Transmission Expansion Planning In The Western Interconnection – The Planning Process and the Analytical Tools That Will Be Needed to do the Job

Glenn Drayton, Michael McCoy, Mario Pereira, Edward Cazalet, Mary Johannis, Dennis Phillips

***Abstract* - Within the Western Interconnection there is a growing realization that the traditional long-term planning processes and analytical methods used to evaluate wires and non-wires alternatives fail to address many of the questions arising from deregulation and the perceived need for new infrastructure to facilitate markets and to assure reliability. In addition, homeland security issues may influence transmission infrastructure expansion. This paper describes the region's evolving transmission expansion planning process and the role OPF[1] modeling plays in aiding decision-making and consensus building. It identifies some opportunities for improvement in modeling, highlights two state-of-the-art models with capabilities that go beyond those of other models currently used for long-term transmission planning and makes a case for why we need to invest in better modeling and databases.**

***Index Terms*—Electricity pool market, market models.**

I. Introduction - Transmission expansion Planning in the Western Interconnection

A. The Planning Process – Developing Consensus Within the Western Interconnection

The Western Energy Crisis of 2001 raised a number of concerns regarding the impact of changes in the electricity industry on resource and transmission adequacy. The Western Governors Association (WGA) recognized that the changing electrical industry regulatory structure has "uncoupled the historical linkages between new generation development and transmission construction" [1] with no new industry structure to enable the construction of necessary transmission yet in place.

It is assumed that the three proposed western regional transmission organizations (RTOs) will eventually provide mechanisms to promote the construction of needed transmission infrastructure within their service areas.[2] To provide coordination at the boundaries of the three RTOs, the Seams Steering Group – Western Interconnection (SSG-WI) was established to:

- Provide a central forum to further the development of a robust West-wide interstate transmission system that is capable of supporting a competitive and seamless West-wide wholesale electricity market;[3]
- Develop consensus on issues related to differences in RTO practices and procedures.

While the RTOs are developing, a number of sub-regional planning processes have been established, in conjunction with SSG-WI, to facilitate transmission planning and expansion for specific geographical areas within the Western Interconnection. It is likely that, at least, some critically needed transmission infrastructure projects in the West will coalesce through these processes.[4]

B. The Role of Modeling – Building Consensus Around Better Decision Making

Given that the historical linkages between new generation development and transmission construction have been severed with no new industry structure to enable the construction of necessary transmission, what role can "modeling" play in developing a new consensus?

In transmission planning it is generally true that "everything depends on everything else". A power system is a complex network of injections and withdrawals of power flowing according to physics on multiple system lines and elements. Adding a new transmission line affects the flows on the entire network and will change the incentives for location of generation and the costs to loads. The human mind simply cannot deal with such complexity and therefore transmission infrastructure decisions must be informed by use of transmission modeling.

How electric energy and transmission and distribution

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[1] OPF – Optimal Power Flow – is an hourly least-cost system dispatch which conforms to Kirchhoff's Laws.

[2] The three Western RTOs include: Gridwest, WestConnect and the CAISO.

[3] SGG-WI established the Planning Work Group (PWG) to provide a forum for this transmission expansion planning.

[4] The sub-regional transmission planning processes include: the Northwest Transmission Assessment Committee (NTAC), the Southwest Transmission Expansion Plan (STEP), the Southwest Area Transmission (SWAT), the Colorado Coordinated Planning Group (CCPG) and the Rocky Mountain Area Transmission Study (RMATS).

services are priced at both the wholesale and retail level affects the economics of wires and non-wires alternatives. Thus, it is not enough to simply compute a least-cost solution to simulate the electricity market in the transmission model; rather real markets and pricing structures must be considered and reflected in the model in order to accurately depict the economics of proposed new transmission infrastructure.

Also challenging are the linkages between wires and non-wires alternatives. Building a transmission line changes the economics of generation investment and location decisions. It also changes the economics of consumption decisions and distributed generation investments. And of course, the reverse is true, that investments in central station and distributed generation and changes in consumption decisions change the economics of transmission. Again, models are essential in measuring and predicting these effects and developing consensus among governmental entities, such interested stakeholders as environmental groups, and generation, transmission and end-user investors.

