System Dynamics and the Electric Power Industry

Andrew Ford[a]

Jay Wright Forrester Prize Lecture, 1996

Andrew Ford is associate professor of environmental science and regional planning at Washington State University. He was formerly a staff member of the Energy Systems and Policy Group, Los Alamos National Laboratory, and associate professor of systems management at the University of Southern California. At WSU, he teaches system dynamics modeling with an emphasis on environmental issues in the West.

Abstract

System dynamics has been used extensively to aid in resource planning in the electric power industry. The many applications constitute a major body of work that has proven useful to large and small power companies as well as to government agencies at the local, state and federal level. The work has been performed by utility analysts, government planners, consultants and academics. One of my recent publications on electric power was honored with the 1996 Jay Wright Forrester Award. This article documents the major points in my award address to the 1996 International System Dynamics Conference. It summarizes the impressive body of work that system dynamics practitioners have accumulated over the past several decades. It gives my interpretation of the important and unique features of the system dynamics approach. I argue also that we have contributed to useful change in the electric power industry. © 1997 by John Wiley & Sons, Ltd. Syst. Dyn. Rev. **13**, 57–85, 1997

(No. of Figures: 9   No. of Tables: 4   No. of Refs: 54)

Introduction, purpose and acknowledgments

This article tells a story of electric power in the U.S.A. It is organized chronologically starting with the birth of the industry in the 1880s. I will explain the main historical developments that gave rise to a capital intensive, price regulated power sector in the United States. I will pay particular attention to the difficult "energy crisis" years of the 1970s. I will explain how the industry survived the difficult years, and I will summarize some of the factors behind the current interest in deregulation.

This article was prepared for the *System Dynamics Review* with several goals in mind. First, I wish to carry on the useful tradition established by Khalid Saeed (1996) in providing a written documentation of the Jay Wright Forrester Award Lecture. Next, I would like to provide a gateway to an impressive body of work for system dynamicists interested in energy. Finally, and most importantly, I wish to share my reflections on why system dynamics practitioners have been successful in this industry. I will argue that our success has arisen primarily from the power of system dynamics to help us "see the feedback" at work in the system. This feature, more than any other feature, has allowed system dynamics practitioners to make a useful and unique contribution to the industry.

The Jay Wright Forrester Award is truly an important honor. I want to thank Professor John Sterman and his colleagues on the award committee for honoring my work on electric power. And I especially wish to thank Professor Jay Forrester and

[a] Program in Environmental Science and Regional Planning, Washington State University, Pullman, WA 99164-4430, U.S.A.

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his colleagues from MIT for developing the methodology of system dynamics which made my work on electric power possible.

System dynamics applications to electric power

Table 1 lists 33 publications on the applications of system dynamics to electric power.[1] The table begins with the national energy modeling project, which has been led by Roger Naill and his colleagues from The AES Corporation in Arlington, Virginia. Naill became interested in the energy problem with his masters research on the exploration and production of natural gas. His thesis was completed in 1972, the year before the 1973 oil embargo. Naill published his natural gas results in *Toward Global Equilibrium* (Naill 1973). He then expanded the model to include oil, coal and other fuels. The models were national in scope and designed to simulate policies that would aid the U.S.A. to reduce its dependence on foreign oil. Naill moved to the newly formed Department of Energy in the late 1970s. He organized the Office of Analytical Services to provide model-based support on US energy policy. His team provided analytical support on a wide variety of energy issues during the difficult years of the 1970s, throughout the 1980s and into the 1990s. His twin articles in the *System Dynamics Review* provide an excellent description of the model and its use at the Department of Energy.

Energy 2020, the second model listed in Table 1, is similar in design to the national model used at the Department of Energy. Energy 2020 was developed by George Backus and Jeff Amlin to deliver a multi-fuel model into the hands of individual energy companies and state agencies. The model has been used by dozens of governmental agencies across the United States and Canada, and the model is now in use in several countries in Europe. The best descriptions appear in the proceedings of the Energy 2020 users conferences listed in Table 1.

Table 1 gives four references on the Conservation Policy Analysis Model (CPAM) and the Resource Policy Screening Model (RPSM), two models used by resource planners at the Bonneville Power Administration. I developed these models with the help of Jay Geinzer and Roger Naill from The AES Corporation. The best general description appears in the April 1987 issue of *Energy Policy*. The *Operations Research* article is noteworthy for its description of uncertainties in the Northwest power system.[2]

Three articles on electric cars and their impacts on the electric utility company are listed next in Table 1. This research used system dynamics to simulate automobile purchase decisions by consumers (i.e., gasoline cars or electric cars?). The important feature of the model was the integration of vehicle choice with a model of the power company. The model was used to argue against utility

Table 1. System dynamics applications to electric power

The national model (Fossil2, Ideas)
Naill, *Managing the Energy Transition*, Ballinger, 1977
Naill and Backus, *Technology Review*, July 1977
Naill *et al. System Dynamics Review*, Winter 1992
Naill, *System Dynamics Review*, Summer 1992
The AES Corp, An Overview of the Ideas Model, Oct 1993

Individual companies and state agencies (Energy 2020)
Backus and Amlin, *Proceedings of the 1985 System Dynamics Conference*
Systematic Solutions Inc., Introduction to Energy 2020, Jan 1988
Central Maine Power Company, The Energy 2020 Users Conference, June 1989

The Pacific Northwest Hydroelectric System (CPAM, RPSM)
Ford, Bull and Naill, *Energy Policy*, April 1987
Ford and Bull, *System Dynamics Review*, Winter 1989
Ford and Geinzer, *Energy Policy*, May 1990
Ford, *Operations Research*, July 1990

Electric cars and the electric utility
Ford, *Energy Policy*, 1994
Ford, *System Dynamics Review*, Spring 1995
Ford, *Public Utilities Fortnightly*, April 1996a

Privatization (UK) and deregulation (USA)
Bunn and Larsen, *Energy Policy*, May 1992
Bunn, Larsen and Vlahos, *Journal of the Operational Research Society*, 1993
Lyneis *et al.*, *Proceedings of the 1994 System Dynamics Conference*
Bunn and Larsen, editors, *Systems Modelling for Energy Policy*, 1996
Amlin and Backus, *Utility Models for the New Competitive Electric Markets*, 1996

System dynamics models at forums or workshops
EPRI Report on Utility Corporate Models (UMF-2), Oct 1981
Los Alamos Report on Utility Regulatory-Financial Models, June 1983
Stanford Report on Coal in Transition (EMF-2), Sept 1978
Stanford Report on Elasticity of Energy Demand (EMF-4), Aug 1980
Stanford Report on Markets for Energy Efficiency (EMF-13), Sept 1996
Stanford Forum on Privatisation and Deregulation, in progress

Emerging areas (electricity & water)
Aslam and Saeed, Electric Power in Pakistan, The 1995 Conference
Wang *et al.*, Infrastructure in China, The 1995 Conference
Dyner and Bunn, Electric Power in Colombia, The 1996 Conference
Sunaryo *et al.*, Watershed Management in Java, The 1996 Conference
Barton and Pumandu, Water Utility Planning in Australia, The 1996 Conference
Ford, Water Uses on the Snake River, *System Dynamics Review*, 1996b
Shawwash and Russell, Water Management in Jordan, The 1996 Conference

sponsored financial incentive programs to promote electric vehicle sales. In my opinion, a better policy is a state run feebate program to promote the sale of any or all of the cleaner vehicles.

Table 1 notes that the privatization of the government owned power industry in the U.K. and the deregulation of the privately owned power industry in the U.S.A. have been the subject of systems dynamics investigations by Derek Bunn and Erik Larsen, by James Lyneis and by Jeff Amlin and George Backus. I will return to the reasons for the growing interest in deregulation later in the article.

The forum and workshop reports listed in Table 1 serve as a gateway to some of the "gray literature." These reports are not as readily available as the journal articles, but they often provide a richer and more practical account of the key features of the models. The reports from the Stanford University energy modeling forum are especially useful. They describe models used in situations where an energy topic has been the focus of several modeling efforts. The forum concept makes good sense in light of Greenberger's (1976) description of the many obstacles to the informative use of models in the political process. Greenberger reviewed a variety of modeling approaches (including system dynamics) and a variety of case studies where models had been misused. The review led him to propose "the development of a new breed of researcher/pragmatist — the model analyzer — a highly skilled professional and astute practitioner of the art and science of third-party model analysis" (Greenberger *et al.* 1976, 339). The Stanford forum is a logical and useful response to his proposal.

The final entries in Table 1 list system dynamics applications to electric power planning and water resource planning that have emerged in recent years. In several cases, these models focus on a major river system where hydro-electric development and irrigated agricultural development have led to unexpected problems. I'll speak to the importance of this emerging area at the conclusion of the article.

