A History of Making Energy Policy

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Abstract:

For more than 30 years, system dynamics has played a noteworthy role in the making of energy policy for many states, provinces, corporations, and countries. This work has covered the spectrum from predictive forecasting, to strategic planning, to assessing policy options, to negotiating policy, to shaping policy, to defending policy, to swaying policy. While the FOSSIL1 model appears to have begun this process, the ENERGY2020 model continues to influence the policy process in functional, but possibly ambiguous, ways.

Introduction:

In his 1992 System Dynamics Review article, Roger Naill[1] described the history of the FOSSIL2/IDEAS national energy policy model. As he notes, it is probably one of the true success stories for system dynamics modeling. From 1978 through beyond 1995, FOSSIL2/IDEAS model was still ***The*** U.S. National Energy Policy Model to most U.S. and international energy analysts. Subsequently, nearly 20 years after FOSSIL2 toppled the then Federal Energy Administration's Project Independence Evaluation System (PIES) for policy evaluation, the Energy Information Administration reestablished its energy modeling prerogative with the detailed, economically-orthodox, National Energy Modeling System (NEMS). In his Forrester-Prize Lecture, Andy Ford[2] described the history of system-dynamics energy-modeling through 1996, with an emphasis on

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informing electric utility policy through modeling. This paper partially discusses intervening activities between 1996 and the present with an emphasis on one thread from the same cloth as FOSSIL2 and Andy Ford's EPPAM work, called ENERGY2020.[*]

ENERGY2020 was an outgrowth of the original (national level) FOSSIL2 model but drew significantly from EPPAM's foundations. Over the years, Andy Ford continues to advance the field with innovative studies[3], with Derek Bunn[4] and Isaac Dyner[5] still expanding the frontier outside the U.S. Papers from recently past System Dynamics Conferences show that many system dynamicists nurture an enduring interest in energy and environmental policy modeling. The ongoing development of ENERGY2020 has not taken direct advantage of these later efforts because client needs constrain its evolution. Nonetheless, the efforts of others play a critical role in corroborating or challenging the approaches used in ENERGY2020, or the results it produces, and thereby they contribute to the validation process all models perpetually require.

In our view, FOSSIL1[6] essentially displaced the PIES model for three reasons. Number one, it ran in 12 seconds while the PIES model took 100 hours. FOSSIL1 analysts could discover and analyze problematic (dynamic) phenomena, and conceive and evaluate the spectrum of policy options before anyone else had a position. Rather than us having to counter any entrenched views with starting-at-square-one discussions of feedback dynamics, it was now PIES who had to counter our results. We could respond near instantaneously to rapidly evolving congressional and White House concerns over the 1979 Iranian energy-crisis. PIES could only fall further behind.

Robert Belden (now a Vice President at IBM) developed a specialized, wickedly-fast, analysts-interface for running and assessing scenarios. The "improved" 12-second turn-around time was disconcerting to all who challenged model results. The yet novel aspect of real-time computer access (thanks to special privileges provided by Dartmouth College's Kiewit Computer Center) gave the appearance of pitting a mere mortal inquisitor against the all-knowing electronic oracle -- despite that not being our intent. In retrospect, this initial decision to trade-off speed for added detail was akin to weaponizing a model.

Secondly, the methodology itself allowed a casual explanation understandable to policy makers. As soon as President Carter's National Energy Plan I (NEP1)[7] became available, Naill and Backus evaluated it with FOSSIL1 and briefed the House Subcommittee on Energy and Power.[8] After a sound-byte from Walter Cronkite on the analysis, Roger Naill was invited to become the Director of the Office of Policy, Planning, and Analysis, where he remained for many years before becoming the Vice President of Applied Energy Services and a sought-after participant for many influential studies.

Thirdly, in a political environment skeptical of optimal economic arguments, the then contrarian analyses of the FOSSIL1 turned previously unthinkable policy considerations into passable legislation. We believe that the ability of FOSSIL1 to reveal the varied,

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[*] You can learn more about the FOSSIL2 and EPPAM history at the System Dynamics Society site: http://www.systemdynamics.org/DL-IntroSysDyn/energy-b.htm

shifting impacts of energy policy over time played a large part in achieving national oil and gas deregulation legislation.

Nonetheless, as FOSSIL1[9] morphed into FOSSIL2[10] its forecasts became the referent for justifying past and present national energy policy. It needed to maintain the status-quo it created where model results needed to consistently reflect the basic character of previous, now "official projections." Political negotiation is often in the details, so some aspects of the model were underplayed (such as the then unthinkable cessation of nuclear power construction) and other aspects overemphasized (such as large growth rates in trifling levels of solar energy). The realities of maintaining policy continuity meant that new information on costs and resource availability could not be allowed to dramatically change results.[*] When justifiable, keeping FOSSIL2 consistent with the results of new "specialized" studies maintained its credibility. Judgmental adjustments for masking second-order distractions to a policy debate or for "correcting" un-modeled details (via constants that become simply known as "cons" in essentially all mature, mainstream models) was a soul-searching balancing act, sometimes dependent on how adamant a Congressman was.

Because Roger Naill and key analysts did understand the model dynamics, they could describe model results in the context of their honest implications for policy -- without the distortions from model over-parameterization. We contend that the enduring success of FOSSIL2 was largely because 1) it superbly honed the mental-model intuition of policy analysts, 2) it focused policy debate around key dynamics, and 3) it automatically scripted the casual arguments supporting a policy recommendation. Roger Naill also implied in his 1992 article that the person using the model rather than the model itself determines the usefulness of the model. A model is just a tool; the application of it and its results are a purely human process. In that context, it is worth noting that several of the original analysts associated with FOSSIL2 still have visibility in national energy policy, such as Michael Maddox and William Veno who are now at Cambridge Energy Research Associates, Phil Budzik, now with the Energy Information Administration, and Francis Wood, now at Onlocation Inc.

To partially maintain a balance between governments and commercial interests, Backus developed the FOSSIL79[11] variant of FOSSIL1 which emphasized the concerns of the energy companies and the policies of most interest to them. Most of the nation's largest oil, gas and coal companies had and used FOSSIL79. The then named companies of Exxon, Texaco, Gulf Oil, Sun Oil, and Atlantic Richfield used the model to focus their business lines and limit ventures in what was considered the bright future of synthetic fuels.[12] The Russians also showed a keen interest in the FOSSIL79, possibly for making their 5-year plans or possibly to analyze the impact of American policy on Russian exports/imports.

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[*] This is currently true for Greenhouse-Gas assessment models used for policy negotiation. A large variance from the "accepted" model results would destroy confidence and thus the momentum for urgently needed (even if imperfect) climate legislation.

By 1980, it seemed to us (Amlin and Backus) that the success of FOSSIL2 was making the model mature too quickly. As the novelty of a new vista waned, the focus turned to details and FOSSIL2 evolved to accommodate the shifting priorities of national interests. While FOSSIL2 grew to have much more supply technology detail than FOSSIL1, its demand sector remained relatively primitive using delays with income and price elasticities. The DEMAND81[13] model was an attempt to place the demand side of FOSSIL2 on the same par as the supply-side, where real decisions-makers made relatively naive forecasts and imperfect investment decisions. By 1981, however, least-cost-planning was the craze, and least-cost assessments on both the demand and the supply-side dominated analyses. The inclusion of “optimized” consumer decisions was a large part of the morphing of FOSSIL2 into IDEAS (Integrated Dynamic Energy Analysis Simulation)[14]. The implementation of energy planning consequently migrated from Washington to states and companies. Thus the center of gravity for energy policy was shifting from the national to the regional level, and ENERGY2020 came into being in 1981 to fill that need.[15]

Overview of the ENERGY2020 Model

ENERGY2020 is an integrated energy model containing detailed energy-demand, energy-supply, and pollution-accounting sectors. It is often coupled in dynamic feedback with regional macroeconomic models. It has been used in over 20 different countries, but most of its work has focused on the U.S. and Canada. Analyses can include any multiple aggregations of regions to include the 50 states plus the District of Columbia, the ten Canadian provinces, and the three Canadian territories.

