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Addressing an Uncertain Future Using Scenario Analysis

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Environmental Energy Technologies Division

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Addressing an Uncertain Future Using Scenario Analysis

Afzal S Siddiqui[1] and Chris Marnay[2]

1. Background

The Office of Energy Efficiency and Renewable Energy (EERE) has had a longstanding goal of introducing uncertainty into the analysis it routinely conducts in compliance with the Government Performance and Results Act (GPRA) and for strategic management purposes. The need to introduce some treatment of uncertainty arises both because it would be good general management practice, and because intuitively many of the technologies under development by EERE have a considerable advantage in an uncertain world. For example, an expected kWh output from a wind generator in a future year, which is not exposed to volatile and unpredictable fuel prices, should be truly worth more than an equivalent kWh from an alternative fossil fuel fired technology. Indeed, analysts have attempted to measure this value by comparing the prices observed in fixed-price natural gas contracts compared to ones in which buyers are exposed to market prices (see Bolinger, Wiser, and Golove and (2004)). In addition to the routine reasons for exploring uncertainty given above, the history of energy markets appears to have exhibited infrequent, but troubling, regimeshifts, i.e., historic turning points at which the center of gravity or fundamental nature of the system appears to have abruptly shifted. Figure 1 below shows an estimate of how the history of natural gas fired generating costs has evolved over the last three decades. The costs shown incorporate both the well-head gas

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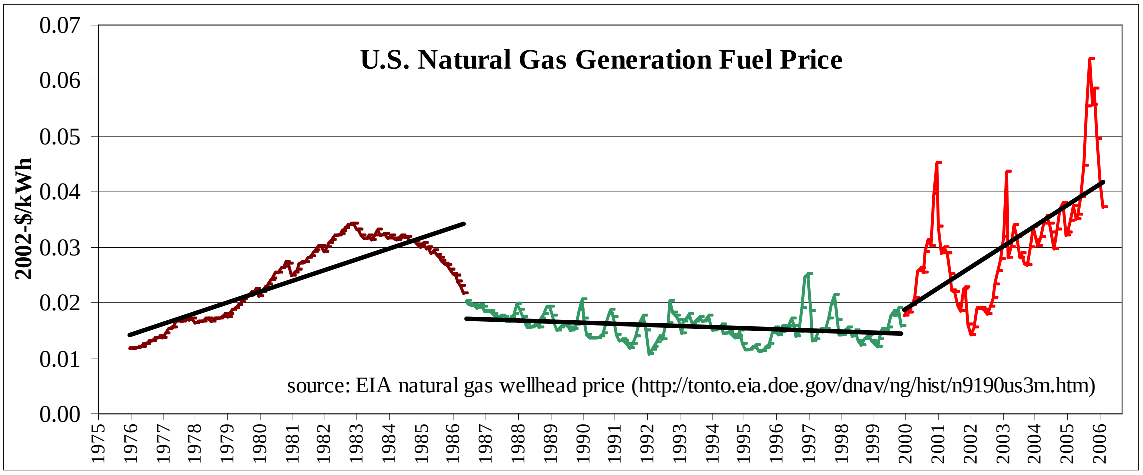
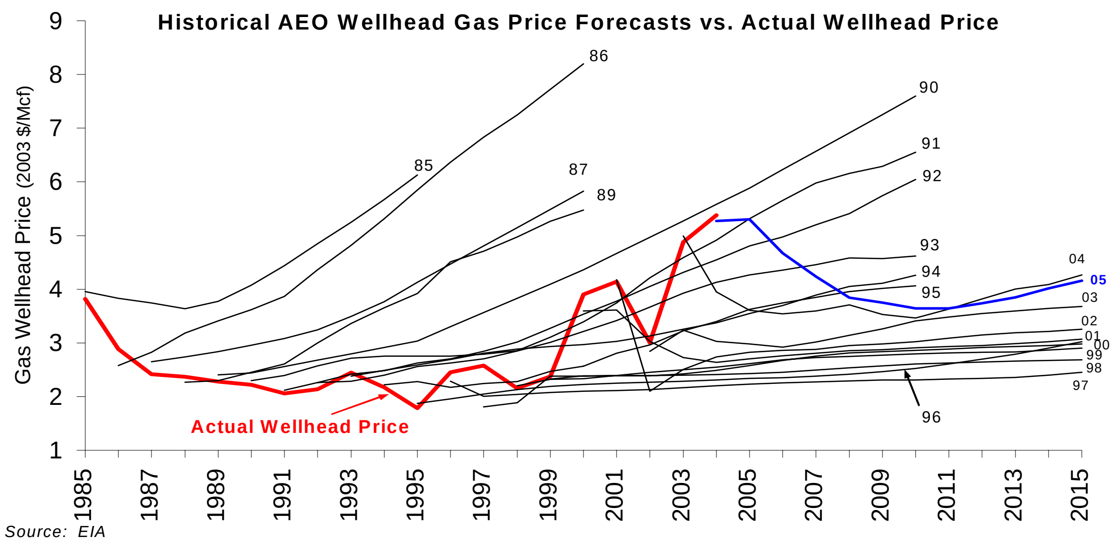
price and an estimate of how improving generation technology has gradually tended to lower costs.