The body of work summarized in Table 1 is an impressive record of application, especially since the majority of the research was not initiated until the mid 1970s. To interpret properly this work, it is useful to review the history of electric power in the U.S.A.

Electric power in the early years

Figure 1 shows a historical time line starting with the "birth" of the industry in 1882 and concluding with the growing interest in deregulation in the 1990s. Table 2 provides more details on the early years.[3] One of the most important developments occurred in the 1880s during the debate over electric transmission .[4] The debate is sometimes called the AC/DC debate. In technical terms it was a debate over AC (alternating current) transmission versus DC (direct current) transmission. In personal terms, it was a debate between the giants of the industry.

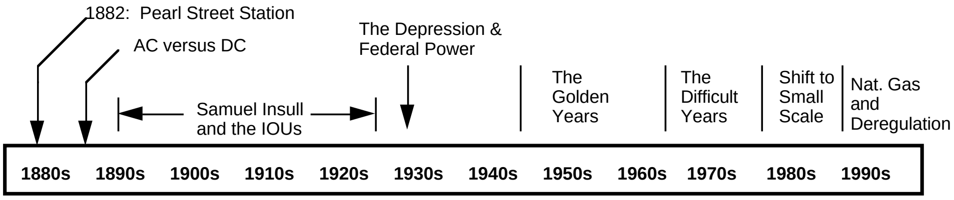


Fig. 1. History of electric power in the U.S.A.

Westinghouse favored AC; Edison favored DC. And in organizational terms, it was a debate over the fundamental shape of the industry.

DC transmission relied on low-voltage power lines running short distances from the generating station to the consumer. AC transmission required transformers to "step up" the voltage for transmission over longer-distance lines. The proponents of DC transmission envisioned an industry with many, small power generators. According to Munson (1985, 55), the "smart money" was on DC. For example, J. P. Morgan is said to have favored small-scale systems that could be mass-produced and sold at a substantial profit to factories and office buildings. But the proponents of AC transmission had an entirely different vision. They saw an industry with larger, more efficient power plants interconnected with a large number of customers. Bigger power stations could be designed to convert fuel into electricity in a more efficient manner. And the bigger power stations could be operated more efficiently if they served a larger number of customers (with diversity in their hour-by-hour demands for power). The vision of larger power stations won out, and Edison's role in the power industry faded.

The most important individual to shape the American power industry is probably Samuel Insull, an Englishmen who emigrated to America in 1881 to serve as Thomas Edison's personal secretary. Insull struck out on his own in 1892, when he took the controls of the Chicago Electric Company. Insull was convinced that the path to large profits in electric power was through the sale of electricity (not necessarily the sale of electrical equipment). By 1907, Insull was a millionaire and the ruler of Chicago's electricity monopoly. By 1911, his engineers had created the world's largest power station. He expanded his business beyond Chicago, and by 1912, his "empire" encompassed 400 communities throughout 13 states.

One threat to Insull's expansion was public power. Some towns and cities argued that electric power is a basic, public service. They took over the electric power facilities and financed their subsequent expansion through the sale of public bonds. Fearing the encroachment of public power, Insull devised a plan to give the public limited control over private power. Insull argued that each state should form a "public utility commission" to be staffed by professionals with knowledge of the industry. Insull argued that privately owned utility companies should continue to enjoy monopoly privilege in their service territories so that the company engineers

Table 2. History of electric power in the U.S.A.: the first eight decades

1882	Pearl Street Station	At 3:00 p.m.on Sept. 4, 1882, the "jumbo generator" at Pearl Street Station begins to spin. The electricity is transmitted by DC lines to the Wall Street office of J. P. Morgan and to the editorial room of the *New York Times*.
1880s	AC transmission	William Stanley invents the AC transformer to "step up" to high-voltage transmission over longer lines. George Westinghouse installs AC systems.
1880s	AC versus DC	The first major battle over the *scale* of power generation pits Westinghouse versus Edison. Edison (and J. P. Morgan) favor small, mass-produced generators with DC transmission. Westinghouse favors larger stations with AC lines to a larger group of customers. Despite the controversy over the safety of AC, Westinghouse prevails.
1890s–1920s	Samuel Insull and the IOUs	Insull builds a monopoly power company in Chicago. The organization of the private power industry in the U.S. is established. Monopoly privilege is given to promote investment in *large-scale* generation. The electric rates are subject to regulation by state commissions, which are to guarantee a fair return on investment. The companies become known as Investor Owned Utilities or IOUs.
1930s–1940s	Franklin Delano Roosevelt	The federal government invests in hydro-electric generation in the Tennessee Valley and on the Columbia River. Federal financing permits *large-scale hydro* projects with multiple uses. Aluminium smelters appear to fill the need for a *large-scale consumer* of cheap power. But private power from IOUs building mainly thermal generating units is the rule for most of the U.S.A.
1940s–1960s	Golden years	Three decades of steady growth in demand and steady improvements in the $/kW cost and efficiency of *larger and larger* power generation appear to confirm the value of Insull's organizational model. The period culminates with the construction of extremely large coal plans (i.e., 3,000 MW). The industry also invests in nuclear power stations using the light-water reactor technology. Some power stations are so large that companies from several states must combine to finance construction.

could pursue economies of scale. But he argued that abuses of monopoly privilege could be controlled by the state commissions. The commissions' purpose was to oversee the electric rates charged by the power companies. Rates were to be fixed by the state commissions to allow the power company to recover its costs and to earn a reasonable profit. Utilities, for their part, would commit themselves to building the power stations needed to serve the customers within their service territory.

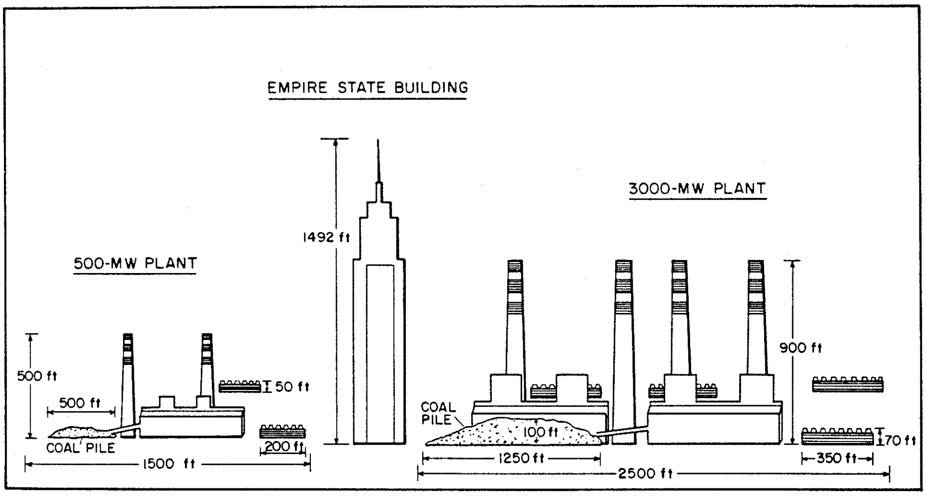


Fig. 2. Comparison of large and small power plants

The golden years

Insull's plan allowed privately owned power companies to grow and flourish in the U.S.A. The private companies became known as IOUs or investor-owned utilities. Today, the IOUs account for roughly 80% of electric power in the United States, a business with close to $1 trillion in assets (Electric Power Research Institute 1996).

Insull's plan set the stage for tremendous growth in the industry. The demand for electric energy grew at around 7%/year, doubling the need for electricity every decade. To keep pace with the rapidly growing demand, the IOUs turned to larger and larger power stations. Company engineers were successful in designing bigger and better power stations during the "golden years" of the 1940s, 1950s and 1960s. Each new wave of power stations allowed the retirement of older, less efficient power stations. Regulatory commissions found themselves reviewing electric rates that were always sufficient. That is, the current rates, multiplied by current electricity sales, always generated the necessary revenues to pay this year's bills and finance next year's construction. Electric rates remained relatively constant (in nominal dollars) over many decades as company engineers succeeded with bigger and better power plants. By the end of the golden years, power plants were coming on line at the immense size of 3,000 MW shown in Figure 2.

The difficult years

The golden years came to an end in the 1970s. Industry engineers could no longer deliver reductions in capital cost with larger power plants,[5] and environmental regulations were driving up the cost of fossil-fueled power stations. The Arab oil embargo of 1973 signaled the beginning of the "energy crisis," and the 1970s witnessed two major increases in oil prices. Higher oil prices translated into higher prices for coal and natural gas, so annual fuel bills rose dramatically. But the biggest problem was the huge rate of inflation. By the end of the decade, the nation was experiencing "double digit" inflation, and utilities were hard hit by an even higher escalation in construction labor costs. Power plants were taking much longer to build, and their costs were much higher than in the golden years. Utilities found themselves with declining internal funds to help pay for construction. When they turned to the Wall Street, they were confronted by unusually high costs of capital.[6] The financial problems were painfully evident from the following headlines in the business press:

Utilities: Weak Point in the Energy Future

Utilities Need Help — Now!

