LBNL-58000

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Real Options Valuation of US Federal Renewable Energy Research, Development, Demonstration, and Deployment

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March 2005

http://eetd.lbl.gov/ea/EMS/EMS_pubs.html

Published in the proceedings of the 10th Annual Power Research Conference on Electricity Industry Restructuring.

This work described in this paper was funded by the Office of the Assistant Secretary of Energy for Energy Efficiency and Renewable Energy, Office of Planning, Budget and Analysis of the US Department of Energy under Contract No. DE-AC03-76SF00098.

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Real Options Valuation of US Federal Renewable Energy Research, Development, Demonstration, and Deployment

Afzal S Siddiqui[*], *Chris Marnay*[+], *and Ryan H Wiser*[#]

Abstract

Benefits analysis of US Federal government funded research, development, demonstration, and deployment (RD^3) programmes for renewable energy (RE) technology improvement typically employs a deterministic forecast of the cost and performance of renewable and non-renewable fuels. The benefits estimate for a programme derives from the difference between two forecasts, with and without the RD^3 in place. The deficiencies of the current approach are threefold: (1) it does not consider uncertainty in the cost of non-renewable energy (NRE), and the option or insurance value of deploying RE if and when NRE costs rise; (2) it does not consider the ability of the RD^3 manager to adjust the RD^3 effort to suit the evolving state of the world, and the option value of this flexibility; and (3) it does not consider the underlying technical risk associated with RD^3, and the impact of that risk on the programme's optimal level of RD^3 effort. In this paper, a rudimentary approach to determining the option value of publicly funded RE RD^3 is developed. The approach seeks to tackle the first deficiency noted above by providing an estimate of the options benefit of an RE RD^3 programme in a future with uncertain NRE costs. While limited by severe assumptions, a computable lattice of options values reveals the economic intuition underlying the decision-making process. An illustrative example indicates how options expose both the insurance and timing values inherent in a simplified RE RD^3 programme that coarsely approximates the aggregation of current Federal RE RD^3. This paper also discusses the severe limitations of this initial approach, and identifies needed model improvements before the approach can adequately respond to the RE RD^3 analysis challenge.

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1. Introduction

Since at least the oil embargo of 1973, research, development, demonstration, and deployment (RD^3) efforts funded by the US Federal government have sought to improve the performance of and expand the use of renewable energy (RE) technologies. The US Department of Energy's (DOE) aggregate annual budget for RE technology improvement RD^3 is currently approximately US$250 million per year.[1] Because non-renewable energy (NRE) costs have exhibited volatile and unpredictable prices, these public investments could be thought of as insurance against future increases in NRE costs. However, the discovery of new oil fields outside member states of the Organization of Petroleum Exporting Countries (OPEC) together with improvements in extraction and delivery methods in the 1980s and 1990s led to lower than anticipated oil prices during this period. The cost of other conventional fuels, most notably natural gas, which emerged as the fossil power generation fuel of choice, also remained largely stable for roughly the last decade and a half of the twentieth century (note the 1986 through 1999 period in Figure 1). As a result, some began to question the value of Federal funding for RE RD^3. While Federal research likely reduced the costs of many RE technologies, the decline and stabilisation in conventional energy prices ensured that overall renewable energy supply remained modest (see McVeigh *et al.* (2000)), and seemed to reduce the need for sustained future Federal government RE RD^3 funding (see Cohen and Noll (1991), Taylor (1999), and Taylor and Van Doren (2002)).

[1] RE research here is taken to be the joint budgets of the technology programs in wind, solar, biomass, and geothermal within the US DOE.