The history shown in the above figure is alluring because it appears to break neatly into three periods. Within each period, the future would have seemed somewhat predictable, while conversely the two regime switches (in the mid 1980s and at the turn of the century) were dramatic and apparently unpredictable. Prices during our current regime, which began with the gas and electricity meltdowns during 2000-2001, are clearly not predictable month-by-month or year-by-year, but an increasing trend and high volatility do seem to have become the norm, and based on the 2000-present history alone, this is the future regime that would be planned for. The pattern shown in the figure is quite troubling to a modeler because no model currently conceivable of would have produced a correct forecast back in 1975. This is both because the regime shifts themselves could not be identified and because any forecast dependent upon data from a prior regime would appear to be fairly useless in any subsequent regime. But, while mathematically we cannot conceive of such a model, intuitively, we can readily imagine all manner of erratic and disturbing futures full of unpredictable discontinuities, and it is exactly this contrast that suggests the value of scenario analysis. In other words, in some ways our intuition and fears are more useful guides to planning for the future than rational analysis based on recent history.



Finally, it should be noted that the record of point forecasting has been mixed.[3] The above graphic shows how Annual Energy Outlook (AEO) forecasts have evolved over the last two decades. The various trajectories show the price forecasts1 made in the noted years. Note these are point estimate forecasts, not side cases or scenarios. Forecasts consistently fell year-by-year until the suspected regime shift at the turn of the century, which shows that recent history has a strong influence on forecasts. Not surprisingly, the actual path of prices has varied significantly, lying below the bounds of historic forecasts until 1995, but within the range afterwards. The current forecasts foresee the high prices and volatility of recent years declining and damping such that by 2015, the price is again close to the convention wisdom of recent AEOs. While on the one hand the forecasts in

[3] This graphic is taken from Figure 9 of "An Overview of Alternative Fossil Price and Carbon Regulation Scenarios", Wiser, R. and M. Bolinger. LBNL-56403. October 2004

the figure are a sobering reminder of limited ability to conduct forecasts, on the other hand, the variation in forecasts offers a type of uncertainty analysis. Looking at the forecasts together, as shown in the figure, serves as reminder that any one AEO forecasts should not be accepted without question.

The purpose of this paper is to explore scenario analysis as a method for introducing uncertainty into EERE's forecasting in a manner consistent with the preceding observation. The two questions are how could it be done, and what is its academic basis, if any.Despite the interest in uncertainty methods, applying them poses some major hurdles because of the heavy reliance of EERE on forecasting tools that are deterministic in nature, such as the Energy Information Administration's (EIA's) National Energy Modeling System (NEMS). NEMS is the source of the influential Annual Energy Outlook whose business-as-usual (BAU) case, the Reference Case, forms the baseline for most of the U.S. energy policy discussion. NEMS is an optimizing model because: 1. it iterates to an equilibrium among modules representing the supply, demand, and energy conversion subsectors; and 2. several subsectoral models are individually solved using linear programs (LP). Consequently, it is deeply rooted in the recent past and any effort to simulate the consequences of a major regime shift as depicted in Figure 1 must come by applying an exogenously specified scenario. And, more generally, simulating futures that lie outside of our recent historic experience, even if they do not include regime switches suggest some form of scenario approach. At the same time, the statistical validity of scenarios that deviate significantly outside the ranges of historic inputs should be questioned.