Con Edison: Archetype of the ailing utility

Electric industry cutback could result in blackouts

Faced with serious financial problems, some utility companies cut back on the construction of new power stations thought to be needed to serve future demand. Industry experts feared that the long, successful history of "keeping the lights on" was about to be broken.[7] These problems are summarized in Table 3, which continues the historical summary from the previous table.

Figures 3 and 4 use a stock and flow diagram to show the change in the financial situation during the 1970s. Figure 3 shows numerical values representative of the "golden years." The input variable is the *capacity needed now*, which is at 10 GW.[8] The utility has 10 GW of *installed capacity* and another 4 GW of *capacity under construction*. If the construction lead time were around five years, the utility planners would look five years into the future to obtain the *forecast of future need*. Figure 3 shows this forecast at 14 GW based on the 7% annual growth that was common in the golden years. Figure 3 shows the utility with the needed 4 GW under construction. A simple indicator of the financial challenge is to compare the *construction work in progress* with the *book assets* of the company. With new power plants costing less than the older power plants, this utility would face the

Table 3. History of electric power in the U.S.A.: the last three decades

1970s	Difficult years	The golden years come to an end owing to the combined impact of the energy crisis, double-digit inflation and environmental concerns over coal and nuclear power. IOUs have too much generating capacity and too little cash. Public utilities face similar problems. Some utilities go bankrupt. Some utilities question the benefits of large power stations. Other companies question the benefits of rapidly growing demand. Congress passes PURPA to encourage private generation (i.e. cogeneration).
1980s	Shift to small scale	Utilities move to *smaller-scale resources* in four directions: 1. orders for nuclear power plants are canceled; 2. smaller coal-fired plants are preferred over larger plants; 3. purchases from PURPA cogenerators grow; and 4. utilities give their customers direct financial incentives to be more efficient. Efficiency programs are mandated in many states as part of "least cost planning".
1990s	Natural gas and deregulation	Low-cost natural gas and efficient, combined-cycle generators become available at still *smaller-scale*, and it is possible for private companies to finance their construction without monopoly privilege. Deregulation of the generating business is expected, but there is uncertainty about the timing and form of deregulation Utilities are reluctant to add new generating souces. Utilities cut back on efficiency programs as well as on R&D programs to prepare for competition. Planning horizons, that once stretched over 20 years, now focus on competition in the next two years.

challenge of financing $3 billion worth of construction from a $10 billion base. Utilities were able to meet this challenge throughout the golden years.

Figure 4 shows the same stock and flow structure, but a different set of numbers. The starting point is the same as the previous figure: a $10 billion company has 10 GW of capacity which is exactly the amount needed to meet current needs. But the projections for the future are quite different. First, the lead time is much longer. By the 1970s, lead times for new coal and nuclear power plants could stretch out to 10 or 15 years. Figure 4 assumes a 10 year lead time to keep the illustration simple. Utility planners expected power demands to continue growing at the historical rate of 7%/year, so the *forecast of future need* is shown at 20 GW. I show 8 GW of *capacity under construction* to reflect a situation where the utility is not doing enough to keep pace with forecasted demand. With new power plants costing more than the older plants, the construction work in progress is now shown at $10 billion. The power company now faces the challenge of financing $10 billion in expansion with an asset base of only $10 billion.

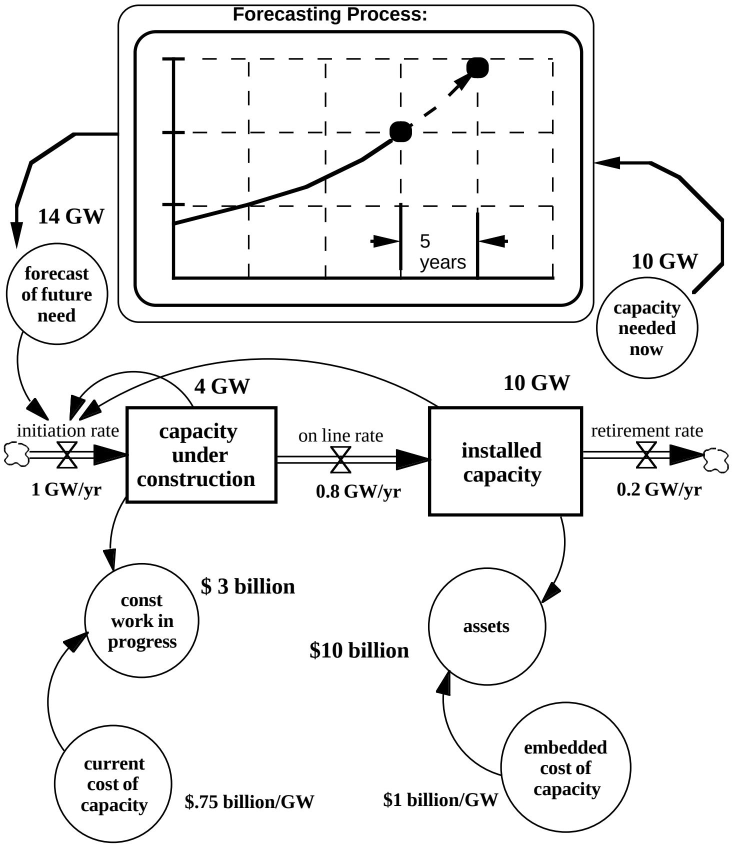


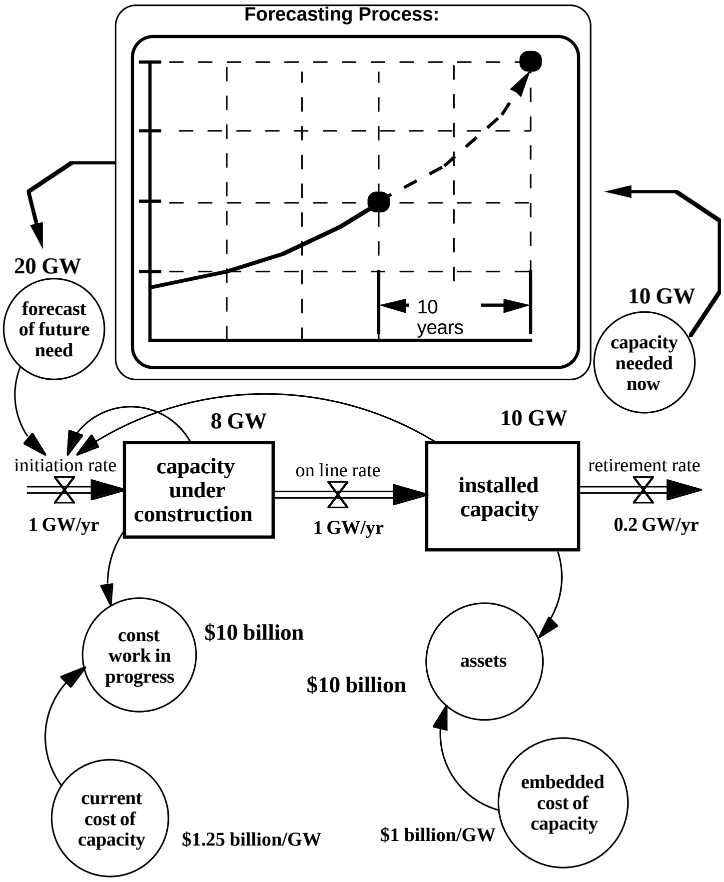
Fig. 3. The financial challenge during the "Golden Years"

The three fold increase in the financial challenge shown in Figures 3 and 4 sheds light on the dire news headlines listed previously. I should emphasize that these headlines were not necessarily exaggerating the problem. Indeed, the financing requirements of the electric utility industry were so staggering, that one expert estimated that IOUs could require one-third of all new equity available each year to the US business sector (Hass *et al.* 1974, 85).

The IOUs, the regulators and the death spiral

Faced with the challenge shown in Figure 4, the IOU executives turned to the regulators for help. They argued that they had kept their part of the "regulatory bargain" by expanding capacity decade after decade to serve the growing demand for power. They asked the regulators to now "do their part" and raise the electric rates. The IOUs argued that higher rates were needed to cover increased operating

Fig. 4. The financial challenge during the "Difficult Years"



costs and to help the company build its financial ratios to a sufficiently attractive level to regain the confidence of the financial community.