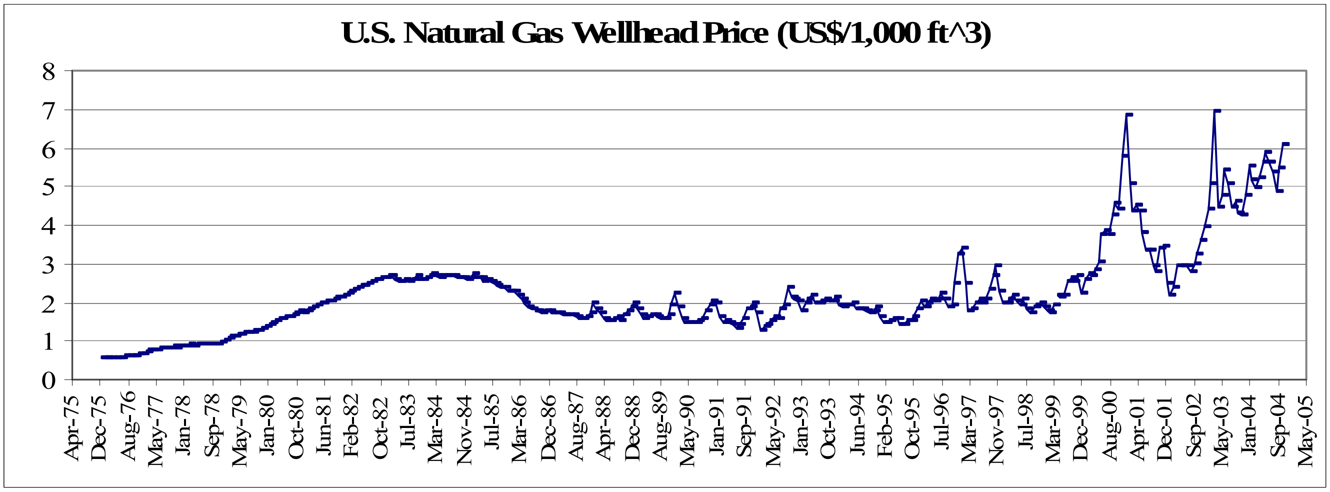

Figure 1. History of US Natural Gas Prices in Current Dollars (source: Energy Information Administration)[2]

Under the provisions of the Government Performance and Reporting Act (1993) (GPRA), the DOE, along with most Federal agencies, is required to annually report its goals and progress towards them, along with a showing of the societal value of its RD[3] efforts programme by programme.[3] In practice, the DOE estimates a limited number of performance metrics for each programme, such as avoided consumer expenditures for energy and carbon emission reductions, based on deterministic assumptions for NRE and RE technology performance and costs. The metrics are based on the upcoming budget cycle, that is, forecasts are based on programme funding levels expected in the Federal budget two years hence, e.g., in 2004 analysis is being conducted for the fiscal year 2006 budget and benefits forecasts typically extend 20-40 years beyond. In essence, these estimates are based on the difference between two sensitivities to the most recent version of Energy Information Administration's (EIA) Annual Energy Outlook (AEO), which is a semi-official forecast for the entire US energy sector for the coming two decades. Both the AEO itself and the metrics estimates rely heavily on the National Energy Modeling System (NEMS), and other forecasting tools. One sensitivity represents the US energy future if the

[2] 1000 standard ft^3 is equivalent to 1.08 GJ.
[3] See for example http://www.eere.energy.gov/office_eere/gpra_estimates_fy05.html.

current RE RD^3 programme continues and successfully meets it goals, while the other estimates the state of the coming world absent the effort. The benefits of the programme are represented as the differences between estimates of the metrics derived from the two sensitivities.

A National Research Council (NRC) study (quite sensibly) recommended the introduction of some uncertainty into the forecasting of the benefits improved RE technology will deliver (see NRC (2001)). The NRC suggested three classes of benefits of RE RD^3 that might be separately and explicitly estimated: *realized benefits*, which is the return on public investment that results if deployment becomes economic and attractive and is what the current GPRA process attempts to estimate; *options benefits*, which is the insurance benefit of being able to capture future benefits in unexpected states of the world; and *knowledge benefits*, which are all of the academic and spin-off returns that might result from research. Because uncertainty is central to the estimation of the options and knowledge benefits of RD^3, the current deterministic approach to complying with GPRA necessarily limits benefit identification and estimation to only ones in the NRC's realized category. The work reported in this paper, together with other research under way at DOE, represent first baby steps towards bringing the NRC's second benefits class, options benefits, into the overall estimation framework.

As noted in the NRC's recommendations, the current deterministic approach to RE RD^3 evaluation fails to capture the important options or insurance value of these public efforts. More specifically, the deficiencies of the current deterministic approach to RE RD^3 benefits estimation are threefold:

(1) it does not consider uncertainty in the cost of NRE, e.g., due to an increase in the underlying cost of oil, natural gas, or coal, or due to enhanced environmental regulations that effectively raise NRE costs, and the option or insurance value of deploying RE if and when economic;

(2) it does not consider the ability of the RD^3 manager to adjust the research effort, i.e., ceasing, decreasing, or increasing research funding, to suit the evolving state of the world, and the associated option value of this timing flexibility; and

(3) it does not fully consider the underlying technical risk associated with RD^3, i.e., it assumes that the goals of the research will be precisely met, and the impact of that risk on the optimal RD^3 effort.

One purely economic analysis, which serves as a guidepost to this work, applies a discounted cash flow (DCF) approach using stylised assumptions to estimate that the net present value (NPV) of Federal RE RD^3 funding is actually less than zero (–US$35.3 billion) (see Davis and Owens (2003)). In other words, using conventional RE and NRE cost forecasts, the NPV is negative and the Federal RE RD^3 programme should be abandoned.[4] However, as the authors go on to demonstrate, the DCF approach is not an appropriate economic analysis under uncertainty. Davis and Owens (2003) seeks to overcome the deficiencies listed above by developing a real options model of RE RD^3 that considers uncertainty and volatility in the cost of NRE (*market risk)*, uncertainty about the future technical performance of RE technologies (*technical risk)*, and flexibility in the timing and amount of RD^3 expenditure. As reported in more detail later, these authors find that accounting for these factors considerably increases the expected benefit of the DOE's RE RD^3.