2. Introduction to Scenarios

In any model, the robustness of the results or significance of the control policy is subject to uncertainties in the underlying parameters. The sensitivity of such outputs from the model may be gauged by varying the input parameters according to some rule. For example, only one parameter may be changed at a time or several may be altered simultaneously. In the former case, the perturbation is known as *sensitivity analysis*, whereas in the latter, it is referred to as *scenario analysis*. Note that these two approaches do not assume that the underlying parameter is random *per se*. Rather, they imply that there is a limit to our ability to estimate or forecast even deterministic parameters, and even instrument measurement errors may necessitate sensitivity analysis. By contrast, a fully stochastic model allows underlying parameters to evolve probabilistically according to known density functions. Then, the model must be solved given this uncertainty. However, the addition of stochastic variables alone does not, except in extreme cases, permit forecasting of regime switches. Also, simulating a wide range of possible outcomes tends to diminish the detail or impact of any one trajectory. In other words, an array (or distribution) of outcomes provides one useful form of information, i.e., the likelihoods of many outcomes, but obfuscates results in the sense that the especially important outcomes are often those that cause anxiety (or glee).

Scenario analysis bridges the gap between completely deterministic and stochastic approaches by allowing several parameters to be varied at the same time without assuming that they fluctuate randomly thereafter. The scenarios created are typically alternative futures in which the parameter values are changed to some other regime of particular interest and stay there without subsequent surprises. In the context of energy policy, a scenario may be an oil price hike in a future year, which would then be used as a deterministic input into a model to determine the impact of this change. It should be emphasised that scenario analysis differs from forecasting, which typically attempts to extrapolate past trends into future paths, given current information and a hypothetical causal nexus. However, forecasting is accurate only when underlying dynamics are thoroughly understood. For the energy sector, this may not always be the case due to the instability of markets and the critical importance of scarcity. Hence, scenario analysis can provide insight into future trends that may be beyond the scope of existing forecasting techniques (see Ghanadan and Koomey (2005)).

This document surveys how uncertainty in mathematical models is addressed with focus on the implications of the pertinent techniques for energy markets. We begin in section 3 by providing a summary of sensitivity analysis, which is the simplest technique. Next, in section 4, we examine the opposite alternative, i.e., that of stochastic models, which includes a discussion of real options analysis. The gap between these two techniques is discussed in section 5, which deals with scenario analysis as applied to energy markets. Finally, in section 6, the salient points of this discussion are summarized and guidelines for policymakers offered.

2. Sensitivity Analysis

As mentioned above, sensitivity analysis is the simplest possible technique for determining how responsive model results are to underlying parameter values. By varying one parameter at a time, *ceteris paribus*, sensitivity analysis can provide answers from an optimization to the following questions:

- By how much does an objective function coefficient have to change before a decision variable is no longer part of the optimal solution?
- Over what range of constraint parameter values is the shadow price valid?
- How does the optimal solution change if a new decision variable is added to the objective function?

The advantage of this approach is that because it changes one parameter at a time, it may not be necessary to re-solve the model to answer such commonly arising questions. Indeed, for linear programs (LPs), expressions are available that delimit the range of the parameter in question for which the initial solution is optimal (see Nash and Sofer (1996)).