The regulators responded by implementing several regulatory changes to raise the electric rates. ("Fuel clause" adjustments, for example, were implemented to automate the changes in electric rates due to changes in the price of fossil fuels.) But the regulators were not sure that meeting all the IOUs' requests for rate increases would solve the problem. They asked about the likely consequence of large rate increases. Would not the higher rates depress the sale of electricity? And could lower electricity sales reduce the utility revenues? If this were to happen, the utility might return to the regulator for yet another rate increase. This vicious circle appeared in headlines as follows:[9]

The Vicious Circle that Utilities Can't Seem to Break: new plants are forcing rate increases — further cutting the growth in demand

The Electricity Curve Ball: declining demand and increasing rates

Figure 5 portrays the vicious circle, along with other feedback loops at work in the system. This diagram is taken from a system dynamics study of the planning problems of a hypothetical IOU. The study used computer simulation to portray the IOU's problems under a wide variety of circumstances.[10] Like many complex models, the IOU model contained hundreds of feedback loops. But the three loops in Figure 5 stood out as most influential.

The "death spiral" in Figure 5 involves the electric rates and the consumers' reaction to the rates. The *indicated price* stands for the price of electricity that regulators would normally allow to let the utility generate the *allowed revenues*. The *actual price* follows the *indicated price* after a delay for regulatory review. If the actual price were to increase, one would expect a decline in *electricity consumption* after a delay for consumers to react. Lower *electricity consumption* could then lead to an increase in the *indicated price*, an increase in the *actual price* and further declines in *electricity consumption*.

The outer loop in Figure 5 shows a negative feedback loop. Starting with an increase in the *actual price*, we would expect a decline in *electricity consumption*, a reduced *forecast of capacity needs*, reduced capacity initiations, reduced capacity, a lower *rate base*, a reduced revenue target, a reduction in the *indicated price*, and a reduction in the *actual price*. Figure 5 labels this loop the "delayed demand control loop" because its controlling influence is felt only after:

- a regulator's delay to adjust prices,
- a consumer's delay to adjust electricity consumption,
- a forecaster's delay to adjust forecasts based on new trends; and finally
- a construction delay for new generating capacity to come on line.

The third loop in Figure 5 is the construction loop. This is a goal-oriented, negative feedback loop to represent the company's desire to bring installed capacity into balance with required capacity. This third loop includes only one delay, but the delay can be quite long if the utility is building large coal or nuclear power plants.

The spiral study revealed that utilities could find themselves in a difficult "downward spiral." Their situation was especially difficult if their customers

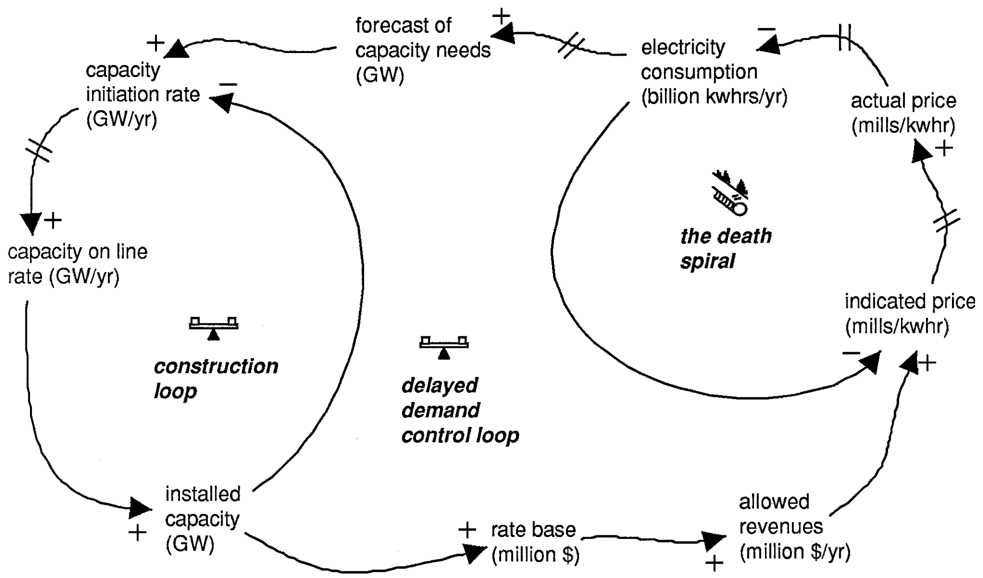


Fig. 5. Key feedback loops in the utility system

reacted quickly and strongly to changes in the electric rate while they were stuck with long lead time power plants under construction. Simply waiting for regulators to grant the requested rate increases would not necessarily solve their problems. We learned that the utility could take steps on its own to soften the impact of the "death spiral." The best way to improve their situation was to shorten the length of the construction delay. This could be done by shifting investments from long lead time generation technologies (i.e., nuclear plants or large coal plants) to short lead time technologies (i.e., small coal plants, geothermal stations or wind machines). We also learned that the debilitating effects of the "death spiral" would be greatly reduced if the IOU were expanding its system to keep pace with slow growth (i.e., 1–2 %/year) rather than the rapid growth of the "golden years." Slower growth rates could be achieved by utility conservation programs that would actively encourage their customers to invest in more efficient energy equipment.

1980s: the shift to small scale

The 1980s was a decade in which utilities shifted emphasis from large power stations with long lead times to smaller, shorter lead time resources. Table 3 notes that the move to smaller scale was manifest in:

- the cancellation of nuclear plants;
- a shift to smaller coal plants;

- an increase in cogeneration; and
- an increase in utility conservation programs.

Nuclear power stations were ordered in great number in the 1960s and early 1970s. They were especially popular with coastal utilities far removed from the nation's coal fields. These utilities invested in light water reactor stations because of a perceived advantage in total life cycle cost. But the high capital cost and long lead times made nuclear reactors one of the least attractive choices for the 1980s. Orders for new reactors fell to zero, and many plants were canceled part way through their construction intervals. The cancellations occurred in both private and public power.[11]

Large coal-fired power plants also fell out of favor in the 1980s. The trend toward extremely large coal plants had led to the 3,000 MW example shown in Figure 2. But the long lead time and high capital costs made the super-large power stations a poor choice for the 1980s. The 500 MW variety shown in Figure 2 became much more attractive for utilities facing major uncertainties in demand growth.

Cogeneration resources were also popular in the 1980s. Encouraged by the passage of the Public Utility Regulatory Policy Act (PURPA) of 1978, private companies invested in small scale machinery to produce both steam and electric energy. These companies were able to sell their “extra electricity” back to the power utility at a guaranteed rate. Cogeneration is attractive because the combined generation of steam and electricity makes more efficient use of fossil fuels. Cogeneration purchases were also viewed as especially attractive to IOUs (and their regulators) facing the problems of the “death spiral.”

The fourth and most dramatic shift in the 1980s took the form of increased emphasis on conservation. Utilities no longer viewed a rapid growth in demand as desirable for the company. They began to pay attention to how their customers used electric energy, and they discovered that electric energy was being consumed in a highly inefficient manner. If their customers could be encouraged to use electricity more efficiently, the pace of demand growth could be slowed, and utilities could reduce the risks of carrying long lead time construction projects to completion.

Figure 6 dramatizes the northwest utilities' commitment to conservation. It shows the northwest wrapped in a thick blanket of insulation. Northwest utilities went from home to home to encourage their customers to take advantage of cost-effective measures like insulation. Utilities provided audits, loans and direct financial incentives to encourage their customers to use energy more efficiently. These programs would have been inconceivable during the golden years. Indeed, it is probably hard for any manager to appreciate why a private company would encourage its customers to use less of its product. But, to their credit, utility managers and regulators saw the wisdom in encouraging efficiency. They had

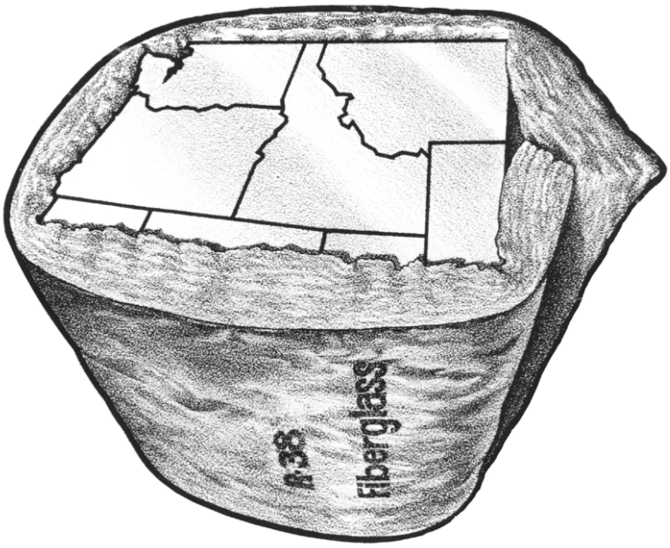


Fig. 6. Wrapping the northwest with cost-effective conservation. Reprinted with permission. *Source*: Bonneville Power Administration

learned that it made good business sense to help customers plug the leaks in their houses. Helping to plug the leaks was much less risky than investing in long lead time power plants.