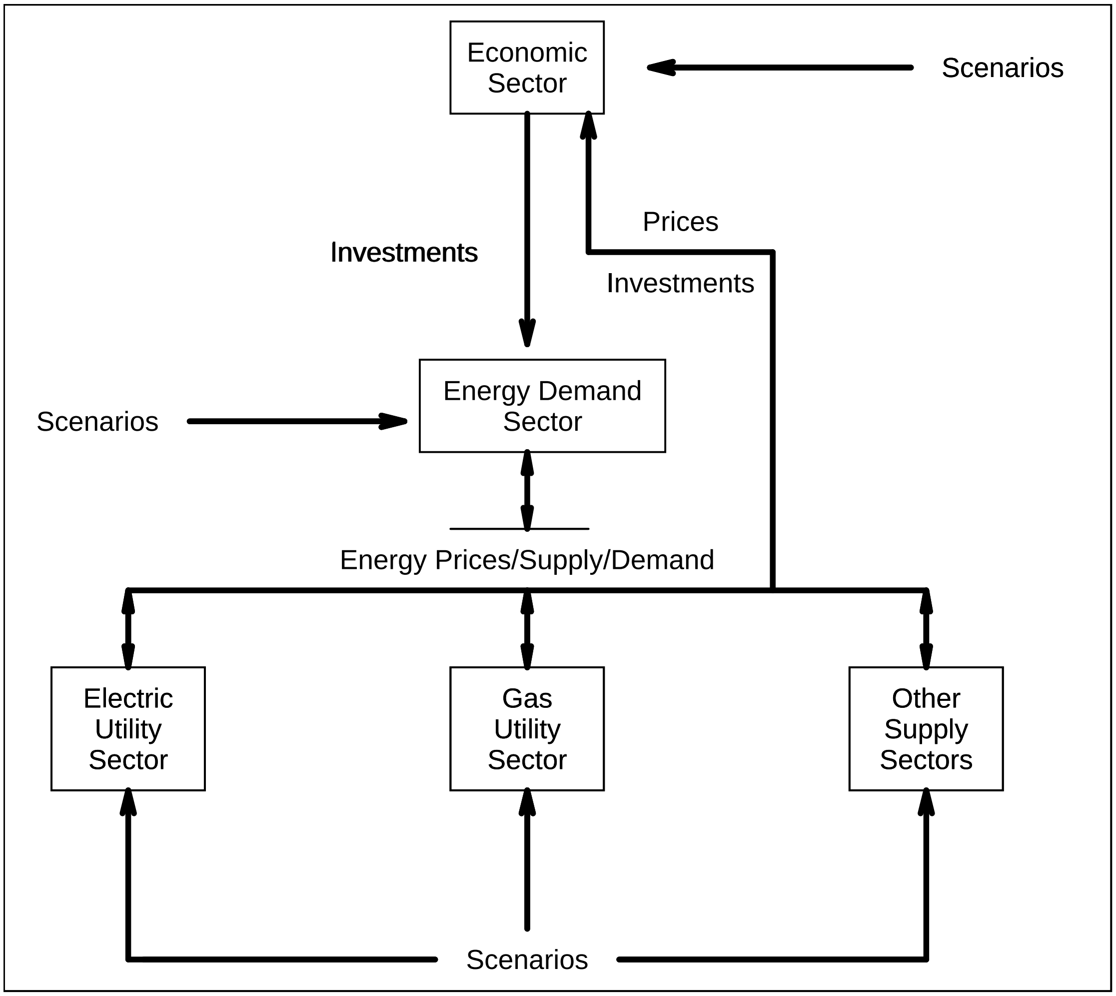

Figure 1. Basic ENERGY2020 Structure

Figure 1 depicts the overall construct of the model. As a policy model, it emphasizes scenario testing capabilities in the form of external/internal technical and behavioral uncertainty, policy interventions, based on reference-mode starting points (i.e., consensus-framed reference modes). There are literally thousands of policy levers.

The model simulates energy demand for three residential categories (single family, multi-family, and agriculture/rural), over 40 commercial and industrial categories, and three transportation services (passenger, freight, and off-road). There are typically six end-uses per category (e.g., Process Heat, Space Heating, Water Heating, Other Substitutable, Refrigeration, Lighting, Air Conditioning, and/or Electromechanical). Technology and fuel choices are endogenous across six fuel families (oil, gas, coal, electric, solar, and biomass) and 30 fuel products. The transportation sector contains 45 modes including various types of automobile, truck, off-road, bus, train, airplane, marine, and alternative-fuel vehicles. Only data limits the number of end-uses, technologies, and modes the model simulates. The model also determines cogeneration, fungible demands (fuel switching), energy-based feedstock, municipal resale demands, and power pool resale demands.

Figure 2 depicts the basic structure of the demand sector.

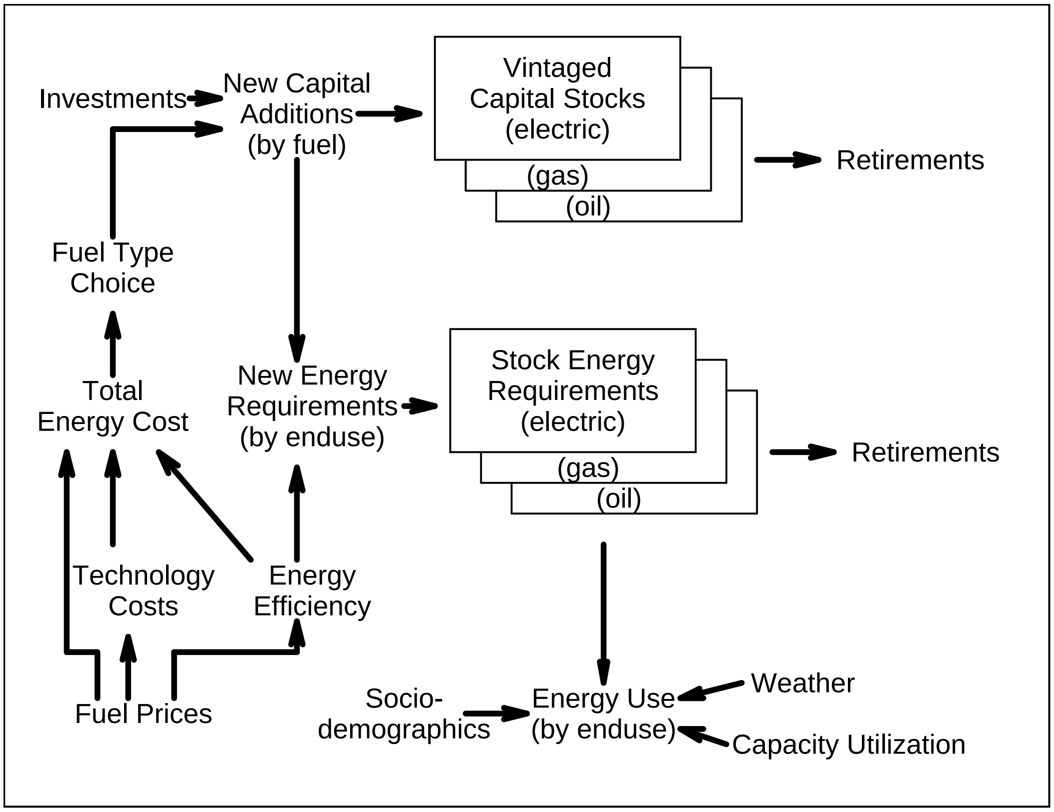

Figure 2: Demand Sector Overview

ENERGY2020 supply sectors include electricity, oil, natural gas, refined petroleum products, ethanol, land-fill gas, and coal supply. The model simulates primary energy production, emissions associated with it, energy distribution, and the use of energy to make energy (as is the case with electric generation). The supply sectors included in a particular implementation of ENERGY2020 will depend on the characteristics of the area being simulated and the problem being addressed. If the full supply sector is not needed, then a simplified module determines delivered-product prices.

