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# MODELING THE INTERACTION BETWEEN THE TECHNICAL, SOCIAL, ECONOMIC AND ENVIRONMENTAL COMPONENTS OF LARGE SCALE ELECTRIC POWER SYSTEMS

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## ABSTRACT

Missteps and finger pointing have plagued the deregulation of the electric power system that began in the 1990s. It has been impossible to clearly and systematically delineate the issues so that meaningful policy decisions can be made. Missing from most discussions is the interplay between the economic, technical, social and environmental factors that influence the production, transmission and consumption of electric energy. This paper outlines our study of these interactions and development of computer models suitable for use by both policy makers and researchers. The main effort is focused on the development of simulation models, which extend beyond traditional disciplinary boundaries. Such models will enable us to simulate short-term behavior, such as, electricity prices and congestion in the near term, and long-term behavior, such as, investment in new generation and transmission.

## KEY WORDS

Interdisciplinary modeling, power plant construction, system dynamics, transmission congestion, power system planning.

## 1. INTRODUCTION

California was one of the first states in the west to restructure its electricity markets. The blueprint for a competitive electric industry in California was issued in 1994 and implemented by the Legislature in 1996. The new markets opened for business in 1998. By the summer of 2000, a full-blown crisis had emerged in the form of unprecedented outages and price spikes. The crisis conditions continued through the fall of 2000, spread throughout the west, and continued into the winter and spring of 2001. Then, to the surprise of many, chronic outages and price spikes did not appear in the summer of 2001. Electricity demand was below levels reported in the previous year, and natural gas prices fell dramatically. New power plants came on line, and many more entered construction. As the year 2001 drew to a close, many were predicting that the current building boom will lead to a glut of electricity supply. It appears that the western electric system experienced a boom and bust pattern of private investment that appears in industries like commercial real estate. Will we see a repeat of boom and bust, or were the conditions in 2000-2001 a one-time event? Some argue that the western system experienced a one-time event, akin to a “perfect storm.” But others warn of a repeat of the crisis conditions of 2000-2001 unless we enact fundamental changes in wholesale electricity markets [1]. Still others call for public investments as the key to “break the cycle of boom and bust” [2].

The California experiment has been reviewed by a variety of groups looking for lessons on electric industry restructuring [3-5]. Researchers at WSU have contributed to the analysis of recent trends in several areas:

- research on pricing regimes [6], market transparency [7] and bidding activity under transmission constrained systems [8] helps one understand some of the market forces on suppliers,
- research on consumer behavior helps one understand the surprisingly responsive behavior of California electricity consumers during 2001 [9],
- research on investor behavior helps one understand the sluggish behavior of investors whose construction of new power plants lagged behind the growth in demand [10].

This paper outlines our initial research on these interactions and development of computer models suitable for use by both policy makers and researchers. Our expertise is focused on the Western US and emphasized in our discussions. However, the ideas and models will be designed for applicability to large scale power systems in general.

## 2. BACKGROUND

This section outlines the variety of forces at work on the electric power system, illustrating the complexity of understanding the impact of new electric market policies.

### 2.1 System Security and Market Operations

Under deregulation, precisely determining the transmission system operational limits has become exceptionally important because effective market operations require unfettered trades. These limits are bound by concerns of reliability. Operations are governed by the concept of security, which says the system should survive any credible contingency. More specifically, the response to a disturbance must satisfy standard operating criteria that have been established by regional councils, such as, the newly formed Western Electricity Coordinating Council [11]. These criteria include both dynamic and static performance measures, such as, allowable frequency and voltage variations that depend on the severity of the event. The response of the system to a given disturbance is a function of the distribution of loads and generation as well as the specific equipment connected to the system at the time of the event. While there has been great progress in analytical techniques for determining system limits, the primary approach to analyzing disturbances is through computationally intensive simulation studies using detailed models of the network. These studies assume particular stressed system operating conditions and investigate all major contingencies. The results provide guidance for planners as well as detailed instructions for operators of the system. Operator experience is critical for implementing these guidelines.