Our analytical tools also need to have better ways to model uncertainty and its effect on the investment decisions. If the risks are high, and the risks are not properly understood and allocated fairly among investors and consumers, investments may not be made. Better modeling of the uncertainties and the adaptability of future investments to these uncertainties can help to build a consensus on the risks and sharing of the risks of power infrastructure investment. In addition, primarily because of the issues of dimensionality, no models adequately address the uncertainty in the assumptions about long-term expansion alternatives that is inherent because of imperfect knowledge of the future. The uncertainty of the costs to construct and operate a resource and the ability to optimally locate both generation and transmission alternatives are on a par with fuel price and hydro uncertainty.

Finally, few analytical tools dynamically model such energy-constrained resources as hydro and wind power. Because of the temporal complexity of hydro operational decisions, most models use a static, hard-wired approach to incorporate hydro and wind resources. A least-cost thermal dispatch around this hard-wired scenario does not realistically account for the constraints or flexibilities of these resources participating in the marketplace. Therefore, models that dynamically model energy-constraint resources depict generation injections into the power system in a more realistic manner resulting in a much more likely power flow in the OPF model.

C. Better Decision Making – Lessons Learned

In 2003, the SSG-WI PWG conducted several planning studies [2] that were designed to meet the following objectives:

- To identify opportunities where the development of additional transmission facilities could further facilitate competitive and efficient markets;
- To provide policy-makers with information concerning transmission impacts of various energy policies being considered by State, Provincial and Federal entities;
- To identify for generation developers major transmission additions that could be necessary to deliver a wide range of generation resources to load.

These analyses simulated the Western electricity market in 2008 and 2013 using standard optimal power flow (OPF) modeling technology.[5] The studies identified the net economic benefits associated with alternative expansion scenarios that were designed to mitigate uneconomic congestion under varying assumptions about future load growth, fuel price, hydro inflow and resource portfolio scenarios. It is important to note that these studies did not address resource or transmission capacity needed to maintain system reliability or to mitigate local market power, nor did they optimize transmission and generation expansion. In fact, the generation expansion scenarios selected were bookend rather than expected scenarios in order to bound the transmission infrastructure needs.

The studies identified certain physical limitations in the Western Interconnection that, at times, tended to strand less expensive generation, raise generation costs to the consumer, and drive up the incremental value of transmission capacity.[6]

While many insights were gleaned from the SSG-WI PWG studies, some of the most fundamental questions facing decision-makers were not addressed. Questions such as: Who benefits and who should pay for transmission expansion projects? What reliability benefits are associated with each scenario? What environmental benefits are associated with each scenario? Where/when/how often will market power be an issue? What are the financial risks and who is exposed? And from a homeland security perspective – which long-term expansion scenario provides the most security? What are the incremental costs?

These unanswered questions indicate the need for better models, databases and decision-support systems. With those needs in mind, the SSG-WI PWG [7] identified the following list of "opportunities for improvement "in long-term OPF modeling:

- Developing a systematic common methodology of reporting, estimating, validating and maintaining all relevant load, resource and transmission data for the power system of the Western Interconnection;
- Modeling the physics and economics of resource adequacy and reliability;

[5] The OPF model used in the SSG-WI report produced a least-cost dispatch of all thermal generation projected to be in-service in the Western Interconnection and for all 8760 hours of calendar years 2008 and 2013. Sensitivity studies were performed for alternative generation and transmission expansion scenarios assuming high, medium and low fuel price trajectories and hydro inflow conditions. Due to modeling limitations, generation from hydro, wind, and solar resources was determined exogenously and treated as a model input.

[6] The relative change in net economic benefits between expansion strategies was estimated as the difference between the annual capital, fuel and O&M costs of serving system loads.

[7] These model improvements were actually identified by the Model Improvement Group (MIG), a sub-group of the SSG-WI PWG, whose function is to advance SGG-WI's modeling capabilities.

- Incorporating dynamic resource acquisition logic;
- Modeling dynamic dispatch of cascaded hydro plants, wind and solar;
- Accounting for uncertainty in inter-temporal decision logic affecting longer-term resource acquisition, hydro storage, annual maintenance scheduling and unit commitment decisions in an appropriate manner;
- Simulating spatial and temporally correlated uncertainty in hydro inflows, runoff, and bus bar loads in a stochastic manner;
- Simulating short- and long-term uncertainty in fuel prices and load growth in a stochastic manner;
- Tracking net revenues and costs to owners and end-users;
- Simulating gaming market-power behavior;
- Simulating multi-year study horizons;
- Dynamically scheduling annual maintenance;
- Evaluating system performance under high risk, low probability events, e.g., severe weather excursions, etc;
- Adapting program formulation to changes in constraints, decision logic, dimensionality, and advances in technology.