For large-scale models, however, such as NEMS, closed-form expressions bounding the effects of varying parameter values are not available. Consequently, re-running the model entirely may be necessary to determine how results change, especially for large perturbations in underlying parameters. Indeed, since small perturbations will most likely not affect the output of the model and are likely to not be of interest to policymakers, re-running something like NEMS would be required for any interesting sensitivity analysis. Due to the long run times of this model, it then makes sense to perform scenario analysis in NEMS to consider the effects of changing several underlying parameters simultaneously. Hence, constraints on computing time dictate that scenarios be selected judiciously, a process that we will address further in the next section.

3. Decision Making Under Uncertainty

A comprehensive way of addressing variability in underlying parameters is offered by stochastic models such as the Stochastic Energy Deployment Systems Model (SEDS) under development by EERE. In this case, uncertainty in the parameters of interest is specified by probability density functions. That is, some of the influential parameters in calculations are cast not as known quantities, but as tendencies. The resulting stochastic program may then be solved in stages where a decision made in the initial stage under complete certainty is affected by some random occurrence after the fact. Since the decision-maker needs to take this interaction into account when making the initial decision, the objective function of such a problem typically includes an expectation over the probability density. Consequently, the output of such a decision-analysis tool is an optimal first-stage policy followed by recourse decisions in subsequent stages depending on the realized value of the uncertain parameters. For example, a manager operating a power plant with start-up costs would maximize expected discounted profits by setting the optimal generation level in the current period while anticipating future uncertain electricity and fuel prices. In other words, a prudent manager should avoid starting up a marginally profitable power plant today since there is the risk that it may become unprofitable in the next time period. Hence, because the realized states of nature are not known in advance, the solution to the manager's power plant operating problem is not an *optimal schedule by period* as in a deterministic environment, but an *optimal policy* that indicates electricity and fuel price thresholds at which to turn the generator on and off.

While stochastic programs are usually solved numerically, certain stylized cases may yield analytical or quasi-analytical solutions. For example, a canonical investment problem in the theory of real options assumes that the value of an investment opportunity follows a geometric Brownian motion (GBM) stochastic process, i.e., one in which successive percentage changes are independent of each other. Contrary to traditional investment analysis using deterministic discounted cash flows (DCF), the presence of uncertainty suggests a higher threshold return is necessary to initiate a project. By accounting for uncertainty, the real options approach recognizes that the investment opportunity itself has inherent value that increases over time as more information about the opportunity is revealed. As a result, it is worthwhile to delay the investment. On the other hand, the longer the delay in exercising an "in the money" project, the lower its net present value (NPV). By trading off these two opposing forces, the real options approach finds the optimal investment threshold price that maximizes the expected NPV of the investment project inclusive of the option value stemming from the managerial flexibility delay provides (see Dixit and Pindyck (1994)). While the assumption of GBM for a price process may not always be justified, the canonical real options problem is nuanced enough to provide insight into why real-life business managers often wait longer than the NPV suggests is prudent before proceeding with seemingly profitable projects. Similarly, they often do not shut down unprofitable projects because they realize that shutting down in the presence of uncertainty and re-start costs incurs an opportunity cost.

Since the real options approach is suited for investment and operational analysis, it has been applied extensively in energy markets. For example, Näsäkkälä and Fleten (2005) models the spark spread as a two-factor arithmetic Brownian motion stochastic process in order to determine investment and upgrade decisions in a gas-fired power plant. Similarly, Siddiqui and Marnay (2006a) considers the investment decision of a microgrid and illustrates how it may be altered under operational flexibility as well as multiple sources of uncertainty. Where closed-form solutions are not available, numerical methods, such as simulation or lattices, may be used to analyze high-granularity operating policies or compound options (see Siddiqui and Marnay (2006b) and Siddiqui, Marnay, and Wiser (2007), respectively). Indeed, the real options approach is flexible enough to incorporate various price process specifications and operating states. From a managerial perspective, real options are useful in providing not only investment values, but also threshold conditions at which to make optimal decisions under uncertainty.

In spite of its appeal in user-friendly applications such as SEDS, stochastic programming may not be amenable to large-scale models of energy markets, e.g., of the scope of NEMS. Indeed, an inherent trade-off exists between the potential detail of a deterministic model such as NEMS and the big-picture abstraction of a stochastic one. A useful compromise between the two addresses uncertainty by running various scenarios in a detailed deterministic model, the approach discussed in section 5.