Obviously for reliable performance, market based generation scheduling must be subservient to these physical system limits. Yet, many of the electricity market studies have completely ignored transmission problems. To be sure, security calculations do not lead naturally to useful market rules. More typically, the ISO, or equivalent, will analyze the proposed schedules and trades for security on a one-day ahead basis. If trades produce system violations, then adjustments are made to the schedules to relieve the congestion under the ISO rules. During operations, modern Energy Management Systems (EMS) provide sophisticated online security analysis applications to assist the operators in ensuring that the power system continues to be operated securely as events unfold during the day. Thus, one of the fundamental challenges in the deregulation of the electricity industry is how to impose transmission limits in a fair and transparent manner while at the same time maintaining reliability. Accurately determining the available transmission capacity (ATC) remains an active area of research.

### 2.2 Demand Response

Demand-side resources were acquired during the late 1970s and 1980s as utilities and commissions across the west embarked on programs under the rubric of least-cost planning, demand-side management and integrated resource planning. Here in the Northwest, utility sponsored efficiency programs from the 1980s are credited for saving around 800 aMW in the public service areas and a similar amount in the IOU service areas. During the 1990s, however, these programs were reduced as utilities began to prepare for a new era of competition. The region's remaining effort focused on market transformation programs. Due in part to the aggressive demand-side programs in the 1980s, for example, California consumers reported the 7th best efficiency (annual kwh per person) in the nation [12]. As in the Northwest, many demand-side efforts were reduced in the 1990s as the utilities prepared for retail competition.

The surprising news on the demand-side appeared in the year 2001. By all accounts, consumers reduced electricity consumption relative to previous years. Estimates of the reduction range from 5% to 15% depending on the area, time and the group performing the study. The full extent of the reduction and the underlying causes requires further research. Equally important news appeared on the demand-side in the Northwest during the crisis conditions. Major load reductions were achieved through a variety of demand-exchange programs, buy-back programs, and dispatchable DSM. These reductions were credited for "keeping the lights on" in the Northwest [13].

### 2.3 Environmental Factors

Environmental impacts from electricity generation vary widely across the WECC. Coal-fired generation in the Southwest and rocky mountain areas generate $SO_2$ and $CO_2$ emissions. These emissions contribute to both regional and global pollution problems. In the urban areas of California, older gas-fired generators generate $NO_X$ emissions, which combine with hydro-carbon emissions from other sources to form urban smog. The $NO_X$ emissions are especially important in the heavily polluted south coast air basin where a market for emissions credits has been established. Early in 2000, credits were available for less than \$2 per MWh of generation from a typical generator. As allowable emissions were lowered, however, the market hit "cross over." Prices climbed to over \$30 per MWh [14] in the summer of 2000 and to \$84 per MWh [15] by the winter of 2001.

In the hydro-dominated Northwest, the major environmental challenges are associated with the endangered salmon populations of the Columbia River system. The Columbia River salmon and steelhead runs have declined by ten-twenty fold due to a combination of many factors including harvesting, dams, irrigation and livestock grazing. Federal resources comprise much of the Northwest hydro system. These facilities are operated to serve the electricity marketing goals of the BPA, subject to broad oversight by the NPPC and the Biological Opinion issued by NMFS. By the start of 2001, it was clear that hydro-electric generation would be greatly reduced because the Northwest was experiencing the second-lowest run-off since measurements were begun [16]. In March of 2001, BPA declared a power emergency and announced a reduction in flows earmarked for spring fish migration. The flows were diverted to power generation during the emergency period to reduce BPA's costs of purchases in the wholesale markets and to reduce the probability of outages in the northwest.