II. Modeling The Future - A Description of Two State-of-the-Art Commercial OPF Planning Models

Existing state-of-the-art commercial software products are available to address some of the desired model improvements described above. The remainder of this paper discusses the features of two such models, PLEXOS and SDDP. These models were selected because they model complex, cascaded hydro networks, an essential feature in British Columbia, the Pacific Northwest and Northern California. These models have made major strides in implementing important modeling improvements.

A. *The PLEXOS Model - An Introduction with a Focus on Transmission Planning*

PLEXOS is an electricity market simulation model developed by Drayton Analytics (www.draytonanalytics.com and www.PLEXOS.info). This discussion provides background and motivation for the architecture and design philosophy of PLEXOS, then reviews salient features with reference to transmission modeling and long-term planning.

1): Architecture - Drayton Analytics recognized the need for a simulation model that is easily and efficiently maintained, extended, and modified and can be applied with no customization to every electricity market and modeling project. Clearly this required a paradigm shift in concept and design. The simulation architecture lays a foundation in which to cast the transmission-modeling problem, not a hardwired solution.

The solution simulations are founded in mathematical programming (MP) techniques (LP, QP, MIP, and DP[8]), which ensure the simulation outcomes are robust, consistent across scenarios, justifiable, and auditable. MP also provides valuable dual as well as primal solution information, such as the marginal value of a transmission expansion. Optimization code speed is improving as fast as computer speed, thus simulation performance is increasing rapidly, in many cases now out performing traditional rule-based approaches while providing compelling advantages.

The traditional approach to simulation is to decide the solution method, then build the model to populate the required data. In contrast, Dynamic Formulation (DF) developed by Glenn Drayton in 1996 and implemented in this model, allows the software to decide the solution approach and formulation based on data at runtime. In this approach, the data model is a framework for describing the "problem" (electricity simulation/transmission planning), and the ‘engine’ dynamically builds the optimization problem(s) at runtime ‘from scratch’. The advantages are: i) the software can scale to any problem size; ii) the analyst controls simulation performance by ‘switching’ data on/off –thus allowing exploration of tradeoffs between simulation runtime and result accuracy; iii) there is no hardwired functional specification – model capabilities can be expanded at will; and iv) simulation performance is maximized (problem size minimized) because the optimization problems are built at runtime to suit the data. Further, the analyst may define any 'generic' constraint, which can involve a combination of decision variables or input data used inside the simulation. For example, complex transmission constraints such as transient stability or voltage restrictions may be modeled in a linear or piecewise linear form. Thus the data structures implement a flexible, comprehensive, efficient, and easily extensible object model.

2): Modeling Capabilities - The planning horizon length and resolution is fully configurable and any sized dispatch period can be modeled. PLEXOS includes a thermal model with unit commitment and inter-temporal constraints. The transmission OPF is fully integrated with the production model. Medium-term (MT) and short-term (ST) modeling are fully integrated. PLEXOS MT Schedule models energy, fuel, emission and any other user-definable constraints that span days, weeks, months, or years and automatically "decomposes" them to shorter term constraints suitable for detailed modeling in ST Schedule. Hydro resources, e.g. pump storage, as well as long- and short-term storages are optimized – even detailed cascading hydro networks can be modeled. Energy and ancillary services co-optimization is comprehensive and fully integrated [10]. The MT Schedule has the ability to optimize strategic objectives, e.g. portfolio financial targets across time, and provide information to the short-term model to simulate ‘real’ trading strategies that reflect medium-term objectives e.g. it can run a Nash-Cournot game at the annual level and decompose to hourly trading strategies.