This paper begins to explore the middle ground between the current deterministic approach employed by DOE to estimate the benefits of its RE RD^3 and the rigorous real options model developed in Davis and Owens (2003). The DOE and the Office of Management and Budget (OMB), which reviews DOE's

[4] Note that the Davis and Owens (2003) estimate is purely economic in the sense that it only considers the monetary benefits, and that it uses discounting, neither of which is true of the current GPRA submissions process. Under the DOE's implementation of GPRA, considerable benefits from RE RD^3 are found, in part due to the different assumptions employed

GPRA submission, are unlikely to move quickly from current practice towards an opaque and complex real options model, which suggests a need to develop a more transparent and intuitive method that might be more readily embraced. Specifically, the framework developed here begins to account for the first two deficiencies described above, using an intuitive binomial lattice structure, but unlike the Davis and Owens (2003) approach, this model does not address technical risk. The goal is to understand whether the current approach used by DOE to estimate benefits might be extended to reasonably account for at least some portion of the insurance value of RD^3, while at the same time not moving to an estimation method too complex to resonate in policy circles. Since this quest is ongoing, the model developed herein does not yet adequately respond to the RE RD^3 analysis challenge, and therefore, some necessary model improvements are identified for future work. Nonetheless, the approach described has been implemented in Matrix Laboratory (MATLAB®), and a simplistic example analysis together with some sensitivities has been run.

The structure of the paper is as follows:

- Section 2 introduces the theory of real options and discusses solution techniques.
- Section 3 constructs the recursive stochastic dynamic programme (SDP) used to evaluate the real option and illustrates its economic intuition.
- Section 4 provides a stylised numerical example and summarises preliminary results from this example and some sensitivities to it.
- Section 5 concludes and discusses next steps for research in this area.

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by the DOE, and in part because non-monetised metrics are given consideration, e.g., overall reduced primary energy consumption.

2. Real Options Analysis

2.1 Relating Public RD^3 to Private Investment and Real to Financial Options

The first step towards deriving an approach to estimating the options value of public RE RD^3 requires establishing the link between the problem at hand and the considerable existing literature on valuing financial options. First, consider the similarity between public RE RD^3 and private investments to which options value accrue. When undertaking an investment, managers are keenly aware of the value that derives from having the option to abandon, delay, or otherwise modify it as new information becomes available. Flexibility allows some of the uncertainty to be resolved before irreversible expenditures are made, enabling managers to make decisions that bring their operations closer to maximising profits. Second, consider a discrete project that need not be deployed until the business climate becomes favourable. Observe that the project has insurance value that derives from its potential profitability, making it similar to a financial instrument that entitles the owner to exercise a future option and potentially benefit. Instruments that capture such derived value are generally called derivatives.

The relevant prospective investment here is similar to a derivative called a financial call (or put) option, which entitles the holder to purchase (or sell) a security at a given strike price. If at the expiration date, the market price of the security is greater (lower) than the strike price, then the holder will choose optimally to exercise the call (put) option; otherwise, the option is simply allowed to expire. At any time prior to its expiration, the option still has a positive value because there is always a possibility, however small, that the stochastic market price of the asset will rise above (drop below) the strike price before the expiration date. Asymmetrically, there is a lower bound on the derivative's price, i.e., zero, just as a project can usually be abandoned. Hence, the value of managerial flexibility can be quantified by thinking of the underlying investment as a real option and then evaluating it using tools developed for valuing financial options. In other words, valuing real investments in RD^3 has characteristics similar to evaluation of a derivative financial instrument. In fact, the real options value in this case is akin to that of a compound American call option, in which enhancements can be undertaken during each period to lower the effective strike price. In general, an American option can be exercised at any time during its life, while in contrast, a European option can only be exercised at a specific time, usually at the end of its life. For example, an American option on a stock would entitle the holder to buy the stock at the stated strike price at any time before its expiration.

2.2 Solution Methods for Real Options

2.2.1 The Black-Scholes Model

Although there is a rich history of financial options dating back at least to ancient Greece, the first formal pricing of an option was made in Black and Scholes (1973). In this formulation, the price of the underlying stock evolved according to a geometric Brownian motion (GBM) process, i.e., the ratio of the price in the future to the present price is independent of the past history of the prices and has a lognormal distribution (see Ross (1999)). Under the assumption of GBM, the famous Black-Scholes analytic formula for the price of a European call option is derived by solving the appropriate partial differential equations (PDEs) with the necessary boundary conditions. The Black-Scholes formula enables determination of the price of a European call option, and together with the put-call parity formula, can relate the prices of European put and call options with the same strike price and maturity date (see Merton (1973)). Furthermore, it can be shown that it would never be optimal to exercise early a simple American call option on a stock that does not pay dividends. In this case therefore, the price of an American call option is equal to that of a European one.