4. Principles of Scenario Analysis

In order to estimate the performance of a particular policy under distinct future conditions, scenario analysis may be used as an alternative to sensitivity analysis or stochastic modelling. Similar to the former, scenario analysis assumes a known shift in parameters, which distinguishes it from the latter. But, unlike sensitivity analysis, scenario analysis permits a coordinated change in several underlying parameters that may reflect a plausible future in which the benefits of a particular policy may be evaluated. Two of the advantages of using scenario analysis over simple sensitivity analysis are that: 1) many of the underlying parameters may be inter-related; and 2) the states of the world of most interest (cause the most anxiety) often involve simultaneous shifts in conditions, e.g., carbon concerns reduce available coal resources while natural gas prices rise because of LNG development restrictions. Consequently, it may not be realistic to perturb only one of them. In contrast to stochastic programming, scenario analysis is less formal in the sense that it incorporates subjective impressions of alternative futures that may be beyond the scope of simulations. On the other hand, it should be noted that the formalism of stochastic models often conceals rather weak understanding of the true parameter distributions. In other words, the distributions assigned to parameters often do not have a solid empirical basis. Instead of specifying probability distributions for uncertain parameters, scenario analysis constructs alternative visions of future states of the world by relying upon expert judgment and implicitly attaching weights to important criteria. After ranking these criteria, scenarios are developed around them to provide insight to policymakers. Therefore, scenarios allow analysts to postulate various alternative futures of particular interest and then to gauge how they deviate from a BAU scenario, such as the NEMS Reference Case.

Formal scenario analysis was initiated in the 1970s at Royal Dutch/Shell in response to the environmental movement and the rise of the OPEC cartel. Both of these unforeseen events led to loss of profit for the multinational petroleum giant. In response to this adversity, Royal Dutch/Shell implemented large-scale scenario planning to address uncertainties in its operating conditions. The strategist leading this effort was Peter Schwartz, who went on to found the Global Business Network (GBN), which is based in Berkeley, CA, USA (see Global Business Network (2006)). While the degree to which scenario analysis was successful in practice at Royal Dutch/Shell is questionable, its advent, nevertheless, forced the company's management to be aware of uncertainties and to plan for them in a more systematic manner. Importantly, rather than relying on traditional forecasting tools, scenario analysis allows discontinuities. According to the GBN:

Scenarios are powerful planning tools precisely because the future is unpredictable. Unlike traditional forecasting or market research, scenarios present alternative images instead of extrapolating current trends from the present. Scenarios also embrace qualitative perspectives and the potential for sharp discontinuities that econometric models exclude. Consequently, creating scenarios requires decision-makers to question their broadest assumptions about the way the world works so they can foresee decisions that might be missed or denied.

According to Schwartz (1991), scenario planning involves developing alternative "stories" of illustrative ideas and options that may be evaluated rigorously through existing models. In order to develop scenarios, a six-step process is recommended:

- Identify an idea to explore that deviates from the BAU scenario (e.g., how will the CO_2 permit trading agreement between California and the UK affect the adoption of renewable energy technologies in California?)

- Enumerate the factors in the system under investigation in order to gain insight into how its modules are connected (e.g., current energy efficiency in California, market for CO_2 permits, expansion of mass transit, current market structures, R&D incentives for renewables, NIMBYism, etc.)
- Order the factors by both importance and uncertainty (e.g., current energy efficiency in California would rank high in terms of importance, but low on uncertainty, whereas the market for CO_2 permits, current market structures, and NIMBYism would rank high on both dimensions)
- Develop scenario plots based on the high-priority factors (e.g., capacity-focused markets/energy-focused markets/public ownership permuted with both low/high CO_2 permit prices and low/high NIMBYism)
- Assess the implications of different scenarios (e.g., re-run NEMS under each of the important scenarios to determine the diffusion of renewables)
- Identify and monitor the model to enable continuous assessment

While not every study with scenario analysis is as explicit to follow this six-step sequence, the prioritization inherent is applied in most cases. For example, the effect of higher fossil fuel prices and caps on carbon emissions are considered as separate scenarios in Gumerman and Marnay (2005). The broader objective of this work is to use these perturbations to the Reference Case scenario in NEMS to determine the effect on the deployment of EERE technologies. Here, the ideas to be explored are clear as are the findings of the exercise. However, the process via which the high-priority factors are identified is not described in the report.