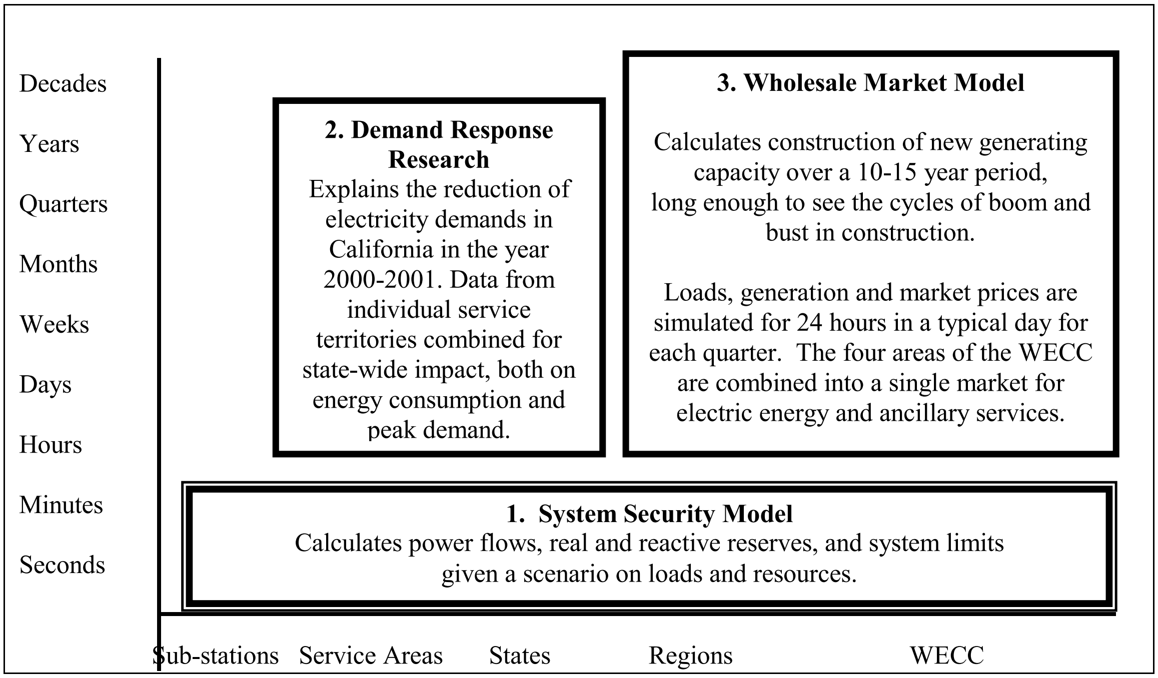
### 2.4. Interactive Simulation of Electricity Markets

Most models in the electric industry are maintained by a small team of analysts who are proficient in the model, the supporting data and the software. The analysts use the models to prepare reports, and the rest of the organization benefits from the reading the reports. This mode of analysis and communication has evolved over time because of the complexity of models and their supporting software. An alternative mode of communication is provided by highly interactive models, sometimes called "management flight simulators" because they provide managers an opportunity to "experience" the simulated dynamics. Management flight simulators are highly valued for engaging student involvement in the classroom [17] and for improving the learning of a diverse mix of professionals in large organizations [18]. Management flight simulators have been developed at WSU to engage students on alternative policies to reduce urban air pollution and to improve the salmon runs in the Columbia River system [19].

Models of electric systems may also be designed to promote highly interactive simulations and group learning, as we have demonstrated in recent research for the Electric Power Research Institute [20]. The EPRI project provided workshop participants an opportunity to experiment with alternative investment and contracting strategies in competitive markets. A related project for the CEC provided staff the opportunity explore alternative patterns of power plant construction that would arise from different combinations of investor groups [21]. The CEC model represented a system with approximately the same loads, resources and markets as in California. The model was later expanded to represent the loads and resources in the WECC and to generate scenarios to promote discussion of the redesign of wholesale markets [10].

## 3. RESEARCH ISSUES

Figure 1 shows the spatial and temporal boundaries of our previous research on the western electric system. The system security modeling is represented by the 1st of three boxes located at the base of the diagram. The security model represents the power flow and system dynamics, which operate in seconds on a spatially complex grid system. Loads are described at the level of sub-stations, while the scope of the model extends to cover the entire WECC. The model calculates power flows, real and reactive reserves and system limits for a specified scenario. The grid structure of the WECC is represented in explicit fashion, so the system security model provides the foundation for proposed research on power networks. We highlight the system security "box" in Figure 1 with a double boundary to emphasize the extra challenges of representing the grid network in explicit fashion.



**2. Demand Response Research**
Explains the reduction of electricity demands in California in the year 2000-2001. Data from individual service territories combined for state-wide impact, both on energy consumption and peak demand.