Electric supply, often in the form of multiple companies across multiple regions, populates nearly every model configuration. During the time of experimentation with electric industry deregulation, ENERGY2020 could automatically configure itself to simulate individual and collections of over 3000 electric utility companies. The electric utility sectors determine capacity expansion/construction 20 categories of resources, rates/prices, seasonal load shape variation due to weather, and changes in regulation. The model dispatches generation by plant according to the specified rules whether they are optimal or heuristic and simulates transmission and emission constraints when determining dispatch. A sophisticated dispatch routine selects critical hours along seasonal load duration curves as a way to provide a quick but accurate determination of system generation. Some detailed AC/DC load-flow simulations with ENERGY2020 can include thousands of transmission nodes.

Figure 4 shows the basic components of an ENERGY2020 electric sector.

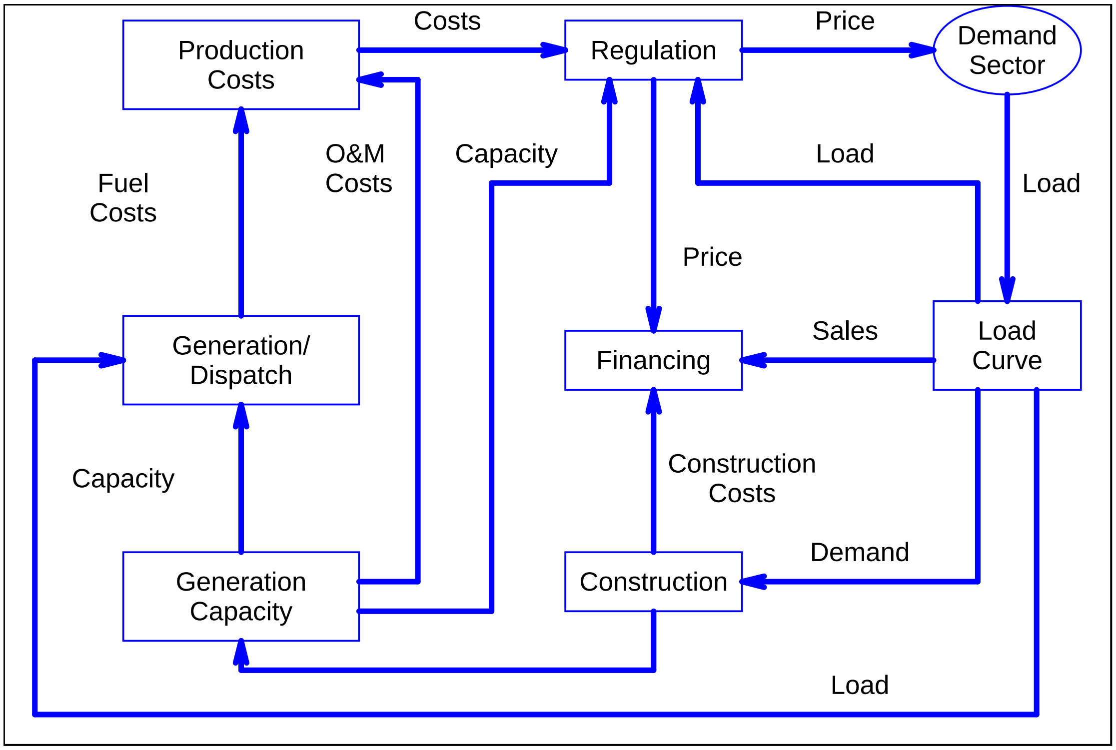

Figure 4: Electric Sector Overview

Actual utilities do use optimization routine for dispatch, so the properly-contained inclusion of optimization within the model should not cause inconsistencies within the system dynamics approach. However, when the ENERGY2020 framework includes optimal dispatch, other parts of the model must change the information flows to the dispatch module for generation to match historical realities. Such revisions modify the impact and subsequence dynamics of policy interventions. The resultant analyses can then bypass unintended consequences that more idealized intervention might entail.

What can justify having so much detail in the model? We call it the “bus-stop” problem. Policy involves many components of society: large and small industry, energy companies, departments within companies, voting consumers, national, state/provincial, and local government officials, regulators, and intervener groups. The policy discussion is most important to those who feel threatened by any proposed changes. Their world view is often narrowly defined in the context of where they are in the chain, or the path, that leads to policy interventions. We must start the discussion at their “bus stop” to connect the abstractions of the model to their tangible world. If the model cannot consider what is important to them, they quickly decry “What good is it?” Nonetheless, a question of balance remains. Entrenching the model as a continuing part of policy process can lead to unremitting “improved” detail without comparable “improved” feedback structures. Resultant unmanageable information flows create a growing gap between the model and decision-makers. The consequence may be a simplification of structure rather than reining in detail. Blind trust may replace tested understanding. A spiral of knowing less and less about more and more can ultimately remove any usefulness the model had to inform policy.

An early misstep in the ENERGY2020 development was an effort to define a set of policy options based on the dominate feedback and leverage points within the model. After constructing a comprehensive, easy-to-use portfolio of policy options, no inter-personal interaction with any stakeholder ever started with any of those options. To explain or argue about what was "really" important only alienated would-be-supporters, created distrust, and bespoke "irrelevance." Even after 30 years, every new project still starts with the definitionally-unique concerns of the client and policy choices they envision. It is then the job of the modelers to quickly map those "new" policy options onto the model structure, ensuring the model will illuminate impacts of most concern to the stakeholder – even if those impacts are only important to one relevant stakeholder. To put this issue in context, imagine being a politician where one policy option can swing unemployment by 500 persons. Often changes of this magnitude in the model are tertiary level impacts. Nonetheless, in terms of potentially lost votes, that change is easily the margin for re-election or defeat. Policies that cause small changes in energy prices can make or break energy-intensive companies operating under already stressed conditions. "Small" does not mean unimportant. And "small" is in the eyes of the beholder. As policy analysts, cum models, we worry most about those dominant loops and find fixating on detail to be time-consuming distractions, but the problem being addressed is a problem because it has a human consequence. In the case of ENERGY2020, having the detail for the wrong reason seems to be much more effective for successfully implementing a policy than leaving out the detail for the right (modeling) reasons.

