# A Hybrid Model Architecture for Strategic Renewable Resource Planning

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A consortium of governmental agencies in a resource-limited region sought the services of an interdisciplinary team of five consultants to construct an analytic model to guide strategy choice with respect to a limited but renewable resource. This resource is of recognized strategic importance to the country, and is essential to the country's economy and domestic quality of life. The consultancy team, in collaboration with personnel from a local planning agency, developed a set of three linked models—a model *triad* composed of a System Dynamics model, a hybrid Multi-Sector Input-Output model, and a series of Decision Analysis models. This model triad was designed to enhance policy analysts' understanding of the consequences of alternative policies for managing the resource. It provides a quantitative picture of physical, engineering and economic measures of performance of the resource supply and demand system as a function of current and future policy choice. In particular, the triad provides interpretable pictures of magnitudes of economic, security and technological risks and rewards attached to capacity expansion decisions and supply and demand-side policy options.

Because the model triad explicitly accounts for uncertainties about oil prices, contaminant levels, rates of resource replenishment and levels of economic growth, the consequences of a policy in the context of particular external conditions is presented as risk profiles of possible values at each point in time. Once these consequences have been assessed for quantities of interest to the user, decision analysis tools can facilitate the summary and analysis of and choice among those policies, taking into account the preferences of different decision makers. While model-based policy analysis frequently seeks to optimize policy selection on the basis of some forecast of future events, this approach is not appropriate for this study. Because large uncertainties impact the renewable resource sector in the region under study, adherence to such an approach would be misleading and even dangerous, for it would lead to selection of a policy that is over-engineered to an assumed future. The team chose instead to examine policy robustness systematically as a function of varying assumptions regarding the future and, in addition, to take into account uncertainties in the likelihoods of possible scenarios.

This model triad allowed clients, for the first time, to perform integrated "what if" analyses of possible decisions as they impact and are impacted by the economy, environment, land allocation, advances in technology for resource procurement, security issues and other factors. It also allows the client to compute levels of uncertainty associated with variations in policy choice so that they can actively manage risks.

While the three models included in the model triad are linked together, each model performs separate tasks:

- The System Dynamics Model is designed to analyze the implications of particular policy choices and specific external conditions over time, in the context of uncertainty regarding energy prices, resource replenishment and contaminant levels (which directly impact resource availability). The System Dynamics model output provides the decision analysis model with probability distributions (risk profiles) specifying the consequences of policies under particular external conditions. While the system dynamics model contains an endogenous economy sector, in most cases the clients preferred to drive the economic variables of the system dynamics model with outputs from the Multi-Sector Input-Output model. Particular types of policy choice that can be studied in the system dynamics model include the effects of investments in particular resource procurement, creation, purification and recycling technologies, resource conservation initiatives, changes in several types of resource storage, and shifts in land use. By conducting large-scale Monte Carlo runs, the system dynamics model output provides insights about values of particular infrastructure investments, the cost of resource products to consumers, and the risks of shortfalls in resource delivery in the event of disruption of procurement from particular domestic and foreign sources. The system dynamics model time horizon was between 15 and 20 years. To capture possibly significant effects of rare brief events (even when lasting just a few days), a model timestep of one day was used. The System Dynamics model includes multiple sectors, including a simple population/demographics (including both local population growth and migration), resource-related capital construction or in use, technology learning curves and energy efficiency, replenishment, domestic and commercial demand (the former indexed by per-capita income and resource price, and varying in conservation conditions), capital cost and amortization, variable costs, and land. A production-function based economy sector is designed to help understand the effects of resource pricing on demand, the impact of land on economic growth, the impact of resource shortfalls on the economy, and the impact of land pricing on rates of economic growth. Data for the system dynamics model is collected from a variety of governmental agencies, institutions, and the published literature. Model results were cross-checked for validity against known historical values for a variety of intermediate quantities. Insufficient data and time was available to complete calibration of the economy sector; the clients preferred to drive the model with a disaggregated (albeit quasi-static) hybrid Multi-Sector Input-Output macroeconomic model (described below). Stochastic variation in replenishment rates was simulated through a calibrated seasonal ARIMA model based on 50 years of data. Variation in contaminant levels were incorporated using an ARIMA model plus a linear trend, and were calibrated against multi-year time series where possible. Oil price behavior was modeled using a standard securities (ARIMA) model formulation. Given the techniques by which the three types of stochastic variation were incorporated into the model, model simulation constitutes numerical (Euler) integration of a stochastic differential equation.