**3. Wholesale Market Model**
Calculates construction of new generating capacity over a 10-15 year period, long enough to see the cycles of boom and bust in construction.

Loads, generation and market prices are simulated for 24 hours in a typical day for each quarter. The four areas of the WECC are combined into a single market for electric energy and ancillary services.

**1. System Security Model**
Calculates power flows, real and reactive reserves, and system limits given a scenario on loads and resources.

Figure 1. Spatial and temporal dimensions of previous research at WSU.

Our demand size research is depicted as the 2nd of three boxes. The research was launched to explain the response of California electricity consumers during 2000 and 2001. The study makes use of billing data from distribution companies to determine the extent and factors behind the surprising reduction in electricity consumption in the summer of 2001. Figure 1 depicts the spatial dimension ranging from individual service areas to cover an entire state. The study will shed light on peak demand reductions, so we depict the study's temporal dimension running from hours to years.

The 3rd box in Figure 1 depicts the WSU model of the western electricity market. The model operates with load and resource data from the four regions of the WECC. The model simulates hourly operations for a typical 24 hour day in each quarter of a year. We assume adequate interconnections between all loads and all resources in the west, so wholesale market is treated as a single market. The simulations begin in 1998 and run for a decade or more to allow sufficient time to see the patterns of power plant construction.

### 3.1 Interactive Simulation of the Wholesale Market

The wholesale market model has been constructed using system dynamics, a simulation method pioneered by Forrester [22] and explained in texts by Ford [19] and Sterman [23]. System dynamics has its origins in control theory and has been defined by [24] as that

*branch of control theory which deals with socio-economic systems and that branch of management science which deals with problems of controllability.*

The approach is valued in a rapidly changing electric industry with high uncertainty and high risk [25]. The model is implemented with Stella, one of the "stock-and-flow" programs to permit highly interactive experimentation from a user interface.

The wholesale market model operates as if the loads and resources in the WECC interact in a single market with ample transmission links throughout the system. Market prices are based on the simulated actions of a system operator which finds the wholesale price for each hour to bring forth the generation to meet the demands for electric energy and ancillary services. Some generation (such as hydro and nuclear) is bid as "must-run" capacity. Most generators submit bids at their variable costs. The remaining generators submit bids well above variable costs, a form of strategic behavior known as economic withholding. With no withholding, the simulated prices reflect competitive conditions, and the results are checked against the "counter-factual" benchmarks published by the California ISO. With user-specified withholding, the simulated prices are checked against the actual prices reported by the California ISO [10].

Our wholesale market model was constructed to help one understand if power plant construction would appear in waves of boom and bust. The boom/bust pattern is common in industries like commercial real-estate which face long lead times to bring new capacity to market [1]. We were concerned that the construction of new power plants might also appear in waves of boom and bust. The resulting cycles in wholesale prices and reserves could be devastating for an industry in which production and consumption must occur simultaneously across a complex grid.

Investment in new generating capacity is based on an endogenous theory of investor behavior, which includes the long delays for permitting and construction. Investors are represented as "merchant investors" weighing the risks and rewards of investing in gas-fired combined cycle capacity based on estimates of future market prices. The theory has been tested in the WECC system and found to be successful in explaining the under-building that occurred in 1998-1999 and the over-building that appeared in 2000-2001 [1]. This pattern of boom and bust arises from a combination of the delays in power plant construction and the real limitations on investor's ability to anticipate the future trends in the wholesale market.

The previous models have proven useful in showing the tendency for boom and bust in power plant construction and in revealing the market price implications of boom and bust. They are also noteworthy for their interative, transparent design and the extensive effort at cross checking simulated behavior with actual behavior. As we look to the future, however, it makes sense to alter the underlying simulation approach to improve the prospects for simulating long-term construction dynamics within the same model that simulates short-term operations.