Transmission augmentation can reduce incidences of out-of-merit-order dispatch. Thus it is desirable to model competitive bidding behavior endogenously. However, there

[8] Linear Programming (LP), Quadratic Programming (QP), Mixed Integer Programming (MIP) and Dynamic Programming (DP).

still exists a significant gap between the restrictions of the theoretical models and practical simulations, e.g. Cournot requires a demand function, which may not be sensible at the hourly level; whereas, Supply Function Equilibrium overcomes this, but neither model says anything about inter-temporal strategic behavior. Although these theoretical models provide valuable information, the approach in PLEXOS is to simulate strategic behavior with deliberate consideration of the inter-temporal nature of the problem. We want the "biggest bang for the buck" i.e. a practical approach to strategic bidding that captures the essence of the theory, but is not restricted by the theoretical framework. Included in this model are: i) dynamic and inter-temporal revenue targeting algorithms that simulate real-market behavior driven by user-defined revenue requirements by portfolio – these can be based on historical returns; ii) Residual Supply Analysis[9] – where historical observations provides regression equations for use in setting bid cost markups dynamically in the simulation; and iii) Nash-Cournot – a practical implementation of a Cournot game with transmission and congestion. In all cases, bidding is truly dynamic, i.e. bids are calculated automatically and account for supply/demand balance including generator and transmission outages, congestion and loss factors. The simulation starts with the least-cost solution, so bidding optimization does not add significantly to overall runtime.

This model includes a feature to evaluate new resource additions. The MT model 'looks ahead' and attempts to rank potential new generation and transmission projects. Entry decisions can be based on economics, reliability criteria, or a combination of both.

PLEXOS includes a comprehensive Monte Carlo model for generator and transmission forced outage modeling. Maintenance timing is also dynamic and can be optimized to account for transmission availability, i.e. reserve sharing between areas. Any input can be stochastic – commonly used examples are demand, hydro, and fuel prices. Any combination of: i) historical sequences as samples, or ii) synthesized sequences based on input expected values and error distributions can be modeled. Solution of multiple sample runs is seamless, and statistics are produced on all outputs, e.g. distributions of augmentation benefits can be derived rather than provided just as a point estimate.

Any number of data scenarios can be set up in one database. Execution can be batched and automated from other programs. Thus, scenario analyses can be automated, and transmission expansion benefits can be calculated with 'the push of one button'. Reporting is comprehensive and easily extensible (new outputs can be added easily).

PLEXOS has users in every region of the world including transmission operators, generating companies, transmission companies, regulators, and consultants. The software has been used extensively for analyzing transmission expansion in Australia, and more recently by the CAISO.

[9] This feature of the model was developed in co-operation with the California Independent System Operator (CAISO).

3): Challenges - PLEXOS is built from the ground up to evolve as requirements change and new solution methods become available. Many challenges remain in the context of long-term transmission planning. An outstanding problem is dealing with dimensionality. The shear size of the simulation can be problematic when transmission is modeled in its entirety for entire regions, e.g. WECC is modeled with approximately 13500 buses and 17000 lines. A fast-solving OPF is available in this model, but it ignores losses. Automatic temporal aggregation allows rapid analysis of many scenarios. But further work is needed on full integration of stochastic sampling, strategic bidding using hot-started models to speed execution. PLEXOS can also make use of parallel processing LP codes. Perhaps the biggest challenge lies in overcoming the deterministic nature of mathematical programming codes. Although data may be stochastic, each 'sample' is solved in a deterministic fashion. This model partly overcomes this problem in its method of decomposition – ensuring the 'look-ahead' is not perfect, but in the medium-term, especially with long-term hydro, PLEXOS will benefit from a greater emphasis on realistic decision-making under uncertainty.

B. *The SDDP Model*

1): Introduction - The optimal operation of a hydrothermal system determines, among many things, an operational strategy that produces generation targets for each hydro plant at each stage of the planning period. This strategy should minimize the expected value of the operational cost along the period, composed of fuel cost and penalties for failure to supply load. This is a very complex problem. It corresponds to the following optimization problem with a non-separable objective function (the worth of energy generated in a hydro plant cannot be measured directly as a function of the plant state alone [3]):

- A multi-period hydro reservoir operation with decisions coupled between stages;
- Stochastic modeling because there is uncertainty in the forecasts of future inflow load, fuel prices, etc.;
- Large-scale reservoir systems in sometimes-complex topologies including extensive transmission and thermal systems.