Another macroeconomic study using scenario analysis is a report by the International Energy Agency (IEA) on the impact of high oil prices on the global economy (see International Energy Agency (2004)). Since the IEA is a research body of the Organisation for Economic Cooperation and Development (OECD), which comprises most of the prominent market democracies, it is able draw upon a wealth of data in formulating research topics. Furthermore, the IEA is able to use its proprietary World Energy Model in tandem with the OECD’s Interlink model and the International Monetary Fund’s Multimod model, which are used to generate the projections in the *OECD Economic Outlook* and the *World Economic Outlook*, respectively. While it is not completely clear how the scenario of a high oil price (of US$35/barrel, which is US$10/barrel higher than the average price in 2003) is developed, it does seem to be given high priority because of the high correlation between oil prices and inflation rates in OECD member countries. Since the oil price had increased by US$10/barrel in 2003 over three years before, it seems to be a plausible scenario both in its focus and magnitude. By including such a level shift in its model, the IEA quantifies its effect on the GDP (0.4% lower in each of the two subsequent years), inflation (0.5% higher over the same time period), and unemployment (up to 0.2% higher) for the OECD countries. The authors are careful enough to break down the analysis by oil importers and exporters. Not surprisingly, the IEA finds that there is a net welfare transfer from importers to exporters, which diminishes after three years as global trade in non-oil goods and services recovers. Nevertheless, there is a net welfare loss worldwide due to the higher prices in importing countries, which outweighs the higher revenues in exporting countries. The report concludes by indicating the adverse impact of higher oil prices on developing countries, which suffer greater welfare losses due to their greater oil intensity.

On a more ambitious scale, the Intergovernmental Panel on Climate Change (IPCC) incorporates scenario analysis in its forecasts of future carbon emissions and effects on human activity. Due to the complexity of its modelling efforts, the IPCC encounters many levels of uncertainty. For example, a typical sequence of analysis in predicting climate change is as follows: under a BAU scenario, increasing economic output causes carbon emissions to grow at a certain rate; carbon emissions trapped in the atmosphere prevent reflected heat from leaving the earth at a certain rate; the ensuing heat causes ambient earth temperature to increase; a higher global mean temperature causes polar icecaps to melt at a given rate; the release of fresh water into the earth's oceans alters their salinity; this change in salinity then causes the thermohaline current to slow down or even to switch off completely; finally, the reduction in thermohaline circulation prevents warm water from reaching northern Europe. Indeed, uncertainty in any of these factors could have dramatic consequences for predicting climate change. For this reason, a recent IPCC concept paper sketches out how uncertainty may be treated in the IPCC's Third Assessment Report (TAR) (see Manning and Petit (2003)). In line with the concept of scenario planning, the authors quickly realize that risk analysis with strict numeric probabilities may not be tenable because the phenomena at study in climate change are not stationary. Therefore, individual scenarios are assigned likelihoods that are determined qualitatively by pooling the opinions of experts. Beyond these weightings, Manning and Petit (2003) encourage authors to justify underlying assumptions, to identify data quality or scarcity, and to recognize the limitations of models.