### 3.2 System Security and Markets

Operational planners employ detailed engineering studies to find the maximum allowable loadings in particular areas and the associated transfers across key interfaces of the grid. The loading must be such that following any credible contingency (disturbance), the system can still maintain frequency and desired voltage levels. Disturbances act at several time scales and studies use different models for each. For example, immediately following a fault, electro-mechanical oscillations may develop that require control actions within fractions of a second to prevent successive tripping of equipment. Alternatively, the disturbance may lead to overload and subsequent equipment overheating, which may allow for several minutes before action is required. The complexity of these phenomena and other engineering concerns is what renders difficult the coordination of system limits with the market. That is, the limits are a complex function of the loading and generation patterns, the available reserves, type of a disturbance and resources available for response, and so on.

There has also been a wide body of research on basic market mechanisms and supplier bidding strategies, usually based on a game theory framework (e.g., [26-29]). These models are also done at a more detailed level then are needed for the longer term studies in this work.

The challenge here is to develop appropriately detailed transmission models that, while capturing the complexity of the network, are not so detailed as to prevent useful studies of longer term trends. For purposes of our initial studies, we are developing a five area aggregate model of the WECC. We employ a DC load flow model that can be extended at a later date with flow constraints approximately representative of the major paths, such as Path 15, in the WECC.

### 3.3 Demand Response

Electricity demand is generally seen to be determined of two sets of factors: (1) end-use devices (e.g., lighting, motors, resistance heat, electronics, etc.), and (2) usage-patterns or schedules. Changes in demand—both short-term (hourly, daily, weekly) and long-term (seasonal, multi-year)—are produced by a variety of changes in either or both of these.

Increases in demand are generally produced by growth in population and in economic activity (number of households, sizes of firms), by the addition of new types of end-use equipment (e.g., office computers, server farms, home theaters), and by the acceptance of new standards/expectations about how equipment should be used (e.g., 24-hour illumination, 3-shift work schedules). Decreases in demand result from control changes (e.g., lower thermostat settings, new lighting protocols), from elimination of earlier uses (e.g., removing unnecessary office lighting), changes in operations/maintenance schedules (e.g., shifting high intensity energy uses to off-peak hours, maintaining cooling equipment for optimal performance), replacement of equipment with more efficient models or process strategies (e.g., electronic lamp ballasts, variable speed motors), and from high-efficiency design for new buildings and production processes.

A wide variety of public policies aimed at reducing demand have been implemented in the U.S. (and particularly in California and the Pacific Northwest) during the past twenty years. These have included improved product performance standards; new product R&D, education, training, and pilot testing; and subsidies and incentives to encourage the adoption of new technologies and operating practices. Reductions in both total energy use and peak demand have been targeted, with time-of-use rates and interruptible electricity rates being the primary policy instruments used to address the latter.

Benefits to both end-users in terms of reduced electricity costs (and assorted non-energy benefits to productivity and output quality) and to the society (in terms of emissions reductions and preservation of capital for non-energy uses) are widely recognized to result from energy efficiency improvement. But, while significant efficiency gains have resulted from these policies [30], overall demand for energy has continued to increase in the U.S. at rates higher than the rates of either population or GDP growth [31]. Electricity demand has increased at an even faster rate, with peak demand growing as well.

A well-developed literature on behavioral response to energy efficiency incentives and opportunities has shown that response to be strongly influenced by information, attitude-intention-behavior linkages, feedback on effects of action, belief, social structural and cultural factors [32-33]. This is true of firms as well as individual consumers (e.g., [34-35]). Stability and change in demand side practices are sharply constrained by the structure of the built environment, existing production processes, infrastructure, natural conditions (e.g. weather), business conditions, organizational capacity, and supply-chain capacities and characteristics [36-37]. Making out the structure and dynamics of the sorts of socio-technical systems involved requires both interdisciplinary perspectives and careful analysis—things that have been in short supply in energy policy and energy R&D agendas [38].

As we look to the future, it makes sense to include a simulated demand response within an integrated model of the long-term dynamics of boom and bust and the short-term operating conditions. The demand-side modeling might focus on the longer-term dynamics of consumer reactions to retail rate changes, or it might deal with the more rapid dynamics of consumer response in a real-time pricing program.