Calibration and Validation

Despite this detail, the model engine that performs the simulation only represents a small percentage of the ENERGY2020 application.[*] Vast historical databases support the model. A hierarchical system is used to combine often contradictory data. One time-series data set, for example, the Statistics Canada report on *Energy Supply-Demand in Canada*[†], acts as the referent set, and data in other sets fill in the composite energy, environmental, and economic picture by using proportionality and normalization to ensure a single self consistent "super-set." Data-fusion algorithms ensure the historical data are complete enough to define the history at the same level of detail as the model itself – including all state-variables (levels). Because people so often focus on the current conditions as if they represent the greatest reality, collections of state and provincial models are currently validated from 1986 to the latest quarterly numbers.[‡]

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[*] ENERGY2020 is written in the PROMULA (ADS) language (www.promula.com). We have attempted to translate the model to more modern system dynamics languages but the packages cannot manage the size and data transfer issues.

[†] http://dsp-psd.tpsgc.gc.ca/Collection-R/Statcan/57-003-XIB/57-003-XIB-e.html

[‡] Although the model previously reproduced history from 1975; it now begins in 1986 because of changes in governmental data collection.

Once a client specifies the regional associations and problem definition, the model assembles and aggregate locale-specific data as appropriate for automated parameterization. To facilitate communication and a client-bond with the model, the calibration underscores the unique characteristics (physical, institutional, and cultural) that affect how people make choices, invest, and use energy. The calibration process estimates structural parameters using simple averaging or least-squares. Forward and inverse modeling then take advantage of parameter, structure, and data uncertainty to adjust secondary parameters (within the limits of estimated error) to *exactl*y reproduce history. Because any discrepancies at the interface to demand, supply or macroeconomic sectors can initiate transients, any inconsistency in the parameterization can initiate anomalous transients that can mask the dynamics of interest. In most instances, initial policy preferences produce minimal variation over the reference forecast. Therefore, to clearly inform decision-makers of why a policy had or did not have the expected attributes, the model needs to unambiguously illuminate only the differential dynamics caused by the policy.

The model does allow the user to exactly specify a future case, through 2050 if desired. This "future history" might have little connection with reality. By explicitly allowing such an option, the calibration process can point out where parameterization is well outside its range or that the forecast imposes implausible dynamics. Typically, a "future history" does not change the dominate dynamics of the system. Therefore, its use for policy design can still guide policy development to avoid embarrassing outcomes. Given the inevitability of negotiating the reference case, the explicit recognition of the process, via "future history," affords a transparency that bestows trust among adversarial interests and a beneficial counterweight to external "spin-doctoring" pressures.

In 1982, Andy Ford introduced us to Los Alamos National Laboratory efforts on sensitivity analysis. These tools combined Latin Hypercube designs with regime-dependent partial-correlation-coefficients methods.[16,17] The module we call HYPERSENS can rank the structure, data, and assumptions that contribute most to the uncertainty of model results.[18] Optimally robust plans can be quickly determined with minimal data requirements. We use this capability in a multitude of ways. Data collection has a large expense, especially in a regulatory environment. If we can prove specific data do not matter, resources can be allocated to acquire and better understand the data that does matter. The uncertainty analysis can set bounds on confidence intervals. We often first let the policy portfolio be the uncertainty, using the reference case. Once the sensitivity analysis reveals which policies offer the desired outcomes, we use HYPERSENS in a second round to test the policies against situational uncertainty (e.g., oil prices, economic growth, regulatory changes) to demarcate robust policies. Given specifying criteria (such as staying within a margin for costs, profits, or emissions), the confidence intervals capture probabilities of effect that decision-makers can use to select policies portfolios consistent with their risk aversion.

One particular outcome of the sensitivity analysis worth mentioning is the impact of the budget constraint. The budget constraint in ENERGY2020 simply compares the current budget for energy with a status-quo (smoothed) value. Behaviorally, it successfully captures the short term *demand* response to price spikes – where there is a transient reduction in usage that recovers partially as other parts of the consumer's budget adjust. It represents the shortest loop-time-constant used in the model (~18 months). Its average value is unity. Overall, the model response is dominated by long construction delays and assets' lives, yet narrow uncertainties in the statistically estimated gain on the budget response has the largest sensitivity for future prices and supply capacity. The reason is that the system does not have a fixed long-term goal. Changes in demand change supply expectations of new capacity needs. These expectations affect future price and thus future demand, and thereby further affect future supply. The key point however is that the budget constraint has no significant impact on the selection of the most effective policy. Absolute sensitivity and sensitivity for a purpose are two very different issues.

The calibration, sensitivity, and uncertainty quantification improve confidence in the model results. Supplying an instrument for stakeholders to explore the difference between their mental models and the causal explanations associated with model results seems to be the most potent form of confidence building.

As will be shown later, the model's forecasts have been disturbingly accurate, even 20 years later. Retrospective assessment of past forecasts indicates compensating errors on unrelated dynamics that were not part of the model. Thus, historical or future accuracy is apparently not a basis for assuming validity. Establishing metrics that quantify validity remains an area of active research at Sandia National Laboratories.[19]

Lastly, in what we think of as a validation process, ENERGY2020 is not the product of group modeling.[20] John Sterman provides reproducible evidence that mental models have significant limitations.[21] In a detailed model like ENERGY2020, there are too many degrees of freedom to refute concerted efforts of applying confirming biases. If a process of interviewing individuals is first used to selectively piece together a causal story consistent with the data, then later group review of model results becomes a falsification process focusing on why aspects of the model (and most alternatives) are wrong rather than why they are right. We find this approach very efficient at producing a (not necessarily satisfying) consensus for policy assessment within the short cycle-time for most corporate and political decisions. What we have often discovered is that the feedback loops experts (and the management in charge of them) presume are present either did not really exist or did not operate in the manner assumed. For example, demand side management programs may have nothing to do with reduced energy use or the forecast thereof because of cross-purposed success metrics. The program could be to subsidize the efficient use of energy, and thereby be attracting *new* business, and thus, new (albeit efficient) energy use. More commonly, regulatory, operational, and financial information would be collected, as was required, but never used.

On the reverse side of this coin, the ability of the model, from a consistency perspective, to give the appearance of outthinking stakeholders, led to situations where inquiries to resolve known problems with the model generated fanciful client explanations of why the model was assuredly "right." The good news is that these events provided opportunities to restore an environment of productive skepticism.

Model Structures:

This section highlights a few of the policy relevant features of ENERGY2020. Full documentation of ENERGY2020 is currently available at the California Air Resource Board website.[*] This documentation is unfortunately a bit dated. As noted previously, the model changes, often dramatically, depending on the policy interest of the client. Regrettably, documentation and validation efforts remain an underfunded aspect of essentially all SD modeling projects.

Demand Sector

The ENEGRY2020 demand sector considers energy a derived demand. Energy demand is a consequence of using capital stock in the production of output. For example, the industrial sector produces goods in factories which require energy for production; the commercial sector requires buildings to provide services, and the residential sector needs housing to provide sustained labor services. The occupants of these buildings require energy for heating, cooling, and electromechanical (equipment/appliance) uses.

The amount of energy used in any end-use is based on the concept of energy efficiency.[22] For example, the energy efficiency of a house along with the conversion efficiency of the furnace determines how much energy the house uses to provide the desired warmth. This warmth is what is called the service or the service-energy. The energy efficiency of the house is called the capital stock energy or process efficiency. This process efficiency is primarily technological (e.g., insulation levels) but can also be associated with control or life-style changes (e.g., less household energy use because both spouses work outside the home.) It is associated with the economic output and is measured in unit of $-of-output/BTU-service. The furnace efficiency is called the device or thermal efficiency. Thermal efficiency is associated with air conditioning, electromotive devices, furnaces, and appliances and is measured in units of BTU-service/BTU-primary. Primary energy is the input fuel.[†] Device efficiencies are limited by the laws of thermodynamics; the process efficiency is not.