Because of these complexities, the hydrothermal operation of large-scale systems has been traditionally carried out without taking into account transmission constraints, or considering them in a very simplified way. Another traditional approach has been to consider the transmission system, but with a very simplified representation of the hydro system by, for example, specifying a "single" water value for hydro plants, neglecting time-related constraints or water inflow uncertainties, and conducting snapshot operation optimization (classical OPF problems). These approaches are not suitable for systems with a significant hydropower component and complex regional power exchanges, such as is the case in the Western United States. These modeling approaches do not adequately address the information necessary for: cost-benefit studies for transmission reinforcement; evaluation of spatial distributions of spot market prices through the electric network; and locational marginal pricing impacts, and other type of evaluations.

In the 1970s and early 80s, simple simulation tools were widely used to carry out planning studies and hydrothermal scheduling. Hydro resources and inflow uncertainty often had a poor representation, using an aggregate model for the hydro system, which did not allow the detailed evaluation of transmission reinforcements in terms of energy benefits. The development of the economies in countries with significant hydro resources motivated the financial system (World Bank, IDB, etc.) to foster the development of integrated simulation and optimization tools capable of representing adequately transmission constraints and hydrothermal scheduling. In this context, SDDP was developed by Power Systems Research (PSR at www.psr-inc.com) in the early 1990's with the following features:

2): Model Overview - SDDP is a transmission-constrained probabilistic hydrothermal scheduling model, which determines the optimal stochastic operation policy of a multi-reservoir hydrothermal system without aggregating hydro plants or using other approximation techniques. Since its inception, SDDP has become the operations simulation module in a group of related programs that deal with: optimal interconnections and generation expansion, optimized use of contracts and derivatives, and Nash-type decision-making by players in a deregulated environment [5,6,7]. In particular SDDP has been used with planning models OPTGEN and MODPIN to perform system expansion studies [9].

The model is used for medium and long-term operation studies (1-15 years) and the following aspects are represented in detail:

- Operational details of hydro plants (water balance, limits on storage and turbine outflow, spillage, filtration, head changes effect, environmental constraints etc.) along complex cascades;
- Detailed thermal plant modeling (unit commitment, "take or pay" fuel contracts, non-linear efficiency curves, fuel consumption constraints, multiple fuels etc.);
- Representation of spot markets and supply contracts;
- Hydrological uncertainty: use of historic time series or multivariate stochastic inflow models that develop synthetic hydrology representing the system hydrological characteristics (seasonality, time and space dependence, severe droughts) and the effect of macroclimatic phenomena (e.g. El Niño);
- Detailed transmission network: Kirchhoff laws, limits on power flows in each circuit, losses, security constraints, export and import limits for electrical areas etc.;
- Load variation per load level and per bus, with monthly or weekly stages (medium- or long-term studies) or hourly levels (short-term studies).

The solution algorithm is based on a decomposition scheme known as stochastic dual dynamic programming—hence the acronym SDDP-- [4] which approximates the expected future cost function of stochastic dynamic programming by piecewise linear functions. No state discretization[10] is necessary and the combinatorial "explosion" with the number of states – the well known "curse of dimensionality" of dynamic programming - is avoided. In a transmission-constrained hydro schedule, each stage in the SDDP algorithm corresponds to a linearized OPF with additional variables and constraints.

Moreover, the structure of the decomposition solution scheme allows the introduction of parallel processing in the algorithm and a significant reduction in CPU time. Parallel processing facilitates modeling of very large-scale generation and transmission systems. It is standard to perform mid-long term operations studies for systems with hundreds of generators (hydro-thermal) with the representation of the full transmission network (thousands of busbars and circuits) on a stochastic basis with a reasonable computer effort.

The formulation is readily modified to add new constraints and can explicitly deal with different bidding strategies, which is to some extent handled through data changes.

Besides the least-cost operating policy, the solution includes a wide variety of marginal (shadow) prices such as: bus spot prices; wheeling rates and transmission congestion costs; water values for each hydro plant; marginal costs of fuel supply constraints; and others. These prices provide important economic signals to either planners or an expansion-planning model. For instance, the distribution of circuit flows and the marginal cost at each node (bus marginal cost) together can indicate the need and payoff for circuit reinforcements.