The Bonneville model

I interrupt the historical review to provide a quick glimpse inside one of the models from Table 1. My purpose is to provide a few details to allow readers to appreciate the difference between the system dynamics approach and the more common approach used by utility companies. I select the Bonneville conservation model for discussion, but readers should know that my main observations apply to all utilities, not just to Bonneville.

The Bonneville Power Administration was created in the 1930s when the federal government invested in hydro-electric development on the Columbia River. Bonneville's job is to market the electric power from federal resources in the northwest. Like many utilities, Bonneville encountered some serious difficulties in the 1970s. Like many utilities, Bonneville too saw the wisdom of shifting to small scale resources in the 1980s. Bonneville became a national leader in conservation programs with the creation of a separate Office of Conservation in 1983. This Office turned to system dynamics to provide analytical support for policy issues regarding the magnitude, mix and timing of conservation programs.

Fig. 7. Design of the Conservation Policy Analysis Model

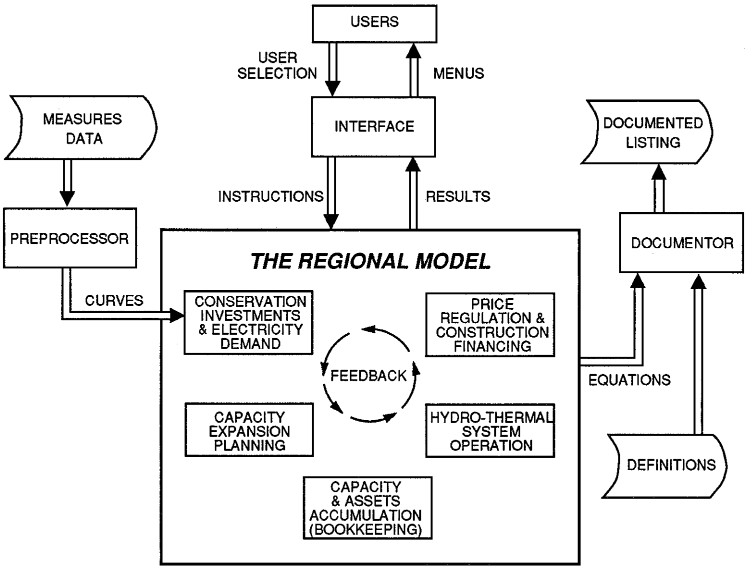
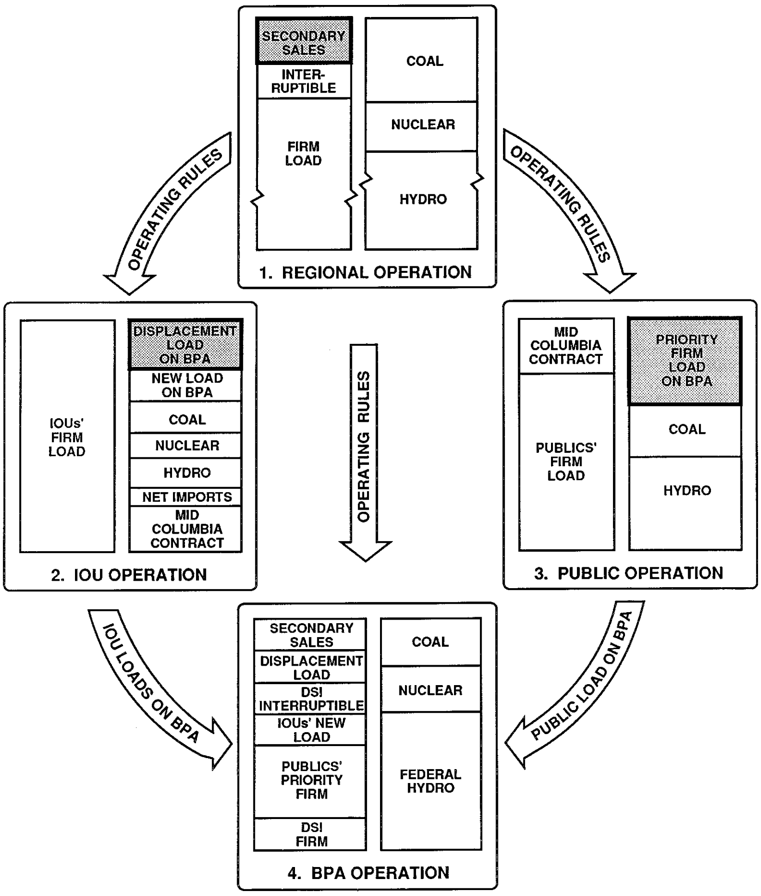


Figure 7 shows the sectoral design of “The Regional Model,” the first of several models constructed for Bonneville. The diagram depicts five separate “sectors” to keep track of electricity demand, capacity expansion planning, book keeping, system operations and the setting of electricity rates. The model was originally constructed in DYNAMO, and it will be appreciated that each “sector” is simply a group of DYNAMO equations devoted to a different part of the system and that the information feedback loops will be automatically closed when the entire collection of equations are simulated on the computer.

The system operation sector is shown in Figure 8 to give a taste for some of the modeling details. Figure 8 shows a four-step procedure to calculate the annual operating costs for the three groups of utilities in the northwest. Starting at the top of Figure 8, the sector conducts a regional comparison of the loads and resources.[12] This comparison reveals the best way to balance the supply and demand for electric energy for the entire region. In this illustration, the system would be balanced by the sale of secondary energy to utilities outside the region (the shaded box at the top of Figure 8). The regional comparison yields “operating rules” that all utilities will follow. In this example, utilities will run nuclear and coal plants at full availability, but oil- and gas-fired plants will remain idle. The separate balancing of loads and resources reveals that neither the IOUs nor the public utilities can satisfy their demands unless they place loads on Bonneville. Bonneville’s operations are portrayed at the bottom of Figure 8. Bonneville meets the loads from the direct service industries and, the loads from retail utilities, as well as having some extra energy left over to sell on the secondary market.

Fig. 8. Simulating hydro-thermal system operations



The approach in Figure 8 was implemented in a highly aggregated manner. All the IOUs coal-burning units, for example, were combined into a single category rather than treating each and every unit. The calculations were also aggregated over the 12 months in a year by treating total annual loads. Our simplified calculations were then checked against the more detailed results available from Bonneville's existing models of system operations. After benchmarking, the Figure 8 approach provided a unique portrayal of system operations. The unique feature was not the estimated operating costs, but the inclusion of the operating costs within a system dynamics model that automatically closes the feedback loops in the system. To appreciate this unique advantage, it is worth describing the common utility approach to computer simulation.

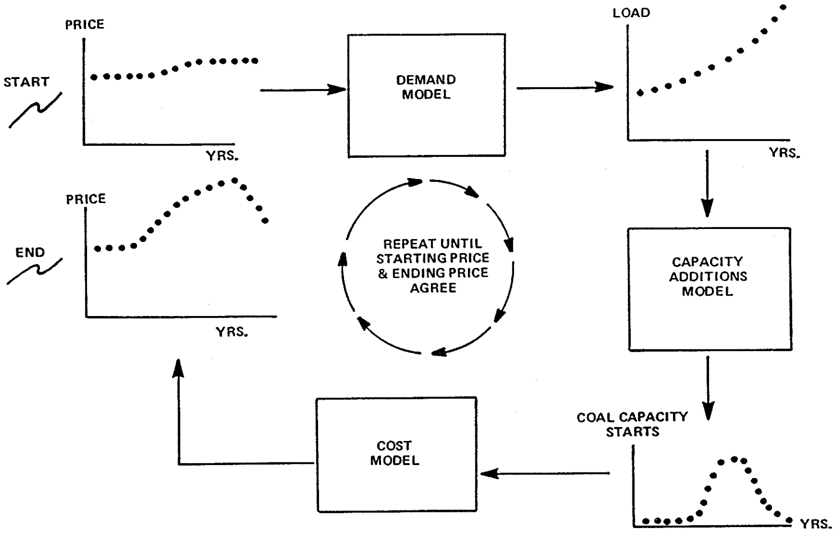


Fig. 9. The iterative modeling approach often used by utility companies

The common utility approach

The common utility approach is to link a series of departmental models together as shown in Figure 9. This diagram shows three models for simplicity, but a large, well staffed utility might develop a modeling system with 30 or more models. Figure 9 begins with a set of electric rates needed as input to a demand model. The output of the demand model takes the form of electric load for each of 20 years in the future. These results could be fed to a capacity expansion model. The output of the expansion model is shown as a plan for new power plant construction during the 20 year planning period. This plan would form the input for a third model to calculate the utility revenue requirements and electric rates. The electric rates at the end of the process are then compared with the rates used to start the modeling. If the two sets of rates are significantly different, the utility analysts might adjust the input rates and repeat the entire sequence of calculations. Through artful manipulation of the starting rates, the modeling team might obtain a consistent set of projections with a small number of iterations.