Note that this approach does not include the number of vehicles, households, square-feet of building space, or even population as a driver of demand – like essentially all other demand models.[23] “Households” is a much more tangible concept and easy for people to grasp. Yet not all cars have the same mileage; income allows larger houses, more travels, and more energy intensive toys. Efficiency measures describe the physical process, and statistically viable methods, such as qualitative choice theory (QCT)[24], can capture the behavioral choice process that trades-off efficiency with other cost components and preferences.

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[*] http://www.arb.ca.gov/cc/scopingplan/economics-sp/models/models.htm

[†] For transportation, the process efficiency measure is $-of-output/mile and the device efficiency is miles/BTU-primary.

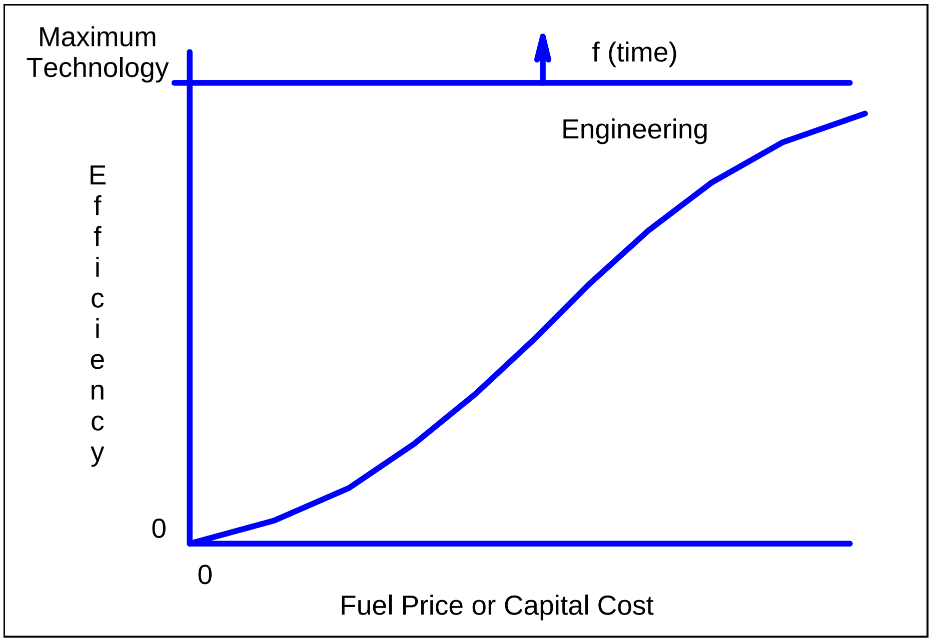

Figure 4: Efficiency Trade-off Curve

The model simulates investment in energy using capital (buildings and equipment) from installation to retirement through three age classes or vintages. This capital represents embodied energy requirements which will result in a specified energy demand as the capital is utilized, until it is retired or modified. The energy requirement embodied in the capital stock (as depicted in Figure 2) changes only by new investments, retirements, or by retrofitting. The energy efficiency of the capital has a limit determined by technological or physical constraints. The tradeoff between efficiency and other factors (such as capital costs) is depicted in Figure 4. Maximum efficiency levels change with technological advances that are exogenous, such as government R&D program goals (as opposed to endogenously based on competitive need or on R&D investments). The efficiency of the new capital purchased depends on the consumer's perception of this tradeoff. For example, as fuel prices increase, the efficiency consumers choose for a new furnace is increased despite higher capital costs. The amount of the increase in efficiency depends on the perceived price increase and its relevance to the consumer's cash flow.

Consumers determine which fuel and technology to use for new investments based on perceptions of cost and utility. Marginal trade-offs between changing fuel costs and efficiency determine the capital cost of the chosen technology. These trade-offs are dependent on perceived energy prices, capital costs, operating costs, risk, access to capital, promotions/advertising, regulations, values, perceptions, and other imperfect information. Given even limited historical data on only analogous choices, historical usage has shown that QCT generates a robust estimation of behavioral responses. QCT implies an ordinal utility function for alternative choices.[25] It is important to avoid the pitfall of cardinal utility or assuming a choice without an alternative.

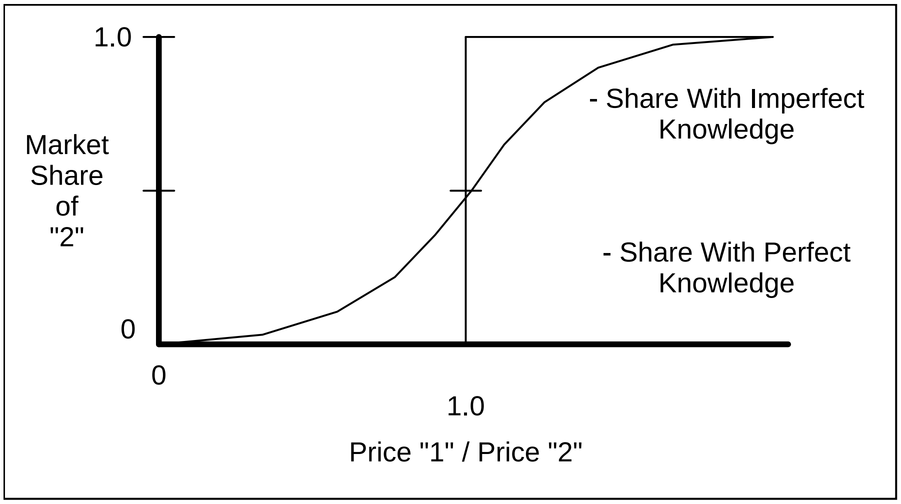

Figure 5: Marginal Market Share Calculation

Not all investment funds are allocated to the least expensive energy option. The same QCT logic used to efficiency versus capital-cost choices works for technology category or fuel choices. In QCT, uncertainty, regional variations, and limited knowledge make the perceived utility of choice a distribution The investments allocated to any fuel type are then proportional to the fraction of times one fuel is perceived as less expensive (has a higher perceived value) than all others. Figure 5 graphically shows this process with the simplification of using only price as a measure for the utility of the choice. QCT is the basis for all decisions within the model.

Rather than using price elasticities to determine how demand reacts to changes in price, ENERGY2020 explicitly identifies the multiple ways price changes influence the relative economics of alternative technologies and behaviors, which in turn determine consumers' demand. In this sense, price elasticities are outputs of, not inputs to ENERGY2020. These price elasticities change over time depending on the state of the system and the information available. Both of these features are the opposite of what most other demand models assume, but they have the advantage that reviewers can compare elasticities estimated from actual data to the model. Further, the model does not contain discount rates. It does contain interest rates, but those only serve to estimate the *actual* cost of selecting a choice. No one we have ever met was able to perform a discounted cash flow estimate in their heads. Further, in the actual decision-making setting, we never found anyone using discount rate unless they were actual net present value financial calculations over an investment scenario. Hence, we think of the discount rate as a convenient ex-post calculation, like elasticity, but not as a component of the forward simulation.