## 4. PROJECT RESULTS TO DATE

This research is expanding models for studies of long term performance of the power system. The objective is to understand the various influences on the electricity system performance and characterize these influences with sufficient accuracy to allow useful simulation studies. We are concentrating on including the following:

- general transmission constraints and associated market rules that influence regional transmission investments,
- ancillary service market structures, such as, the pricing of reserves and capacity, or the equivalent

in terms of operation rules, that influence generation and transmission investment,
- regional variation in generation sources and demand growth,
- demand side incentives and pricing, particularly with regards to the impact on boom-and-bust investments in generation and transmission,
- the role of environmental constraints on these investment patterns.

This section discusses our observations and development results to date.

### 4.1 Modeling Approaches

Our main goal is to develop a system of models that will illuminate the interactions among the many factors in the WECC system. Still, the detailed modeling approaches of engineering studies on a minute-to-minute or hour-to-hour basis differ greatly from system dynamics studies designed to gain insight into trends developing over years or decades.

Precise understanding of the future power system performance requires careful analysis of the transmission system. The details involved in accurately modeling a transmission network cannot be easily incorporated into market models. Even for daily operations, where specific details of the interconnections are known, most power exchanges use a simplified linearized transmission model to avoid computational problems. For the broader analysis proposed here, the data problem is even more difficult as longer term changes are nearly impossible to map into the detailed models of the network and generators. Instead, new approaches are being pursued, approaches which are labeled as the “system dynamics” approach and the “engineering” approach.

The system dynamics approach is grounded in the ideas of control engineering. The emphasis is on information feedback and icon-based modeling with clear portrayal of the stocks and flows. The models are equivalent to a coupled set of first-order differential equations, with a separate equation for each stock in the model. Other variables are usually referred to as auxiliaries. The underlying math is hidden in the lower layer of the model and, typically in the software, can only be accessed on explicit user’s request. Fig. 2 shows the Stella® model of a simple first order system - peak demand with exponential growth. Models in other system dynamics development programs, such as Vensim®, appear similar.

The simulation of long-term dynamics (such as power plant construction) in such software is generally straight-forward, but the simulation of short-term dynamics (such as hourly price spikes) stretches the inherent numerical methods. Furthermore, it is generally unnecessary, and computationally time intensive, to include the fine detail of such fluctuations for a long term study. Our previous system dynamics models dealt with the numerical challenges by designing the models to operate with time in “hours” and simulating a typical 24-hour day for each quarter of a year. This approach has been useful so far, but we expect to make more progress in the future if we turn to “engineering” methods to provide the hourly prices.

In contrast to the system dynamics, the engineering approach to modeling requires an explicit mathematical description of the relations among the system variables. One must first write down the equations and build the model in the appropriate simulation environment from there. Fig. 3 shows the Simulink® model of the previous system. A common issue for both modeling approaches when performing simulations with the model is dealing with algebraic constraints. Such constraints arise in more complex systems. The network equations that we face here are an example of such constraints. These constraints can easily be incorporated in the model when using engineering approach because of its explicit mathematical nature. Under the system dynamics approach, it can be difficult to represent these relations and to satisfy these constraints and one must resort to using approximate methods or external functions outside the normal modeling paradigm.

### 4.2 Transmission Network Model

In order to investigate the network impact on the long term wholesale market dynamics we divide the WECC system in 5 main areas interconnected with each other by means of equivalent ties. This is shown as Fig. 4.