The iterative approach in Figure 9 was popular with utilities because it allowed them to take advantage of existing models. The existing models were often developed in separate departments and had grown to be quite complex in order to serve each department's need for detail. They were sometimes implemented in different programming languages, and they sometimes resided on different computers, depending on the needs of each department. The principal drawback of the iterative approach is the long time interval required to prepare and complete an internally consistent set of projections. In practical terms, the iterative approach seldom resulted in a consistent set of projections.[13] The more common approach was simply to ignore the inconsistencies that arose from the lack of information feedback within the system.

Single-company models

Faced with the problems in Figure 9, some utilities developed a single computer model to cover all aspects of the company. The models were frequently developed by outside consultants who had established their credibility with one of the departmental models. The single models were designed with a single programming language and to reside on a single computer. They were successful in reducing the time interval required to obtain a comprehensive projection, but the common utility models were not successful in simulating the information feedback at work in the system. In a forum with 12 corporate models convened by the Electric Power Research Institute, for example, all but one of the models ignored the price feedback loop shown in Figure 5 (Electric Power Research Institute 1981). And in a workshop with 13 models of utility regulatory-financial problems, all but two of the models ignored the price feedback loop shown in Figure 5 (Ford and Mann 1982). In both of these workshops, the exceptional models were system dynamics models.

The first workshop was conducted in 1981 to compare “corporate models.” The forum members agreed that the top-priority issue needing modeling support was utility conservation programs. Each modeling team agreed to a common collection of assumptions about inflation, economic growth, fuel prices, etc. Then each team adopted a common description of a conservation program. Each team performed a variety of computer studies to show the simulated impact of the conservation programs. The modeling results were arranged side-by-side to allow a broad comparison. Each model’s results were labeled by letters (i.e., A, B, C) to preserve anonymity, but I can report that “Model D” was the system dynamics model. The forum team compared the simulations with an eye toward general conclusions about modeling approaches. They were not out to label one result as “right” and another as “wrong.” Rather, they wanted to learn if the differences in underlying approach would lead to qualitatively different findings. Their findings are especially noteworthy to system dynamics practitioners because of the prominence of “Model D”, the only system dynamics model at the forum. Remember that the forum members were especially well informed on corporate planning issues and computer simulation models. Also, remember that many of the modeling teams had committed company resources to approaches other than system dynamics. Given the unusual qualifications and position of the members, their observations are worth repeating in detail:

> Model D consistently displayed startlingly different and counterintuitive patterns of behavior — so much so that it quickly became the focal point of the Working Group's efforts to compare model capabilities ... Model D was found to be less detailed, contain fewer equations (by far), and cost less to develop and run than the detailed models ... From this information alone, it might have been concluded that Model D was likely to be "inferior" to the larger models ... By the time the group had completed a very probing assessment of Model D, a number of important changes in the thinking of the group had occurred ... The underlying bases for the dynamic features were highly intuitive, but were also likely to cause more rapid response and a greater degree of instability (i. e. large price elasticities reduced demand which lowered revenues and led to a spiraling decline in financial performance) ... Overall, what initially could have been dismissed as an interesting but unsuccessful experiment in small model building came to be viewed as a potentially useful and powerful corporate modeling tool.

I consider the forum report to be one of the most resounding endorsements of system dynamics, and, of course, the report is a resounding endorsement of the team from Florida Power and Light Company and Pugh Roberts Associates that developed Model D.[14]

The Florida team joined a dozen other utility modeling groups in a workshop conducted at the Los Alamos National Laboratory in 1982. The modelers assembled to review different approaches to simulating the financial problems that plagued IOUs at the end of the 1970s. The number one issue was "regulatory reform," a general term for a variety of proposals to improve utilities' cash flow through higher rates or lower taxes. Thirteen models were represented, but only two of the models closed the feedback loops shown in Figure 5. One was the Florida model; the second was my model of the "death spiral." The workshop provided an opportunity to compare model designs and the modeling environments. The conventional view (from the 11 models without feedback) was that price feedback could be distracting to top management. Several of the most experienced modelers argued that utility companies invested considerable time and expense arriving at their best demand forecast. The conventional view was that price feedback could confuse top management because each new simulation might show a different pattern of demand growth. The conventional modelers also argued that closing the price feedback loop required them to specify the price elasticity of demand. With uncertainties in the price elasticity, they suggested that closing the loop would be speculative rather than informative. The Florida Power and Light team responded to this criticism by acknowledging the importance of delivering a credible forecast to various commissions but they argued that they could turn to conventional forecasting techniques to meet this need. They argued that they had an entirely different goal in mind for the system dynamics model — their goal was to generate insights, not numbers.

Personal reflections on system dynamics and electric power

The impressive body of work in Table 1 raises interesting questions about system dynamics and electric power. Did any of us make a difference in the world? And did the system dynamics approach give us the power to make a difference? Or might we conclude that system dynamics is simply a convenient tool in the hands of a lot of bright people?

My experiences in energy have convinced me that system dynamics is much more than a convenient modeling tool. I am convinced that system dynamics has led the investigators listed in Table 1 to focus on the key feedback loops in the energy system. Our training leads us to first "see the feedback" in our minds. Our ability to translate our mental models into computer simulation models allows us to test our ideas through computer simulation. My experiences with energy industry modeling convinced me that the ability to simulate the information feedback in the system is a truly unique feature of the system dynamics approach. In the case of the electric power industry, the ability to simulate the interplay of the feedback loops in Figure 5 proved to be an important and unique feature of system dynamics.

But did we make a difference in the world? I have posed this question to many of the investigators listed in Table 1, and I have asked myself if any of my own studies have led to concrete changes in the industry. The collective response to this question is initially disappointing. None of us can point to a major piece of legislation or a major investment project that was shifted in a useful direction because of one of our studies. But I believe that our contributions will not be measured in large, dramatic "victories." Rather, we all contribute in a number of small ways to gradually shift opinions in a useful direction. When the work in Table 1 is judged in this manner, I believe we can all take some credit for contributing to useful change in the electric power industry. I believe the fundamental contribution of system dynamics has been to add a unique voice to the many voices calling for a shift to small scale resources in the 1980s.[15] I believe the industry shift to smaller coal plants, cogeneration and conservation was extremely beneficial to the power companies, their stock holders and their customers. I also believe the shift to small scale benefited the environment as well.

The 1990s: natural gas and deregulation

I turn now to the final decade in my historical account of electric power. Table 3

Table 4. Northwest utilities' marginal generating resources in the 1990s

Marginal generating resource for the Northwest	early 1990s: coal gasifier & combined cycle	late 1990s: natural gas fired combined cycle combustion turbine	Change
Typical size	420 MW	228 MW	46% smaller
Lead time	7 years	4 years	43% shorter
Capital cost	2,520 $/kW	684 $/kW	73% lower
Availability	80%	92%	15% larger
Efficiency	36%	47%	30% greater
Levelized cost	60 mills/kWh	30 mills/kWh	50% lower
Sulfur dioxide	0.04 tons/GWh	0.02 tons/GWh	50% smaller
Nitrogen oxides	0.50 tons/GWh	0.07 tons/GWh	85% smaller
Carbon dioxide	985 tons/GWh	497 tons/GWh	50% smaller

noted that the 1990s are dominated by the debate over deregulation. Industry leaders are now reexamining the organizational model established by Samuel Insull at the start of the century. They are challenging the basic assumption that a utility needs monopoly privilege to invest in electric power generation. Table 4 will help us understand why these questions have been raised in the 1990s.

Table 4 lists the marginal generating resource appearing in the 1991 and 1996 plans of the Northwest Power Planning Council (1996). These resources are called upon after the region's utilities have "used up" a variety of other resources such as conservation and small scale hydro. In the early 1990s, the marginal resource was a combined cycle generating plant that would burn natural gas from a coal gasification unit. The typical unit would be 420 MW in size, take seven years to build, and cost the utility $2,520 per kW. The levelized cost of the electric energy is a life cycle measure of the combined costs of capital and fuel. Table 4 reports the 1991 resource at 60 mills (6 cents) per kWh of energy delivered to the transmission system.