2.2.2 Difficulties of Valuing American–Style Options

Since an RE technology under development could be deployed at any time, a benefit estimate must be found that is akin to valuing a compound American call option, which may be exercised early. However, an analytic formula to price such an option cannot be readily derived because exercising these instruments early is sometimes optimal, making direct solution of the PDE impossible. In effect, cash flows are dependent not only on the past, but also on expectations of future prices. The complex uncertainty specification particular to American put and compound American call options also applies to real options, in which the manager has the flexibility to abandon, deploy, or expand the underlying project. Indeed, a real options problem is not directly analogous to valuing a simple financial American call option because the strike price is not fixed, and indeed it can be effectively lowered by undertaking further investment. In this case, a backward induction procedure is necessary because the very nature of the option changes.

One such solution approach uses a discrete-time analogue of the PDE in which all derivatives are replaced by finite differences. Under this approach, American put options and real options can be priced by starting off with terminal-time boundary conditions and then solving the resulting grid of algebraic equations and inequalities that approximate the PDE (see Brennan and Schwartz (1977)). This method has the advantage that it can handle conditions such as early exercise or flexibility in projects, and it is employed in Davis and Owens (2003). However, since the finite-difference approach still endeavours to solve the PDEs numerically at each point in time without indicating how the option value relates to the underlying value of the investment, albeit via a discrete-time approximation, it does not reveal the economic structure of the problem. Also, while the problem at hand involves uncertainties at every turn, it should be noted that the finite-difference approach is subject to approximation error.[5]

2.2.3 Discrete Binomial Lattice Approach

Unlike the approach of Davis and Owens (2003), this work employs the relatively intuitive binomial lattice approach. The binomial lattice solution procedure explicitly models the option-pricing problem in discrete time using a backward induction solution technique, in contrast to the finite-difference approximation to continuous time.[6] The lattice approach assumes that the uncertainty in the price of the underlying security may be represented by two possible outcomes at each time step, i.e., the price can either increase or decrease. The outcomes are defined such that their implied probabilities of occurring closely match the probability distribution of the underlying continuous GBM process. Backward induction can then be used to solve the resulting SDP, relying upon the boundary conditions at termination and the recursive relationship between the value functions in each period (see Sharpe (1978) for the original idea, and Cox *et al.* (1979) along with Rendleman and Bartter (1979) for its development). The binomial lattice approach reveals the underlying economic intuition inherent in option pricing since it relates the option value to current and future expected price paths of the underlying investment, and is also free from the numerical instabilities of the finite-differences method. As a result, it can yield an accurate approximation of the option value and optimal deployment date, even with necessarily crude time intervals. The "curse of dimensionality" requires time steps to be limited because computational complexity increases exponentially with them.

[5] While decreasing the size of the discrete time-steps can mitigate this shortcoming, the finite-difference approach has instabilities and inconsistencies, which cannot be easily resolved unless the underlying problem is formulated discretely from the beginning rather than in continuous time.
[6] An example lattice is shown below as Figure 2.

2.2.4 Using Simulation when Binomial Lattices Become Infeasible

Since it employs a backwards solution procedure, the binomial lattice approach cannot be applied to pricing exotic options whose payoffs are path dependent, i.e., that are based not only on the terminal price of the underlying asset, but also on how the price was reached. Although the binomial lattice approach can be modified to accommodate this path dependency, it is often more computationally efficient to use simulation techniques to price exotic options. This entails dividing the option's valid time horizon into several small periods and then generating normally distributed random numbers to simulate the trajectory of the underlying security's price. The terminal value of the exotic option is calculated, and upon completion of a large number of replications, the discounted average of these values is calculated. Due to the law of large numbers, this point estimate is an efficient estimator of the option's price (see Boyle (1977)).

Although almost any exotic option can be priced using simulation, a large number of replications is necessary to ensure sufficient accuracy. For example, precision to two decimal places requires tens of thousands of replications. Estimation efficiency may additionally be increased via variance reduction measures, such as control variates and antithetic variables (see Luenberger (1998) and Ross (1999) for examples of pricing exotic options and further discussion of variance reduction). Finally, since simulation is a forward-induction procedure, it is not always applicable to American options, for which optimal exercise policies are needed in advance. In order to resolve this final dilemma, a new procedure prices American options by first generating a large number of trajectories for the underlying security's price and then estimating a conditional expectation payoff function via least-squares cross-sectional regressions. Then for each simulated price trajectory, a comparison is made at each time period between the value of exercising the option immediately and the estimated value from its exercise in the next period. From this backward-induction step, the optimal exercise policy and the value of the discounted cash flows are determined for each simulated price trajectory. The estimated option price is then simply the average of the discounted cash flows from optimal exercise of the option across all of the simulated price trajectories (see Longstaff and Schwartz (2001)). All of the solution methods summarised here are discussed in full and illustrated via numerical examples in Cortazar (2001).