5. Summary

In this document, techniques are introduced that help researchers address the robustness of models in the face of uncertainty in key parameters, since it diminishes the value of model results or policies based on them. Identifying methods that systematically address uncertainty is critical to effective planning or policymaking. At one end of the spectrum, sensitivity analysis which varies one parameter only, is a simple tool for identifying the significance of uncertainty in any one parameter. Furthermore, since for certain mathematical models, e.g., LPs, it does not necessitate re-solving the model, it can be an efficient approach. In contrast, stochastic programming addresses the uncertainty directly by assigning a probability distribution to uncertain parameters and then solving recourse models. The advantage of this approach is that an optimal policy may be developed to maximize the expected initial-stage objective function. The disadvantage of stochastic programming is that analytic solutions are usually possible only for highly stylised models that may not be realistic, while on the other hand, models with more detail solved numerically require significant computational effort. Finally, the formalism of these models tends to conceal what is often either a weak understanding of parameter uncertainty or one that is almost as limited by historic experience as deterministic models.

Between these alternatives, scenario analysis is frequently employed in business and policy analysis to assess the impact of some particular change of interest in the operating environment. Since they account for the fact that typically several parameters change in tandem, scenarios are more realistic than sensitivity analysis, without being as overwhelming as stochastic programming. Further, a scenario approach allows focus on states of the world of particular importance, typically those that cause particular anxiety. We discuss the origins of scenario analysis and outline the six-step scenario development process of Schwartz and the GBN. Finally, we survey the energy economics literature that applies scenario analysis.

6. References

Bolinger M, R Wiser, and W Golove (2004), *Accounting for Fuel Price Risk When Comparing Renewable to Gas-Fired Generation: The Role of Forward Gas Prices*, Ernest Orlando Lawrence Berkeley National Laboratory Report LBNL-54751, Berkeley, CA, USA

Dixit, AK and RS Pindyck (1994), *Investment Under Uncertainty*, Princeton University Press, Princeton, NJ, USA.

Ghanadan, R and JG Koomey (2005), "Using Energy Scenarios to Explore Alternative Energy Pathways in California," *Energy Policy* 33(9): 1117-1142.

Global Business Network (2006), *Scenario Thinking*, <http://www.gbn.com/AboutScenariosDisplayServlet.srv> (last accessed on 31 July 2006), Berkeley, CA, USA.

Gumerman, E and C Marnay (2005), "Scenarios for Benefits Analysis of Energy Research, Development, Demonstration and Deployment," Ernest Orlando Lawrence Berkeley National Laboratory Report LBNL-58009, Berkeley, CA, USA.

International Energy Agency (2004), "Analysis of the Impact of High Oil Prices on the Global Economy," IEA Technical Report, Paris, France.

Manning, M and M Petit (2003), "A Concept Paper for the AR4 Cross Cutting Theme: Uncertainties and Risk," Intergovernmental Panel on Climate Change Concept Paper, <http://www.ipcc.ch/activity/cct1.pdf> (last accessed on 31 July 2006), Geneva, Switzerland.

Näsäkkälä, E and S-E Fleten (2005), "Flexibility and Technology Choice in Gas-Fired Power Plant Investments," *Review of Financial Studies* 14(3-4): 371-393.

Nash, SG and A Sofer (1996). *Linear and Nonlinear Programming*, McGraw-Hill, New York, NY, USA.

Schwartz, P (1991), *The Art of the Long View*, Currency Doubleday, New York, NY, USA.

Siddiqui, AS and C Marnay (2006a), "Distributed Generation Investment by a Microgrid Under Uncertainty," in Proceedings of the 19th Mini-EURO Conference: Operational Research Models and Methods in the Energy Sector, Coimbra, Portugal (6 - 8 September 2006).

Siddiqui, AS and C Marnay (2006b), "Operation of Distributed Generation Under Stochastic Prices," in 29th International Conference Proceedings of the International Association for Energy Economics, Potsdam/Berlin, Germany (7-10 June 2006).

Siddiqui, AS, C Marnay, and RH Wiser (2007), "Real Options Valuation of US Federal Energy Efficiency and Renewable Energy Research, Development, Demonstration and Deployment," *Energy Policy* 35(1): 265-279.

Wiser, R, and M. Bolinger (2004), *An Overview of Alternative Fossil Price and Carbon Regulation Scenarios*, LBNL-56403. October.

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