Table 4 shows a major change in just five years. By 1996, the marginal resource had changed to a combined cycle combustion turbine that would burn natural gas directly.[16] The typical unit would be only 228 MW in size, would take only four years to build, and would cost only $684 per kW. The levelized cost would fall to only 30 mills/kWh. The gas-fired generator would be smaller, faster and cheaper; Table 4 shows that it would be cleaner as well.

When thinking about the need for monopoly privilege and state regulation, the most startling feature of Table 4 is the dramatic change in construction costs in just five years. At $2,520 per kW, the 420 MW coal gasification facility would cost over $1 billion. But the typical 228 MW gas turbine would cost a little over $150 million. The proponents of deregulation are arguing that private companies should be able to finance a $150 million investment without the need for monopoly privilege. They argue that now is the time to eliminate monopolies and state regulation of electricity generation. And many believe that deregulation is inevitable. They say that the real debate is over the timing and extent of deregulation. Table 1 noted that system dynamics models have been used in the debate over deregulation. The most extensive work has been completed at the London Business School by Derek Bunn and Erik Larsen. Their work focuses on the shift from government owned power to a private power market in the UK.[17]

Water and power: an emerging area

System dynamics was first used in water resource planning in Hamilton's (1969) study of river basin development. Table 1 showed a body of work on water resources emerging in the 1990s. The examples include system dynamics applications in Pakistan, China, Colombia, Indonesia, Australia and Jordan. It is encouraging to see these many applications because water problems appear to be a serious challenge around the world. The severity of the problems is evident from the following comments from officials of the United Nations and World Bank:

> Stressing that 1 billion people lacked adequate clean water supplies, UN officials on Wednesday expressed fear that a war over water could erupt in the next 50 years. Water issues may be a contributing factor to breaking peace, like oil was in the past said one UN official. A World Bank official blamed inefficient irrigation. He noted that 80% of water is used for irrigation purposes in developing countries, but 45% of it doesn't even reach the plants. The World Bank official estimated that around $800 billion would be needed to finance water investments in the developing countries over the next decade. *Lewiston Morning Tribune*, June 6, 1996

My own research has shifted to water resource management in recent years. I live and teach in the northwest, where huge rivers dominate the region. Listening to the debates over competing visions for the rivers, I cannot help but "see the feedback" in the system. Further, my initial encounters with water resources modeling suggest that the key feedback loops are left out of many of the conventional models. Finally, I cannot help but notice that debates over water use in the western United States are frequently conducted in a hostile and adversarial manner.

I believe system dynamics can be put to good use in water resources, especially where key feedback loops cross boundaries between disciplines. Where antagonists are inclined to use models as "intellectual weapons" in water battles, system dynamics practitioners can contribute with "management flight simulators" to promote group learning. My first effort in this direction was a group learning model of the Snake River (Ford 1996b).

Summary and conclusion

System dynamics practitioners have accumulated an impressive record of applications in the electric power industry. System dynamics has given us a unique capability to "see the feedback" at work in the power system. Our work has contributed to useful change in the power industry, and we are building a record on water resource systems.

However, my main conclusion applies to all system dynamicists, not just those studying water or power. If you "see the feedback" at work in you own field, system dynamics will give you the opportunity to contribute in a unique manner. May your contributions lead to better understanding and to a better world.

Acknowledgments

Much of the research described in this article grew out of a Dartmouth College project to apply system dynamics to the U.S. energy problem. Our Dartmouth years were an exciting period as students. We all benefited by learning system dynamics from two exceptional teachers — Professor Dennis Meadows and Professor Donella Meadows.

Dartmouth graduates have helped each other in a variety of projects since graduation. I wish to acknowledge those Dartmouth graduates that have worked with me on several major projects. They include Roger Naill, John Stanley-Miller, George Backus, Jay Geinzer, and Pat Barton.

My own understanding of electric power increased substantially when I had the opportunity to join the Corporate Planning Department of the Pacific Gas and Electric Company on a sabbatical. I wish to thank Mason Willrich for inviting me to PG&E for the sabbatical.

My work on electric power has been supported by government agencies at the local, state and federal level, and the work has been supported by public and private power companies. I appreciate the guidance from each of the project managers, especially the ideas and support from Mike Bull, who guided our work for the Bonneville Power Administration.

Notes

1. The 33 publications are not meant as an exhaustive list of system dynamics work on electric power. Additional examples include Zepeda's (1975) analysis of capacity expansion cycles in the U.K. electric system and Rego's analysis of the capacity expansion in Argentina (Coyle 1996). The list does not cover the many examples of system dynamics applications to energy problems in general. Examples include

interfuel substitution in Europe (Moxnes 1990), petroleum resource estimation in the U.S.A. (Davidsen *et al.* 1990) and growth in an oil-dependent economy in Indonesia (Arif and Saeed 1989).

2. The *Operations Research* article was selected by the Jay Wright Forrester Award committee. It describes the iterative use of a system dynamics model to portray the long-term uncertainties in the electric system. We used formal statistical techniques to limit the number of simulations required to obtain estimates of the tolerance intervals on model output. We used a FORTRAN program (Hypersens) originally developed by Mike McKay at the Los Alamos National Laboratory and later enhanced by George Backus for use with system dynamics models, many of our calculations could be conducted more easily today with Vensim (Arthur and Eberlein 1996).

   Our confidence intervals showed how uncertainties in both the demand for electricity and the price of electricity would grow over time. We showed how the uncertainties are "shared" by the utilities in the northwest region. (The analysis was particularly important to the Bonneville Power Administration because it explained how Bonneville could end up with an unusually large share of the uncertainty.) Finally, and most importantly, the article described conservation programs that Bonneville might support in order to reduce the long-term uncertainties on their system.
3. My historical review is taken from several sources, but primarily from Munson (1985).
4. It is extremely difficult to store electricity, so power companies must transmit the electricity simultaneously from the generating stations to the customers. Customer demands for electric power can vary greatly from hour to hour, so companies must maintain sufficient generating capacity and transmission equipment to meet the peak demand for power.
5. For more information on power plant size, see the Los Alamos study of smaller coal-fired plants in the west (Ford 1980).
6. The cost of capital was high because of the high rate of inflation and because utility cash flow was declining. The headlines on the financial problems are documented in my doctoral thesis (Ford 1975).
7. Except for some difficult years immediately after the conclusion of World War II, the electric power industry has been quite successful in expanding generating capacity to keep pace with the demand for power.
8. Electric power is measured in kW, MW and GW with 1,000 kW in a MW and 1,000 MW in a GW. The peak demand for power on some of the nation's largest utilities can be over 10 GW. Construction costs may amount to $1,000 per kW or $1 billion per GW.
9. The vicious circle headline is taken from *Business Week*, May 23, 1983. The article included an example of a New York utility with a large nuclear plant under construction. The utility expected its rates to "soar 45% in three years" if the plant were to come on line as planned. The "curve ball" headline is from the *High Country News*, February 18, 1983.
10. The "spiral" study is described by Ford and Youngblood (1983). Prices are measured in Figure 5 in mills/kWh. There are 1,000 mills in a $. A kWh is the electric energy delivered by 1 kW of power in an hour.

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11. See “Pulling the Nuclear Plug,” *Time*, February 13, 1984 and “A Nuclear Fiasco Shakes the Bond Market,” *Fortune*, February 22, 1982.
12. The northwest electric system is dominated by hydro-electric generation. The system usually has plenty of capacity, but it is constrained by the amount of energy. So, the bar charts in Figure 8 represent electric energy. The shaded boxes stand for the “balancing” energy. Figure 8 does not show a shaded box for Bonneville because the federal portion of the system is automatically balanced when everyone follows the “rules of operation.”
13. In scenarios with relatively constant electric rates, the iterative approach might yield consistent results in the first iteration. However, utilities faced scenarios with large and rapid changes in electric rates in the difficult years of the 1970s.
14. Further information on the Florida Power and Light Model is given in the workshop reports (Electric Power Research Institute 1981; Ford and Mann 1982). See Geraghty and Lyneis (1982) for a description of the advantages of the feedback approach.
15. One of the most important and provocative voices calling for the shift to small scale is Amory Lovins (1985), director of research at the Rocky Mountain Institute.
16. Gas turbines have emerged as the most attractive resources in many parts of the country, not just the northwest. High efficiency and cheap natural gas are key factors. The Northwest Power Planning Council (1996, 5–5) reports that natural gas is selling for $1.60 per million BTUs in 1995, far below the peak value of $3.60 which occurred ten years earlier.
17. Excellent descriptions of the rapidly changing situation in the UK power industry are given by Bunn (1994) and Newbery (1995).