To better understand the implications of shifting risks from the renewable resource to energy dependency by means of investments in resource-producing (but energy consuming) technologies, the model incorporates energy-intensity learning curves for major procurement, generation, recycling and purification technologies. Vintaging effects for such resource capital investments are captured through traditional co-flow structures.

There are a variety of important linkages between the renewable resource and land use policies. Depending on the type of land being discussed, releasing land for development can increase energy consumption of the resource-related infrastructure, impose higher costs of resource purification, reduce resource replenishment, and lessen the region's ability to weather long-standing disruptions in resource sources (either intentional or unintentional). But in the region under study, land development has a variety of significant economic benefits that can help balance some of these costs. While the current model provides insight into implications of changes in land usage on resource storage, local yield and – indirectly – on resource quality, additional work (and particularly calibration of the economy sector) would be required for better understanding tradeoffs associated with such changes on the economy in either the short- or long- term.

- The Decision Analytic model provides a way of reasoning about strategic choice in the face of uncertainty. In particular, decision analysis provides a framework for reasoning about the three dimensions of strategic decision making when the results of strategy choice are uncertain: Strategic choices available to policymakers, uncertainties, and consequences of choices of action and outcomes. Using decision analysis software (TreeAge Data 3.5), the analyst represents decision trees capturing the factors above. Tree event probabilities and the risk profiles associated with terminal nodes are parameterized using outputs from the system dynamics model. For each terminal node, empirical risk profiles were calculated using data from several thousand Monte Carlo runs of the system dynamics model. Due to time constraints, such distributions were approximated analytically using expressions involving sampling functions built into TreeAge software. Based on those decision trees and explicit incorporation of risk preference functions, the decision analysis model can be used to identify a course of action that yields the highest expected benefit to the decision maker, can generate one or more risk profiles for each strategy, and determine under what conditions or assumptions the decision maker prefers one strategy to another. The modeling effort explored the use of decision trees using both standard decision rules (in which each terminal node in the decision tree resulted from a ensemble of System Dynamics trials, each specific to a fixed policy and event scenario) and parameterized decision rules (in which the results from a small number of system dynamics ensembles could be mixed "on the fly" within the decision trees to approximate the distribution resulting from a virtually unbounded set of specific decision rules.) While entirely driven by results from the system dynamics model, the authors found the decision analysis models very useful as a way of summarizing and analyzing the implication of model results for key decisions, and as a way of nimbly exploring how preferred decisions change in the presence of changed assumptions regarding the likelihoods that different scenarios will obtain. The exercise of combining System Dynamics and Decision Analytic frameworks revealed both a powerful methodology and many insights into desirable extensions to the functionality of available software.

- The Hybrid Multi-Sector Input/Output Model characterized the resource flow through a large number of economic sectors. The model incorporates the interaction among different sectors of the economy using the national input/output tables, tables of industry-specific resource usage, and other sources. The model uses this information to estimate both the direct and indirect use of the renewable resource for 19 major economic sectors. For those cases in which the clients sought to investigate the short-term and medium-term implications of sector-specific policies, or sector-specific implications of general policies, the multi-sector Input-Output model was used to provide the system dynamics model with estimates of aggregate industrial resource demand and aggregate GDP. The Input-Output model was structured so as to facilitate the simulation of changing resource demand in successive years, given different levels of industry growth.

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