2.2.5 Copper Mine Investment Problem

The sequential nature of most real investment decisions, including the RE RD^3 problem at hand, may be modelled as a compound American option. A classic paper examines a situation in which a copper mine's operations may be activated, suspended, or abandoned in order to maximise the discounted residual cash flows from owning a lease on the property (see Brennan and Schwartz (1985)). The cash flows in each period depend on the copper price, which is stochastic, and the costs of extraction and maintenance, which are deterministic. The manager's decision each period is either to extract copper at the maximum possible rate, to close the mine until the next period, or to abandon it forever. Given the boundary condition that the mine is worthless at the end of the lease's duration, the mine model is solved via backward induction using the finite-difference approximation to the underlying PDEs. The value of the mine's lease then encapsulates the option value of flexibility in operating the asset subject to market risk. This mine problem resembles the RE RD^3 problem because in the current DOE RD^3 benefits analysis, the success of research is typically assumed, i.e., there is no technical risk. Adapting the mine problem to estimating the ultimate benefits of the RD^3 extends the DOE's current approach to RD^3 benefits estimation because of inclusion of unpredictable market conditions, i.e., market risk. For this reason, Brennan and Schwartz (1985) was chosen as the starting point for the model developed in this paper.

2.3 Application of Real Options Methods to RD^3 Generally and RE RD^3 Specifically

Since real options value flexibility in a sequential decision-making process, they conveniently lend themselves to analysis of RD^3 projects, which pass decision points at various development stages before a technology is commercialised. At any stage, the manager may decide to abandon development, continue RD^3 as planned, or invest in corrective action by allocating more resources to improve performance (see Huchzermeier and Loch (2001)). Assuming an expected market payoff from deployment along with a probability transition matrix of performance improvement from RD^3, the problem may be formulated in discrete time as a SDP and solved along a binomial lattice.

The value of RD^3 flexibility in the face of both market and technical risk could be determined as the difference between two estimates of the benefit: 1. the solution to the SDP, and 2. the traditional NPV, in which all decisions are set to *continue RD^3 as planned* and the project is accepted only if the NPV is positive. Under the real options framework, it is typically found that increased *market risk* increases options value. In other words, a higher variance in the value of the technology under development relative to the conventional/alternative technology will increase its option value as a potentially lucrative upside is paired with a bounded downside. In particular, the value cannot drop below zero, and the manager can abandon the project to stem losses. On the other hand, increased *technical risk*, i.e., greater variance in ultimate technology performance of the technology, could result in lower profits for any given market condition; consequently, technical risk reduces the option value since it diminishes the downside protection available. Hence, under given market conditions, an RD^3 project with high technical risk would require greater flexibility to achieve the same options value.

The application of real options techniques to RD^3 evaluation is not novel, and nor is the discussion of applying these techniques to valuing energy RD^3 entirely new. In Smit and Trigeorgis (2001), the opportunity to invest in RD^3 is examined via real options where two competing firms decide whether a strategic capital investment should be undertaken if its future benefits are uncertain. In contrast to the standard NPV approach, real options considers how a rival firm's response to one's own investment decision would impact upon the RD^3 value. The option-pricing methodology as applied to RD^3 is extended in Grenadier and Weiss (2001) to include compound options, i.e., options on options. In this model, a firm can decide either to adopt a new technology immediately or wait for the next generation's technological innovation to arrive on the market, where RD^3 leading to such breakthroughs follows a stochastic process. If the firm chooses the former path, then it can upgrade to the next-generation technology when available for an additional expense. In effect, when the firm adopts the new technology immediately, it also receives an option to upgrade. By addressing the firm's problem via real options, not only is the compound option evaluated, but also the firm's optimal technology migration policy revealed.

In the energy arena, Awerbuch and Berger (2003) uses the capital asset pricing model (CAPM) to indicate the diversification benefit of RE technologies. Analogous to the role of risk-free assets in financial markets, it is argued that RE technologies, even if they have higher levelised costs, are necessary to an economy that wishes to reduce its overall energy supply risk. Indeed, RE technologies permit the diversification of a portfolio of energy technologies by offsetting the risk inherent in NRE technologies. Consequently, RE technologies, which are deemed too expensive on their own, become desirable when considered from the perspective of risk reduction. Similarly, in Tseng and Barz (2002) and Deng and Oren (2003), the traditional DCF approach to evaluating generation assets is regarded as being obsolete in an era in which firms face volatile spot prices rather than regulated rates designed to facilitate cost recovery. Both efforts then use real options as appropriate market-based instruments to value power plants within the deregulated environment. By incorporating the operational characteristics of the plants, such as ramping constraints and minimum up- and down-time criteria, into their SDP formulations, they indicate that these limits may significantly reduce power plant values.