Client and regulatory commissions have noticed over the years that the model appears to produce demand forecasts with error bands (compared to actual future demands) of only a few percent or less. On one hand we might argue that this is due to the feedback between demand and price within the model. In the early 1980’s research noted what is called the "NERC fan" and attributed the failure of demand forecasting to the absence of price feedback in other forecasting models.[26] Another reason may be that the most accurate forecast practice appears to be an econometric technique called cointegration.[27] Like QCT, its developers (C. Granger and R. Engle) received Nobel Prizes for their efforts. Cointegration, as its name implies, looks for integration and variables related to one another through integration (levels) or differencing (rates). Other than that cointegration in typically atheoretical, its constructs map completely over to system dynamic functional forms. While the system dynamics community often downplays any discussion of predictive capability, in a *relative* sense, it appears that system dynamics is much better at it than almost any other method. Cointegration models do not allow for multiple delay elements within a single feedback loop, but the cointegration estimation process does. The extra degrees of (supportable) freedom from differentiated time constants does necessarily improve the historical "fit" and this appears to reduce error bands of predictions. As noted above, it also appears to work through an unanticipated shock to the system, such as a change in regulatory regime. The theory of cointegration argues this indeed should be the case; cointegration assumes that there is an unambiguous long-term equilibrium condition for the model – which the earlier discussion of the budget constraint shows is not true for ENERGY2020.

Electric Sector

In its early uses, the electric utility sector highlighted the dynamics for completed or to-be-cancelled nuclear power plants. It also anchored the use of the model for demand forecasting by generating electric prices across customer classes and regulatory regimes. As the least-cost planning efforts failed to contain demand growth, the model became the arbiter of new conventional and renewable capacity decisions. Like its EPPAM predecessor, the internal electric utility forecast of demand is not the same as the demand forecast from the ENERGY2020 demand modules. The internal forecast is a forward looking estimate of the demand over the timeframe required for new construction. The delays associated with adjusting this forecast in light of new information seems to explain much of the overbuilding seen in the 1970's.

The high-consequence connected with many of the policy studies ENERGY2020 performs has allowed us to work closely with all level of the energy companies' staff – from the CEO down to the front line of customer service and plant operations. Many utilities have sophisticated forecasting and financial analysis departments. Yet retrodicitive analyses with ENERGY2020 reproduced historical decisions using simple exponential extrapolation for forecasting and rudimentary (endogenous) estimates for future technology costs. We attribute this reality to the inertia within the decision process. All information is compared to past experience. This filtering looks much like exponential smoothing and experience-based intuition about what costs dominate outcomes. By maintaining a one-to-one correspondence between supplier functions and model descriptions, we can challenge clients' and our own "obviously true" assumptions by comparing the model behavior to the behavior of staff actually performing the functions. To connect model abstractions to the concrete realities of decision makers, ENERGY2020 produces the charts and tables that the decision maker already considers an accepted part of their reviews, such as an income statement, sources and use of funds, balance sheet, and generation reports. These have all the detail the decision makers normally consider important – even if we cannot understand their relevance to the problem. Once comfort-levels improve, we could add auxiliary information that we believe might help explain the impact of proposed decisions. We find that if we do not work this way, the model remains external to the process. The counter side of this approach is that the model does become part of the process and the analysis has to recognize that the model itself is part of the real-world feedback dynamics.[28]

The use of the model for deregulation assessment began in 1986, long before deregulation experiments actually began within the U.S.[29] Model design parroted deregulation explorations in Europe, New Zealand, and South America. Rather than having electric utility sectors representing all generation in a region, there were now competing companies. Not only that, these companies could (or had to) split into separate institutions representing retail/distribution, transmission, marketing/trading, and generation business enterprises. Because we needed to model policy, we needed to capture the impacts of energy company mergers, acquisitions, and bankruptcies – concepts as inconceivable as was FOSSIL2 considering nuclear power plant cancellations in the 1970’s.

The collapse of the Soviet Union presented opportunities for ENERGY2020 to guide policy under conditions of sparse, distorted, or non-existent data within a framework of both economic and energy deregulation with Eastern and Central Europe. While optimization models indicated the East Europeans should save energy and use heat-pumps, ENERGY2020 highlighted biomass (manure and straw) supplies, the need for cost-based accounting within utilities, and the need to increase electricity use both for stabilizing (nuclear-power based) grid operations and growing the economic activity with the area.

Once U.S. deregulation experiments began in earnest, U.S. utilities and commissions used the model as a micro-world for them to understand future possibilities and especially the market instabilities due to imperfect rule making.[30] The process of deregulation requires a careful consideration of market power dynamics.[31] The ENERGY2020 model examined how market players could use the rules to take advantage of the market and how payers could fall victim to such activities or counter them.[32] The model also clarified the design for rules that naturally mitigate market gaming. Independent System Operator of New England (ISO NE) used the model to find “gaps” in its rules and to develop more efficient market conditions. When applied to the California market the model showed, before-the-fact, many of the “games” played in the California market, their evolution, and impact on prices. More on this later.

Several utilities, with their CEOs, dispatchers, marketers, and plant operators, spent significant effort learning to effectively respond to predatory market behavior from their soon-to-be competitors. Invariably, however, when the tense events actually did transpire, staff reverted to old decision-making unsuitable for the new conditions. These were smart, well-trained staff who appeared to have internalized the system dynamics.

The use of models for "learning" appears to have validation issues well beyond simply producing a valid micro-world.[30]

Macroeconomic Modules

ENERGY2020 policy analyses often include two-way coupling with a detailed macroeconomic model. Such a coupling establishes the economic impacts of energy/environmental policy and the energy and environmental impacts of national economic policy. For U.S. regional and state level analyses, ENERGY2020 links to the REMI macroeconomic model.[*] For Canadian analyses, the model links to the Informetrica macroeconomic model.[†] The REMI and Informetrica macroeconomic models include inter-state/provincial, U.S., and world trade flows, price and investment dynamics, and simulate the real-time impact of energy and environmental concerns on the economy and vice versa. They are econometric but are dynamic, do include delays, and are not optimization models. This makes them conceptually compatible (at least at the linkage points) with the system dynamics structure of ENERGY2020, and they do self-consistently close several relevant feedback loops. The polarity and over/under-shoot trajectory of the impacts characterize the salient points for decision-makers. A drop in the economy translates to the reduced utilization of productive capacity with reduced energy use or emissions. Reduced utilization reduces prices to later stimulate demand. Therefore, a downturn in the economy is not a sign the energy or emission policy is working. Further, an economic downturn carries political costs that need offsetting by other (possibly delayed) benefits. In many studies, the macroeconomic feedback dominates the criteria for prioritizing policy options.[33,34]

Brief Usage History

We estimate that nearly $15 million have been spent so far on the development of ENERGY2020 at a cost of 250 person years. Over the last 30 years, its client list includes load forecasting, strategic planning, regulatory, and business-development departments, but it also includes prime ministers, presidents, ministers, governors, commissioners, regulatory directors, CEO's, and CFO's. ENERGY2020 has been used in all 50 states, all the Canadian provinces/territories, in over 20 countries, by literally hundreds of electric utilities, and by essentially all the largest energy companies in the U.S.

This section briefly offers a few examples of past policy efforts. Table 1 presents a partial list of the clientele, using names at time of engagement.