References

AES Corporation. 1993. An Overview of the Ideas Model. 1001 North 19th Street, Arlington, VA 22209

Amlin, J. and G. Backus. 1996. Utility Models for the New Competitive Electric Markets. Systematic Solutions, Inc., 534 E. Dayton-Yellow Springs Road, Fairborn, Ohio 45324.

Amlin, J., G. Backus and R. Heeb. 1988. Introduction to Energy 2020. Systematic Solutions Inc., Vandalia, OH 45377.

Arthur, W. and R. Eberlein. 1996. Sensitivity Simulations. *Proceedings of the 1996 International System Dynamics Conference*, Cambridge, MA.

Arif, M. T. and K. Saeed. 1989. Sustaining Economic Growth with a Nonrenewable Natural Resource: The Case of Oil-Dependent Indonesia. *System Dynamics Review*, 5(1): 17–34.

Aslam, J. and K. Saeed. 1995. Electricity Conservation in Domestic Sector of Pakistan: A System Dynamics Approach.*Proceedings of the 1995 International System Dynamics Conference*, Tokyo, Japan.

Backus, G. and J. Amlin. 1985. Combined Multidimensional Simulation Language, Database Manager and Sensitivity Confidence Analysis Package for System Dynamics Modeling. *Proceedings of the 1985 International System Dynamics Conference*, Keystone, CO.

Barton, J. and M. Pumandu. 1996. A Policy Model for a Retail Water Company in

Australia. *Proceedings of the 1996 International System Dynamics Conference*, Cambridge, MA.

Bunn, D. 1994. Evaluating the Effects of Privatizing Electricity. The 1993 Blackett Memorial Lecture, *Journal of the Operational Research Society*, 45(4): 367–375.

Bunn, D. and E. Larsen. 1992. Sensitivity of Reserve Margin to Factors Influencing Investment Behaviour in the Electricity Market of England & Wales. *Energy Policy*, May.

Bunn, D. and E. Larsen, ed. 1996. *Systems Modelling for Energy Policy.* Chichester: John Wiley & Sons.

Bunn D., E. Larsen and K. Vlahos. 1993. Complementary Modelling Approaches for Analyzing Several Effects of Privatization on Electricity Investment. *Journal of the Operational Research Society* 44(10): 957–971.

Central Maine Power Company. 1989. The 1989 Energy 2020 Users' Conference. Portland, Maine.

Coyle, R. G. 1996. *System Dynamics Modelling, A Practical Approach*. London: Chapman and Hall.

Davidsen, P., J. Sterman and G. Richardson. 1990. A Petroleum Life Cycle Model for the United States with Endogenous Technology, Exploration, Recovery and Demand. *System Dynamics Review*, 6(1): 66–93.

Dyner, I. and D. Bunn. 1996. Development of a Systems Simulation Platform to Analyze Market Liberalization and Integrated Energy Conservation Policies in Colombia. *Proceedings of the 1996 International System Dynamics Conference*, Cambridge, MA.

Electric Power Research Institute. 1981. Case Study Comparison of Utility Corporate Models. Report EA-2065. Palo Alto, CA 94304.

Electric Power Research Institute. 1996. Balancing Risk and Return in an Uncertain Future. A product summary from Power Markets and Resource Management Division. Palo Alto, CA 94304.

Ford A. 1975. A Dynamic Model of the United States Electric Utility Industry. Report DSD-28 of the Research Program on Technology and Public Policy, Thayer School of Engineering, Dartmouth College, Hanover, NH 03755.

Ford A. 1980. A New Look at Small Power Plants. *Environment,* 22(2): 25–33.

Ford A. 1990. Estimating the Impact of Efficiency Standards on the Uncertainty of the Northwest Electric System. *Operations Research*, 38(4): 580–597.

Ford A. 1994. Electric Vehicles and the Electric Utility Company. *Energy Policy*, 22(7): 555–570.

Ford A. 1995. Simulating the Controllability of Feebates. *System Dynamics Review*, 11(1): 3–29.

Ford A. 1996a. Electric Vehicles: The Case for and Against Incentives. *Public Utilities Fortnightly*, 15 April.

Ford A. 1996b. Testing the Snake River Explorer. *System Dynamics Review*, 12(4): 305–329.

Ford A. and M. Bull. 1989. Using System Dynamics for Conservation Policy Analysis in the Pacific Northwest. *System Dynamics Review*, 5(1): 1–16.

Ford A., M. Bull and R. Naill. 1987. Bonneville's Conservation Policy Analysis Models. *Energy Policy*, 109–124.

Ford A. and J. Geinzer. 1990. Adding Uncertainty to Least Cost Planning. *Energy Policy*, 331–339.

Ford, A. and G. Mann. 1982. Summary of the Workshop on Regulatory-Financial Models of the US Electric Utility Industry. Los Alamos National Laboratory Report LA-9815-C.

Ford A. and A. Youngblood. 1983. Simulating the Spiral of Impossibility in the Electric Utility Industry. *Energy Policy*, 19–38.

Geraghty D. and J. Lyneis. 1982. Feedback Loops: The Effects of External Agents on Utility Performance. *Public Utilities Fortnightly*, 2 September.

Greenberger, M., M. Crenson and B. Crissey. 1976. *Models in the Policy Process: Public Decision Making in the Computer Era*, Russell Sage Foundation, New York, NY.

Hamilton, H. R. 1969. *Systems Simulation for Regional Analysis: An Application to River Basin Planning.* Cambridge, MA: MIT Press.

Hass, J., E. Mitchell and B. Stone. 1974. *Financing the Energy Industry.* Ballinger Publishing Company, Cambridge, MA.

Lovins, A. 1985. Saving Gigabucks with Negawatts. *Public Utilities Fortnightly*, 21 March.

Lyneis, J., C. Bespolka and B. Tucker. 1994. Planning for a Competitive Environment — The Prospects for America's Electricity Utilities. *Proceedings of the 1994 International System Dynamics Conference*, University of Stirling, Scotland.

Moxnes, E. 1990. Interfuel Substitution in OECD-European Electricity Production. *System Dynamics Review*, 6(1): 44–65.

Munson, R. 1985. *The Power Makers*. Emmaus, PA: Rodale Press.

Naill, R. 1973. The Discovery Life Cycle of a Finite Resources: A Case Study of US Natural Gas. *Toward Global Equilibrium*, ed. D. Meadows and D. Meadows. Wright-Allen Press.

Naill, R. 1977. *Managing the Energy Transition*. Ballinger Publishing Company, Cambridge, MA.

Naill, R. 1992. A System Dynamics Model for National Energy Policy Planning. *System Dynamics Review*, 8(1): 1–19.

Naill, R. and G. Backus. 1977. Evaluating the National Energy Plan. *Technology Review*, July/August, 51–55.

Naill, R., S. Belanger, A. Klinger and E. Petersen. 1982. An Analysis of the Cost Effectiveness of US Energy Policies to Mitigate Global Warming. *System Dynamics Review.* 8(2): 111–128.

Newbery, D. 1995. Power Markets and Market Power. *The Energy Journal*, 16(3): 39-66.

Northwest Power Planning Council. 1996. Northwest Power in Transition. NPPC, 851 SW Sixth Avenue, Suite 1100, Portland, OR 97204.

Saeed, K. 1996. Sustainable Development: Old Conundrums, New Discords. *System Dynamics Review*, 12(1): 59–80.

Shawwash, Z. and D. Russell. 1996. Use of System Dynamics for Managing Water in Jordan. *Proceedings of the 1996 International System Dynamics Conference*, Cambridge, MA.

Stanford. 1978. Coal in Transition. Stanford University Energy Modeling Forum. EMF Report 2.

Stanford. 1980. Aggregate Elasticity of Energy Demand. Stanford University Energy Modeling Forum. EMF Report 4.

Stanford. 1996. Markets for Energy Efficiency. Stanford University Energy Modeling Forum. EMF Report 13.

Stanford. 1996. A Competitive Electricity Industry. Stanford University Energy Modeling Forum. EMF Report 15, forthcoming.

Sunaryo, P., T. Adibroto, H. Budiarto, and E. Maksum. 1996. “Application of System Dynamics on Watershed Management in Java Island, Indonesia,” *Proceedings of the 1996 International System Dynamics Conference*, Cambridge, Massachusetts, July 1996.

Wang, Q., B. Xu, G. Yang and J. Yang. 1995. Coordinated Development of Infrastructure in a Regional Economy. *Proceedings of the 1995 International System Dynamics Conference*, Tokyo, Japan.

Zepeda. E. 1975. The Capacity Expansion Process in the Electricity Supply Industry. *Dynamica* (previously published by the University of Bradford System Dynamics Research Group).