Before NRC's 2001 assessment, major national studies had described the value of RE RD^3 as one of creating options in the case of energy supply and price risks, as well as environmental risks (see NRC (2000), Frey *et al.* (1995), and PCAST (1997)). Hostick *et al.* (2004) does not go as far as using real options, but instead accounts for uncertain future states of the world by conducting sensitivity analysis. This effort is conducted in the context of the DOE's interest in introducing uncertainty in its RD^3 estimation, and in other efforts, the DOE is exploring the use of alternative fossil price and carbon regulation scenarios. Schock *et al.* (1999) determines the value of the DOE's energy efficiency and renewable energy RD^3 budget as insurance against the cost of climate stabilisation, oil price shocks, urban air pollution, and other energy disruptions, using scenario analysis. Baker *et al.* (2004) meanwhile, discusses the value of RD^3 in the face of climate uncertainty. Finally, following up on the NRC's findings, Lee *et al.* (2003) describes the results of a conference that discussed, in part, how to calculate the options value of RE RD^3 and the challenges for such an evaluation.

2.3.1 Davis and Owens (2003)

The specific application of the real options framework to evaluating RE RD^3, however, is relatively new. Davis and Owens (2003) provides the most recent detailed example. An option value of US Federal government funding of RE RD^3 is calculated using a stylised numerical example. The approach assumes that the NRE cost evolves according to a GBM, while RE cost reductions due to RD^3 are also stochastic, i.e., the model has both market and technical risk. The representative RE technology used by Davis and Owens (2003) is wind power, the cost of which decreases with more RD^3 funding. Increased RD^3 funding also reduces the volatility of RE costs as the RD^3 effort helps resolve technical performance risk. Upon solving the PDEs using the finite-differences approach, it finds that, under the example calculation, the value of Federal government RE RD^3 is US$30.6 billion (in year 2000 dollars), a US$66 billion increase from the value implied by the DCF approach. Of this difference, 40% is due to optimal deployment of the RE technologies, while the remaining 60% is purely an insurance value in case of NRE cost increases. The former component refers to the fact that the RE technologies need not be deployed immediately. Indeed, it is possible to calculate the NPV of RE benefits under a number of future deployment scenarios. By selecting the deployment period that maximises the NPV, the RD^3 manager recognises that RE technologies are worth more than their simple "now or never" DCF NPV. While this modification introduces managerial discretion to the DCF model alone, it, nevertheless, ignores market and technical uncertainty. The real options approach accounts for this, along with managerial flexibility, and reveals the value of RE technologies as an insurance policy against NRE cost increases.

The Davis and Owens (2003) results confirm that a deterministic DCF approach to RD^3 evaluation would significantly underestimate the value of RE RD^3 investments. Unfortunately, it seems unlikely that the DOE would be willing to immediately adopt an analytic approach incorporating a comprehensive real options framework. This work attempts to explore the wide gap between current practice and the Davis and Owens (2003) approach to seek an intermediate solution that might capture some of the options value of RE RD^3, without adopting a "black box" analytic approach that is unlikely to be applied by DOE programme managers.

3. Model Formulation

3.1 Representation of NRE Cost Movements (Market Risk) as GBM

To simplify the initial analysis, unlike Davis and Owens (2003), no technical risk is incorporated into the model developed here. Instead, the options value of RE RD^3 is determined assuming research project success but given market risk, i.e., allowing for stochastic NRE costs. RD^3 timing flexibility is partially addressed in that the RD^3 manager has the ability to cease RD^3 as conditions warrant.

NRE costs follow a GBM, which can be adequately approximated via a multi-period binomial process in which the NRE cost in the next period either increases or decreases from its current level, over a total of n periods. If $S(k,i)$ represents the NRE cost with k periods elapsed in the RD^3 project's lifetime and i upward cost movements to date, then for an initial NRE cost of $S(0,0)$:

$$S(k+1,i+1) = u \cdot S(k,i) \text{ with implied probability } p,\ 0 \le k \le n \text{ and } 0 \le i \le k$$

and

$$S(k+1,i) = d \cdot S(k,i) \text{ with implied probability } 1-p,\ 0 \le k \le n \text{ and } 0 \le i \le k$$

$$\Rightarrow S(k,i) = S(0,0) \cdot u^i \cdot d^{(k-i)}$$

where

$$u = e^{\sigma},\ d = \frac{1}{u} = e^{-\sigma}, \text{ and } p = \frac{e^{\alpha} - d}{(u-d)}$$

Here, α is the risk-free interest rate, and σ is the volatility parameter, the standard deviation of percentage changes in historical NRE costs. The discretisation of the GBM along a binomial lattice implies that over any given year, the NRE costs will either increase by a factor of u with implied, i.e., risk-neutral, probability p or decrease by a factor of d otherwise.