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[*] www.remi.com

[†] www.informetrica.com

American Electric Power
American Public Power Association (61)
ANEEL (Brazilian Federal Regulators)
Eastern Canada Premiers
Bonneville Power Administration
British Columbia Hydro
British Gas
Southern California Edison
Canadian Energy Research Institute
Carolina Power and Light
Central Maine Power Company
Cinergy
Powergen - UK
Colorado Rural Electric Association
Companhia Paranaese de Energia (COPEL), Brazil
Council For Energy Resource Tribes
Duke Energy
Edison Electrical Institute
Eesti Energia, Estonia
ENECO (Netherlands)
Enron Trading and Capital
Environment Canada
European Commission – European Union (60)
FirstEnergy
Gornoslaski Zaklad Elektroenergetyczna (GZE), Gliwice, Poland
Green Mountain Power
Hawaii Department of Business, Economic Development & Tourism (59)
Houston Power & Light
Idaho National Engineering Laboratory
Illinois Department of Energy and Natural Resources
ISO New England
Kansas Gas and Electric Company
KN Energy
Latvenergo, Latvia
Lithuanian State Power
Massachusetts Executive Office of Energy Resources (58)
Minnesota Power
NaionalEnergy Board - Canada
National Renewable Energy Laboratory
Natsionalna Elektricheska Kompania, Bulgaria
Natural Resources Canada
New Century Energies
New England Governors' Conference, Inc.
New Hampshire Office of Energy (57)
New York State Electric & Gas
New Zealand Ministry of Energy
Office of the Prime Minister- Canada
Ohio Edison/Centerior
Oklahoma Corporation Commission
Omaha Public Power District
Ontario Hydro Services Company
Ontario Ministry of Energy
Otter Tail Power Company
Pacific Gas & Electric
PacifiCorp
Reliant Energy
RWE Energie – Germany
San Diego Gas and Electric
Santee Cooper
Saskatchewan Energy and Mines
Scottish Power
Southern Company Services, Inc.
Stanford Energy Modeling Forum
TransAlta Corporation - Canada
US Department of Energy
US Environmental Protection Agency
Utilicorp United
Vermont Department of Public Service (56)
Western Interstate Energy Board
Western Resources
Wisconsin Power and Light Company
Wisconsin Public Service Corporation
Zaklad Energetyczny SA, Torun, Poland

Table 1: Illustrative Partial List of Clientele

In 1986, the then Kansas Gas and Electric Company (KG&E) was just finishing the Wolfe Creek Nuclear Power Station.[35] Like many other nuclear facilities, the cost of the plant far exceeded initial estimates. KG&E had stretched it financial position to the limit, and bringing the completed plant into the rate base could produce rate-shock that might cause plummeting demands – and therefore reduce the revenue stream then needed to maintain operations. ENERGY2020 analysis showed that if dividends were temporarily halted (an extreme move for the time) the rate shock would be lessened, and the company would have adequate cash flow. Lamentably, the stock price would also drop precipitously. If it dropped too far, the company might be the first U.S. utility to face bankruptcy. ENERGY2020 showed that if the strategy was going to work, the stock price would drop by about 25%, change slop drop a bit more and then recover – as stockholders realized the demand and revenue were higher than expected. The implemented policy had the worse initial gradient of all policy options tested. If the decline stayed on its downward path beyond what the model "predicted" there would be little chance of corporate recovery. The stock indeed responded as predicted and KG&E later became Western resource, arguably the most successful (and profitable) utility in Kansas.

In Wisconsin, in 1991, all the utilities were brought before the commission to explain the severe energy shortages. Only Wisconsin Power and Light's ENERGY2020 forecast was released from the review. While other companies' forecasts were off by (on average) 600MW, the ENERGY2020 model was off by 10 MW, as based on its forecast from ten years earlier – that showed that the expected reductions from DSM programs would not occur. A key part of this forecast was the demand stimulation due to prices being lower than they would be if new power plants had been built. A second part was the demand model saying that even at zero cost, customers would not embrace demand programs. Surveys later discovered that a large fraction of the free hot-water heater blankets, insulated dog houses, and the refrigerator rebates meant a significant segment of the population had a new second refrigerator in the garage filled with cool Wisconsin beer. There were a few unsubstantiated claims that the high efficiency air-conditioner program made it economic to see one's breath indoors. Peak air conditioner loads did actually increase.

Minnesota Power suffered an 80% drop in load in 1980 due to the world crash of the steel industry. They used ENERGY2020 to forecast the timing of any future recovery of the industry and its impacts on other industrial, commercial, and residential loads. As of 1981, these forecasts allowed MP to have the highest rate of return on assets of any other U.S. utility, and they have maintained the record annually since then.

The State of Illinois used the model for both electric and gas for utility planning and regulation. During the nuclear rate shock era in Illinois, just as in Kansas, the model properly showed the decline and recovery impacts on prices and demand.[36]

Southern California Edison (the world's largest electric utility) has a seven-climate zone version of the model to allow them to forecast their peak and energy demands. From this experience, the California Energy Commission formed a study to look at forecasting, and in a field of 150 models, found ENERGY2020 to be the best for mid-term forecasting.[37]

Southern Company (the world's largest utility company) used the model to provide forecasts for each of its U.S. operating companies (Alabama Power, Georgia Power, Mississippi Power, Savannah Power, and Gulf States Power.) As in the Wisconsin case, when Georgia utilities were brought before the commission for bad forecasting, the ENERGY2020 forecast was shown to be an example of the right way to forecast by the adversarial reviewer contracted by the commission! This version of the model used the concept of "future history" to make sure the ENERGY2020 projections were consistent with the short-term projections produced by the individual operating company's budget offices.

Central Maine Power used the model to justify a new transmission line from Hydro Quebec to Maine.[38] This court case was lost, but years later the State agreed that the model would have saved millions of dollars for the State of Maine had they accepted its conclusions.

In 1991, the federal government of Canada started using the model for climate change and criteria-air-contaminant analyses.[39] Eventually Natural Resources Canada and Environment Canada selected ENERGY2020 to lead the analyses for provincial and industrial stakeholders to define a mutually acceptable policy portfolio that could allow Canada to ratify the Kyoto Accord.[40] This effort involved contentious workshops in all the provinces and with business interests. The model acted as a focal point for discussion and negotiation. Over the two-year effort, in this very public forum, ENERGY2020 analyses made front page news in over 150 newspapers. In the later stages of negotiations, the Office of the Prime Minister guided the efforts. The model indicated that acceptable and conventional policy options could not achieve the desired goal. In the end, key industries and provincial interests, in essence, simply contractually agreed to emission reductions. Those reductions became part of the modeling assumptions. This is not the ideal means for a model to support policy, but it did lead to the approved ratification in December 2002. Although other factors contributed, Prime Minister Chrétien's commitment to do whatever necessary to ratify the Accord contributed to his resignation shortly after this successful effort.[41,42]

During this time, the model's rebound dynamics indicated that transportation efficiencies would worsen despite regulation and data to the contrary. Two years later, a revision to historical data verified the model projections.[*] The use of policy measures constrained by maximum available device efficiencies means that energy (and thereby emission growth) came in lock step with economic growth. The programs tortuously negotiated to meet Year 2012 requirements masked a created inability to hold emissions after 2013. The behavioral response of the model proved more valid than the emission reduction contracts, and Canada emissions continued to rapidly grow despite government and industrial efforts. Environment Canada continues to use ENERGY2020 to evaluate Cap&Trade and Greenhouse Gas (GHG) policy options that could actually reduce emissions to acceptable levels.[43,44]

As a part of the Canadian policy assessment process, the National Round Table on the Environment and the Economy (NRTEE), which at the time existed under the auspices of the prime minister, addressed specific aspects of energy and the environments, much like the U.S. National Academy of Science is often called upon to do. One such project using ENERGY2020 addressed the implementation of a hydrogen economy. Because of the delays and existing infrastructure, the experts agreed with the model that only the local production and use of hydrogen could significantly impact energy use within a 30-year window.[45] Further, the implicit use of electricity from renewable sources to produce the hydrogen had to carefully recognize backup capacity needs and generation scheduling issues that could increase emissions due to fossil fuel generation. A subsequent effort then used ENERGY2020 to reconcile the need for a *long-term* strategy for climate change as opposed to a sequence of short-term responses.[46]

Currently governmental bodies and utilities use ENERGY2020 to address climate change policy options, including Cap&Trade, carbon taxes, conservation/efficiency programs,

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[*] Just because it seems to us so unusual, we note that the use of the model in Massachusetts also caused a re-check and major revisions to their official energy times series data.

and renewable energy. Using the model as a lingua franca, the Bonneville Power Administration and the Northwest Planning Council both use ENERGY2020 to evaluate climate policy and energy/environmental planning issues. The Governor's Offices of Illinois[47] and Wisconsin[*], Ontario Ministry of Energy,[48] California Air Resources Board[49], and the Michigan Department of Environment Quality[50] have recently used ENERGY2020 for assessing climate policies. The largest current effort is associated with Western Climate initiative[51] composed of U.S. western states and Canadian Provinces.