3): Model Applications - SDDP has been used in planning, portfolio management and operational studies in more than 20 countries in Europe, Asia and Latin America and by the system operator in the dispatch centers of 8 countries in Latin America. Specific examples include long-term studies to identify "zones" of the transmission network where the bus marginal costs have similar values. These are regions where transmission is generally adequate. Transmission expansion is generally warranted between these sub-markets when the marginal cost differences are sufficiently large. With an appropriately selected "cost of interruption" these markets will also include areas where the supply is not sufficiently reliable. Moreover, the model has been used to evaluate, in a more detailed fashion, the overall benefits of circuit reinforcements, such as impacts on local spillage, bus spot prices, etc.. In all of these studies, a stochastic optimization of a large-scale hydrothermal system (100 hydro plants, 100 thermal plants, 60 monthly stages, more than 3500 buses and 4900 circuits) with transmission constraints has been performed [8].

[10] "state space discretization" refers to the process that most solution algorithms use to select discrete meaningful values of states in their solution processes (e.g. full, 75%, half full, 25%, and empty where reservoir storage is the state).

III. The Case for Investment in Better Models and Databases

The two state-of-the-art models highlighted in this paper have capabilities that go beyond those of other models currently used for transmission planning.[11] However, the following outstanding modeling challenges remain:

- Evaluating non-wires alternatives accurately;
- Incorporating actual market pricing structures; and
- Making future infrastructure decisions with imperfect information.

Homeland security requirements may require models to consider how the size, location and types of alternatives would reduce the likelihood and consequences of terrorist threats to the power system. There are also challenges in developing and maintaining common databases necessary for such models. And finally, none of the models yet deal with advanced communication and digital control systems that may improve the reliability of the current electric grid.

The recent blackouts and market failures are an indication that we do not fully understand complex power systems and markets. Clearly modeling is a source of understanding that demands investment in new methodologies, models and data. While the benefits of improvements in models are hard to quantify, the costs are tiny compared to the essential role of electricity systems and markets in our societies. The great advancements in computers, software and information management science that are continuing to take place can be applied to solving these important problems. There may be no more important or better application of these advancements than the planning and consensus building for investments in our essential power systems of the future.

Development of better transmission models and data is likely to be a partnership between commercial firms that develop and maintain the models and databases and government and regional transmission operators who will identify model improvements based on the changing electrical powers system paradigm. The needs are clear so we need to find a way to work together to get it done.

IV. Acknowledgements

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VI. Biographies

Edward Cazalet is an independent consultant and has been involved in power system modeling and decision analysis since 1966. He has developed and applied advanced hydrothermal power system market models. He was the founder and CEO in 1976 of Decision Focus, Inc. and the founder and CEO in 1996 of Automated Power Exchange. He has a Ph.D. from Stanford University in 1970 and his thesis focused on power system optimization and markets.

Glenn Drayton has been involved in electricity market design and modeling since 1991 – with particular focus on energy and AS co-optimization and hydrothermal coordination. He founded Drayton Analytics in 1999 to develop the PLEXOS simulation software. He obtained a Ph.D. in Management Science from the University of Canterbury, New Zealand in 1996. The LP formulation proposed in his thesis formed the basis for the energy/AS cooptimization in the New Zealand, Australia, and Singapore electricity markets.

Mary Johannis is a professional civil engineer with over 25 years experience in the water and power planning and modeling areas. In addition to her work at BPA where she led the long-term planning function in the Power Business Line and now is the policy lead for resource adequacy in the Industry Restructuring Group, she has worked for the California Energy Commission, the Northern California Power Agency, the Bureau of Reclamation and the California Department of Water Resources.

Michael McCoy is Vice-President for Research at Becker Capital Management where he specializes in behavioral aspects of the performance of markets. He was a technical specialist in hydrothermal coordination for the Bonneville Power Administration and is a Technical Director of Power Systems Research Inc.

Mario Pereira has several years' experience in the development of power system planning and operations tools such as such as SDDP, used in more than thirty countries in the Americas, Europe and Asia. He has also carried out planning studies in most Latin American countries, USA, Austria, the Balkan countries and China. Dr. Pereira is a co-receiver of the Franz Edelman Award for Management Science Achievement, for his work on hydrothermal coordination in Brazil, and has authored and co-authored four books and about two hundred papers in refereed journals and conference proceedings.

Dennis Phillips has a BSME from the University of Illinois and an MBA Finance & Quantitative Methods from the University of Oregon. In 1975 he joined PacifiCorp (a.k.a. PP&L) working in thermal plant operations. In 1981 he joined BPA and has since worked in resource and transmission planning and power system optimization.

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