3.1.1 Binomial Lattice Method and Example

Besides being a convenient solution method for this canonical options pricing problem, the binomial lattice approach is also instructive for decision-makers because it conveys the economic intuition of the decision problem. Consider a simple two-period example in which the value of an option to buy a stock two time periods hence is valued, and the price of the underlying stock evolves according to GBM. Discretising the price process, Figure 2 shows a binomial lattice that illustrates how the value of the options depends on the state of the world. $S(k,i)$ represents the evolving stock price, either increasing with probability, p, or falling with probability (1-p) at each node. The amount of price increase and decrease are determined by the volatility parameter according to the relationships shown above for u, d, and p. At the terminal period, an American call option written on the stock with strike price E will have a value of $V(2,i) = \max(S(2,i) - E, 0)$, i.e., it will be worth exercising only if the security's price is greater than the strike price. Using the implied probabilities and these terminal values, the value of the option at each of the prior time steps can be determined by using the following recursion, which states that it is the maximum of discounted expected profits from either immediate or next-period exercise, assuming a risk-free interest rate of α:

$$V(k,i) = \max\left(S(k,i) - E, e^{-\alpha}\{pV(k+1,i+1) + (1-p)V(k+1,i)\}\right) \tag{1}$$

In effect, at each point in the lattice, one must decide whether it is better to deploy the option immediately or to wait for more favourable market conditions, given the value of $S(k,i)$ at each node. By starting with the terminal condition and working backwards through the lattice, it is then possible to price the option at the initial node, i.e., find $V(0,0)$.