While the expanded use of renewable energy is touted as a means to create jobs, a combined macroeconomic, energy, environmental analysis indicates the process is mostly one of substitution with little added job creation. Conservation programs on the other hand create service jobs that (modestly) increase personal income. Secondary price effects may stimulate demand and temper emission reductions, but the net impact does appear to increase job creation. The Cap&Trade analyses indicate that it may be difficult to design Cap&Trade regimes that can achieve emission targets because of the market distortions they can readily generate. Carbon taxes are much more effective at producing desired outcomes, and it appears that the proper design of their implementation can promote economic growth even if unilaterally implemented. [52] Unilaterally imposing Cap&Trade regimes primarily causes emissions to move out of state along with some economic activity. For example, coal-fired power plants outside the state border have a significant economic advantage over those with the border. Programs that emphasized reduce energy usage have a better chance of limiting this spill-over dynamic. Even so, Cap&Trade programs offer politically palatable flexibility that will ensure their usage. Climate change is clearly a difficult problem where reductions necessarily have a larger impact on some industries and individuals than on others. The entire process necessarily has to involve a change from status quo behaviors. We find that a change in status quo is often the greatest hurdle to policy. Therefore, whether they are real or perceived, there will be winners and losers. Most policy efforts continue to pursue technical solutions rather than laying out the spectrum of options-with-consequence and facing the value-laden, societal negotiations that ultimately need to take place.

With the 1998 implementation of deregulation legislation in California, a large focus of ENERGY2020 effort revolved around recognizing the distortions the market design imposed. Many conditions, such as bidding in more power than a transmission line could accommodate (thereby creating congestion) allowed countermeasures (such as bidding in a fictitious counter-flow that negated the congestion). However, many conditions could produce cascading price and congestion problems that lacked mitigation options. Actively verifying these market failures did produce some modifications in the rules, but in the form of more restrictive rules that actually increased the distortions. It seemed that incumbent energy companies wanted to maintain some semblance of previous status quo (competition is great as long as it improves my situation) and regulators wanted to maintain some sense of control (the "visible hand" of regulation must be independent of the "invisible hand" of markets).

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[*] http://dnr.wi.gov/environmentprotect/gtfgw/AG_t.html

Market conditions were already unstable by 1999. The Bonneville Power Administration (BPA) had contractual arrangements with the large aluminum smelters that allowed the smelters to obtain energy at very low costs independent of market conditions. In this timeframe, any excess demand on the electric system resulted in meteoric market-price increases. BPA proposed interventions that would effectively shut down the smelting operations. This process would result in significant job losses. In a heated political and socioeconomic environment, ENERGY2020 showed that the "rebound" affect would cause much of the impacts to diminish over time. Stakeholders agreed to the smelter shutdown, and the actual impacts were consistent with the ENERGY2020 assessment.[53,54]

As early as 1996, ENERGY characterized the sequence of events and the energy price they might entail when California "deregulated." The extremely high prices of 2001 were consistent with those earlier assessments. Because the state government of California did not revise the markets in a manner consistent with stable markets, it is not clear how much ENERGY2020 was part of the market feedback dynamics causing the problems – because of its ability to simulate the market behaviors and act as a tool to protect or promote self-interests. ENERGY2020 was so accurate in predicting market behaviors that Congressional investigations of the California Electricity Crisis initially assumed that if the model so accurately predicted such extremely volatile dynamics so well, it must be the source of them. Fortunately, we continuously made "market-gaming" analyses available to all parties: commissions, utilities, independent power producers, the legislators inside California, and to surrounding states. Further, we made sure we had no financial relationship with any party in the market nor were party to any financial transactions of the market. Thus, beyond claiming our model was independent of the market, we could more strongly claim no motive promoting high energy prices. Because Backus made abundant public presentations that blamed the state's deregulatory process for the evolving crises, discussions between him, the governor of California, and one of the investor owned utilities supporting the current regulatory regime became quite contentious. The result was a U.S. congressional hearing to condemn market gaming and to stop the public release of information showing the flaws in the market rules.[55] There was even talk of criminal charges. Ultimately the California Independent System Operator, the Governor's chief economic advisor, and chair of the committee agreed market gaming was an unsurprising outcome, inevitable given the flawed market design. Given the level of economic damage, and the excesses of ENRON tactics, the California deregulation experiment unsuccessfully ended. The governor of California also lost his job, and the key congressional supporter of ENERGY2020 became the new governor's Head of Cabinet. Although its role in the "crisis" is still debated, the key point here is that ENERGY2020's intertwined role in both the policy debate and in the actual policy impacts was unlike that of any other model of which we are familiar.

Prior to 2004 essentially all projects involved both Policy Assessment Corporation (Backus) and Systematic Solutions Inc. (Amlin) along with project partners such as the Canadian Energy Research Institute, Rocky Mountain Institute, NewEnergy, ICF, Inc, and Accenture. As of 2005, Systematic Solutions Inc. became the primary source of ENERGY2020 projects and services.

Parting Perspectives

As modelers, we hold models in an esteemed position where perspectives and assumptions become formalized, where they can be tested, critiqued, reviewed, and where informed decisions replace unenlightened ones. In an ideal world, validated models help policy makers understand and recognize the delayed, feedback consequences of decisions. Many have asked and eloquently answered the question “Why model?” Nonetheless, in a high-consequence decision-making environment, the model has other attributes that can complicate the ethical equation. The model is blamable; it can disorient adversaries, it can implicitly transfer responsibility from one authority to another, it can intimidate, it imbeds positions, and it can coldly present value-laden options. The answer to “Why model?” from a modeler’s perspective may be much different than that of the decision-maker the model serves. A decision-maker would not utilize a model unless the political, legal, and technical characteristics of the problem justified the time, cost, and complications of a model-based advocacy. We argue a successful model is part of the process. If the model is too successful, it falls victim to the status quo it creates and loses its ability to constructively promote change. ENERGY2020 efforts have, thus far, always sidestepped senility by ever heading to the next need, to the next new problem. Each project is treated anew. This inherent renewal process may keep the model “useful” into the indefinite future, maybe even to the year 2020.

Finally, we consider the model is most useful when it challenges hypotheses. We believe model-based policy analysis is not a pursuit of the “right” answer but rather an exploration of what possible wrong “answers” need avoiding. Can the analysis illuminate counterproductive decisions? Can it advance options that ensure positive outcomes when the (irreducibly uncertain) future does not unfold as planned? Determining the “right answer” is a value judgment that the model should repeatedly clarify as the *decision-maker’s* job.

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