submitted at the end of the semester. 5) Problem areas for the projects are taken from local, state, and national situations. A recent EPP project course examined the implementation of hydrogen as a power source, and the teams found technical, economic, and workforce barriers to be significant in potential adoption in shipping and trucking. They concluded that the first large-scale adoption was likely be as micro fuel cells for portable electronic devices.

Each student will select electives in the MSEPS program to match his or her goals. Decision analysis, benefit-cost analysis, environmental law and policy, climate and energy, and behavioral decision making are examples of elective courses which will enable engineers in the power industry to apply broad approaches to the technical, economic, and policy issues inherent in a $250 billion industry where generation is continuing to double every quarter century.

VI. COMPARISON WITH EXISTING PROGRAMS

Masters-level courses in power systems engineering are offered at several institutions; in general, these are offered in single departments (usually electrical engineering). A representative sample includes the following. Purdue University's State Utility Forecasting Group and Power Pool Development Group faculty offer a number of courses at the masters and doctoral levels. The University of California at Berkeley's Energy and Resources Group offers graduate courses in Energy and Society, and Interdisciplinary Energy Analysis. The University of Washington offers graduate courses in Power System Economics, Power System Dynamics and Control, Power System Protection, and Large Electrical Energy System Analysis. Arizona State University has available electives in power systems analysis, power engineering operations, and planning, and a project course. At Cornell, a course is offered in principles of large-scale complex adaptive networks (although without an emphasis on power networks). At Georgia Institute of Technology, courses are offered in Energy System Design, Power System Analysis and Control, Power System Engineering, Power Systems Control and Operation, Power System Stability, Power System Planning and Reliability, and Power System Protection. Howard University offers a masters program in power systems engineering including courses in power system control, power system analysis, and computer-aided power systems control (including load flow, load forecasting, unit commitment, load scheduling, network modeling, fault study, transient stability analysis, reliability, future expansion of systems, security and contingency analysis, online dispatch techniques, and state estimation in power systems). Iowa State University's graduate power engineering courses include Steady State Analysis, Power System Dynamics, Operation and Control of Power Systems, Analysis of Distribution Systems, Transient Energy Function Method, Operation and Control, Computer Applications, Dynamics, System Planning, Optimization, and Voltage Stability. The University of Illinois offers graduate-level courses in Power System Analysis, Power System Operation and Control, Modeling and Control of Electromechanical Systems, Power Systems Control, Power System Dynamics and Stability, Electric Utility Resource Planning, and Computational Techniques and Nonlinear Dynamics in Power Systems. The University of Wisconsin program includes Online Control of Power Systems, and Digital Computer Analysis of Large Power Systems. Washington State University offers Electrical Power Systems, Performance of Power Systems, High Voltage Engineering, and Advanced Topics in Power Engineering (covering intelligent systems approaches and power system dynamics).

It is the view of the authors that a multidisciplinary approach combining engineering, economics, and policy is the best training for future power engineers. It is important to contrast the modeling approach taught in 39-405 and 18-879A with the current typical approaches for analysis and decision making in the changing electric power sector. As the industry restructures, it is becoming increasingly important to capture slow interactions between technical, economic, and regulatory signals over time horizons typical of operations planning, planning, and investments. The new Carnegie Mellon University MSEPS program is intended to help students avoid a strictly discipline biased mode of thinking about the opportunities and challenges in the changing electric power sector.

VII. EXAMPLES OF MULTIDISCIPLINARY POWER INDUSTRY SUCCESSES TO DATE AT CMU

We can offer several examples of multidisciplinary power-related projects already underway at Carnegie Mellon [2].

A. Security and Survivability of the Power Grid [3], [4]

We have investigated the implications of regulatory restructuring on the power grid. We combine engineering load models and Monte Carlo simulations of unavailability of grid resources with economic models of externalities to recommend effective measures to mitigate the consequences of coordinated attacks. One conclusion is that a high priority should be given to replacing street traffic signals with low-power light-emitting diode (LED) signals with a stored energy backup, as signal outages result in large economic and psychological consequences. We find that distributed energy resources have quantifiable positive effects on the robustness of the power grid, in addition to their effects on transmission congestion.

We are now examining the architecture of a survivable power grid by exploring 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 will explore the survivability characteristics of candidate architectures, including distributed agent systems for fast, autonomous control. Our approach incorporates both power engineering and economic analysis.

B. Market Structure and Performance [5]

Competitive markets have beneficial properties in terms of satisfying the desires of customers, managers, and investors. However, if a firm has market power and uses that power to raise price or lower quality, eliminating regulation would be harmful. Before deregulating wholesale electricity markets, regulators need to assess the degree of market power that regulators can exert. The Department of Justice measures potential market power by the structure of the market using the Herfindahl–Hirschman Index (HHI). Unfortunately, the HHI is not a good predictor of potential market power in the electricity industry because of the fact that supply and demand for electricity must balance at each moment and storage is extremely expensive. For example, the HHI for California in

2000 indicated it was a highly competitive market, despite the data showing that firms managed to raise price far above the competitive level. A better indication of market power for electricity comes from the notion of a "pivotal" supplier. A pivotal supplier is a generator that could disrupt the market by withholding supply. Our work has shown that in California during the year beginning in June 2000, one firm would have been able to disrupt the market by withholding supply during nearly 10% of the hours. For almost 50% of the time during the period considered, three or fewer firms acting in concert could have set the market price. If six or fewer firms had acted together, they could have disrupted the market nearly every hour of the year. Only by considering the unique engineering requirements of the electricity market can the Federal Energy Regulatory Commission, Federal Trade Commission, and Department of Justice apply an accurate test for market power.