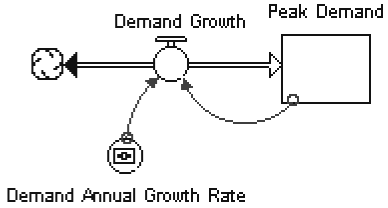


Fig. 2 An example of modeling using system dynamics approach

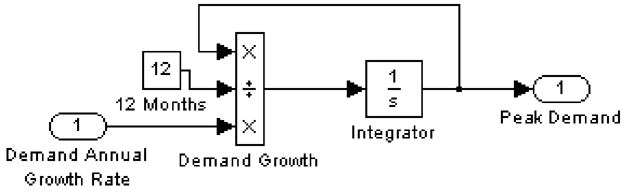


Fig. 3 An example of modeling using engineering approach

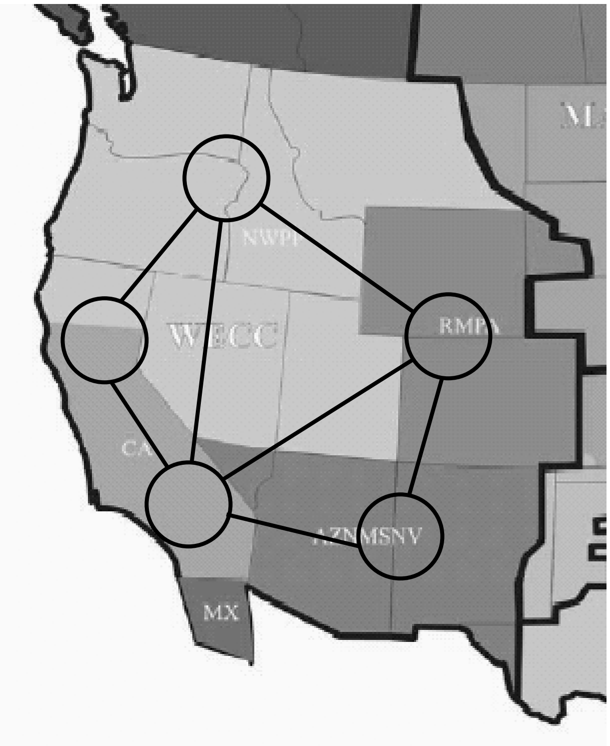


Fig. 4 The WECC five areas and equivalent ties

The areas are based on the WECC regional division as follows: Area 1 is the North West Power Pool – NWPP; Area 2 is the Rocky Mountain Power Area - RMPA; Area 3 represents the Arizona New Mexico Southern Nevada Power Area; Area 4 and Area 5 represent the Northern and Southern California. The reason for breaking the California region in two areas is modeling the infamous path 15.

The generators and loads within each area are lumped and the whole area is considered a single node. The parameters of the equivalent ties between the areas, like capacity and impedance, are to be derived from the explicit network structure. Corresponding to the broader scope of the analysis carried out, we use the DC load flow model for simple calculation of tie loadings and congestions.

Each of the five areas can be viewed as independent markets with the markets interacting via the tie lines. Alternatively, the whole system can be seen as a single market with different locational marginal prices. This five area division is the top level at which we are currently working; however, if the simulations results show the need and there is enough supporting data available this division can be further detailed.

### 4.3 Development of Educational Materials

We are in the process of preparing several instructional modules using interactive simulation of the benchmark system. The modules will be designed for integration into syllabi for senior/graduate level courses in sociology, economics, environmental science and engineering. At this stage, students from engineering will be taking courses within environmental science but our plan is to develop teaching modules that will be used with students from several disciplines learning in the same classroom. This project has also received a supplemental grant to support research cooperation with a group of West African scholars. We expect this will lead to interesting insights on systems in developing countries where weak transmission systems exacerbate the difficulty of designing functioning electricity markets.

## 5. CONCLUSION

This research seeks a deeper understanding of the many issues that affect the evolution of the electric power system. This very large and complex infrastructure is critical to the economy, indeed to the modern way of life, but it is also clear from our decade long experience of trying to instill more market competition in the industry that we don’t understand the issues well enough to predict the consequences of policy decisions about the power generation, transmission and distribution system. Thus, the ultimate objective is the ability to make policy decisions with predictable consequences. Much of the debate in the last decade has been about the appropriate design of the power markets and its interaction with the technical (physical) constraints of the grid (no electrical storage, congestion, etc.). Our proposed research also adds to this interaction long term investor behavior, and the very important issue of social behavior, because it is clear that consumers will respond to policy decisions in ways that are not well understood.

New tools are needed if models are to help power industry policy makers delineate the issues. The authors are developing new simulation tools with an emphasis on interactive simulation and interdisciplinary design. We are exploring new methods with pragmatic goals in mind. We will illustrate the practical value of the new methods with case scenarios for the WECC system. The models will be designed for pedagogic value, both to college students and to professionals in the power industry.

## 6. ACKNOWLEDGEMENT

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