C. Transmission Line Siting: A Quantitative Analysis of Transmission Demand and Siting Difficulty

Despite recurring examples of transmission grid congestion and the widespread call for new transmission construction, transmission line siting is universally described as a difficult and time-consuming process often resulting in construction delays or cancellations of new lines. Problems with individual transmission projects have been attributed primarily to lack of investment incentive, public opposition, regulatory roadblocks, and geographic or environmental constraints. However, most of the information about siting difficulty is anecdotal and project specific, and there is little comprehensive empirical analysis of the factors affecting transmission line siting. Our recent multidisciplinary research addresses the three most fundamental questions of the siting problem: How difficult is siting? What makes it difficult? And, finally, what can be done to ease the problem? We developed four unique measures of the need for transmission capacity and associated siting difficulty, and based on these measures, develops a preliminary model for quantitatively evaluating the factors affecting transmission line siting at the state level.

D. Electricity and Conflict: Quantifying the Advantages of a Distributed System [6]–[8]

Attacking infrastructure is a common military or terrorist tactic. Since a modern economy cannot function without electricity, electric power systems are obvious targets. The rise of organized and systematic global terrorism has increased the need to protect the electricity system in all countries, not just those undergoing conflict or at war. We have made a quantitative comparison of the reliability of an electricity system based on distributed natural-gas-fired units to a traditional system based on large centralized plants. The model shows that the distributed system can be significantly more reliable under stress. The economics of decentralized generation become much more attractive when the system is a combined heat and power system and it is rewarded for the alternative cost of providing the additional reliability and security. Even without considering the benefits of robustness under conflict conditions, a distributed generation (DG) system can result in cost savings with moderate cogeneration. Under the conflict conditions considered, the cost of electricity can be up to 50% lower with a DG system compared with a centralized system. These savings increase if more cogeneration is used. These findings suggest that distributed systems can provide electricity more reliably and at a cost savings both under normal operating conditions and under conditions of stress, such as in a conflict area.

E. Risk Assessment and Financial Appraisal [9], [10]

Financial appraisals typically are conducted using four standard methods approved by the American Society of Appraisers. For large-scale, technically unique projects, such as chemical and power plants, and old industrial practices, these standard methods are insufficient. These types of projects contain political, technical, and economic risks that are not accounted for in standard valuation methods. To include these risks in an appraisal, a Monte Carlo simulation method can be used. Probability distributions are used to model the appropriate uncertainty. Modeling future decisions that may have to be made concerning the project can also be included to add insight to the risk involved. A case study of a nuclear power plant was made. The use of Monte Carlo methods and the modeling of future decisions decreased the worth of the plant by 28% as compared to a standard income capitalization method.

F. 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. Capital investments made today under uncertainty can limit future compliance options or make them very expensive. We have developed a method for computing the cost of operating a moderate-sized, coal-fired power plant under different conditions of future regulatory uncertainty. Using a multiperiod decision model (MPDM) that captures the decisions (both capital investment and operating) that a power plant owner must make each year, the 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 can be calculated.

VIII. CONCLUSION

In this paper, we describe a multidisciplinary program that supports the rapidly changing electric power industry. To be successful, graduates will have to know a great deal more than current programs teach. The program starts from the premise that it is no longer possible to fit into an already crowded engineering curriculum an entirely new electric power systems program. Instead, the proposed program has evolved around the recognition that it is critical to teach broad systematic methods for formulating the problem of interest, and to illustrate these methods in the context of a diverse set of real problems drawn from across the electric power industry. Beginning with this framing, the idea is to build on existing subdisciplines, already taught, in order to provide an option for those interested in electric power.

A design of such a power system curriculum requires relatively few courses specific to electric power. We have described a version of such a program now under development as a track in the existing INI at Carnegie Mellon University.

A reliable and efficient electric power service requires modeling and an understanding of the industry dynamics. The California energy crisis exposed major interdependencies between the quantities and prices of scheduled power, the capacity additions, and the environmental policy. Most interestingly, this crisis evolved through dynamic interactions over fairly long time horizons. Models to analyze and ultimately prevent some of these problems through generalized feedback design in response to economic, technical, and/or policy states a library of models, systematically aggregated over time and space, must be developed in support of software-based tools capable of extracting the interplay of interest.

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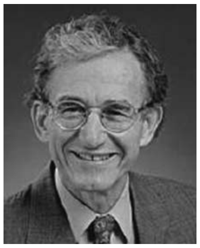

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