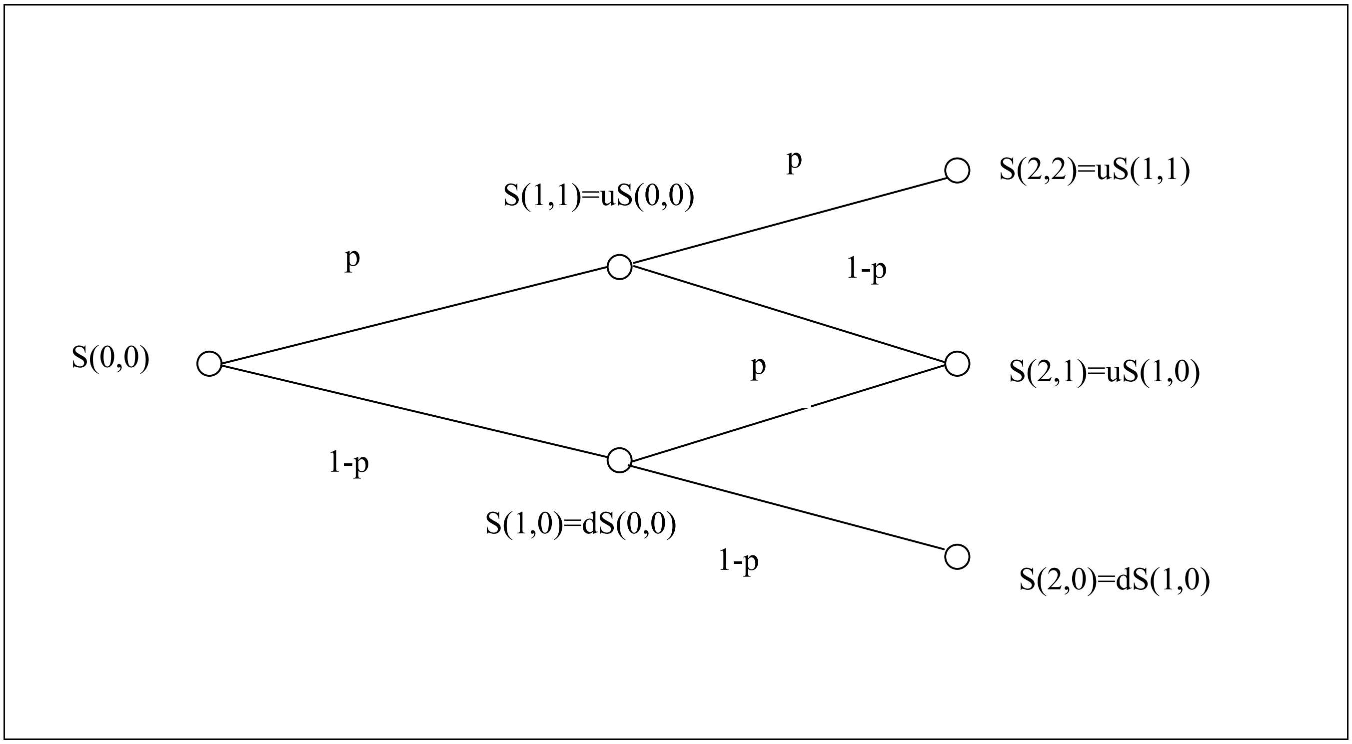

Figure 2. Binomial Lattice for a Random Price Process

3.1.2 Adapting the Brennan and Schwartz (1985) Copper Mine Problem

By extending the set of decisions at each period to include the possibility of abandonment, Brennan and Schwartz (1985) applies the options pricing method to their copper mine problem. This application is somewhat analogous to a simplified RE RD^3 funding problem because at each time step the project can be abandoned, expanded, or fully deployed. Once deployed, the investment's cash flows equal the discounted, uncertain profits accrued over its residual lifetime. For the RE RD^3 problem, this corresponds to the expected cost savings of RE relative to the expected cost of NRE. Note that in this model formulation, deployment is a one-time irreversible decision. If not deployed, RD^3 on the technology can continue and guarantees enhanced future performance, translating into lower RE costs and an increased probability of future deployment. The similarity between the research and mine problems suggests extending the Brennan and Schwartz (1985) approach to an analysis of RE RD^3.

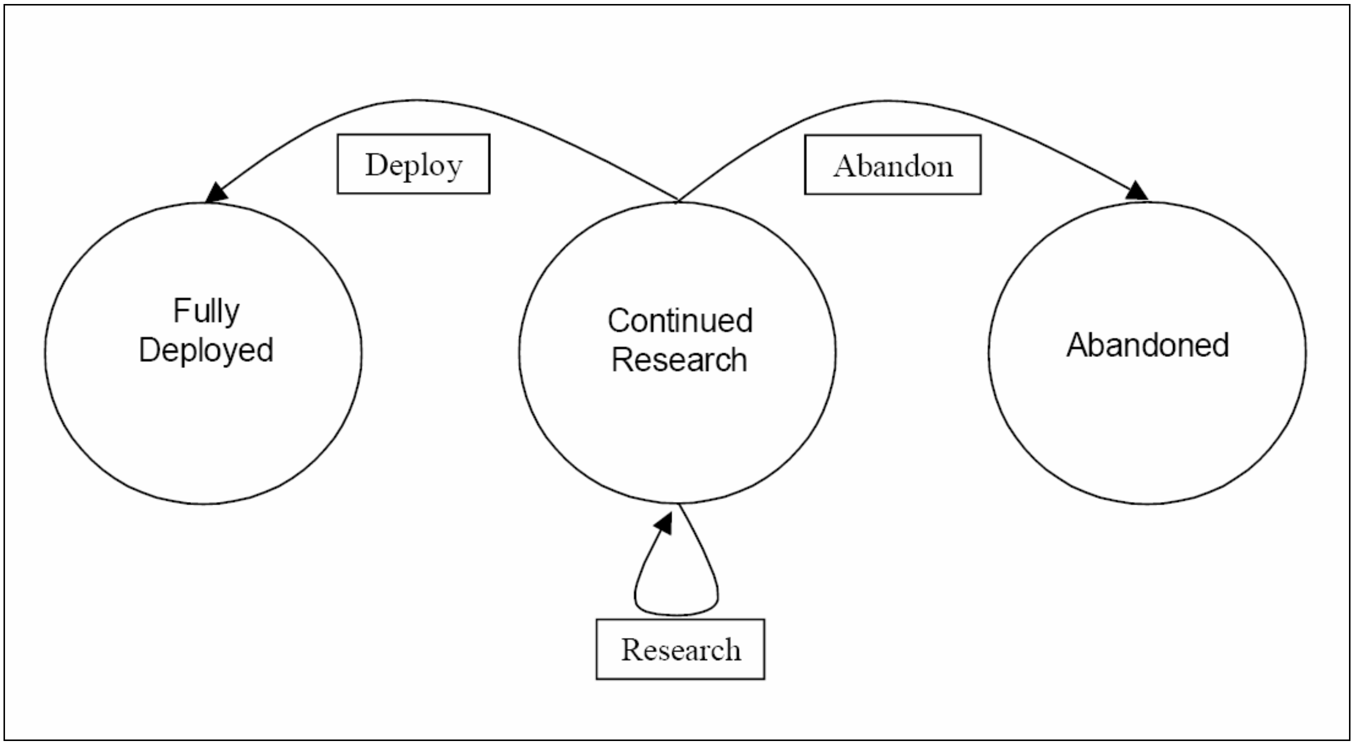

Figure 3. RD^3 Transition Diagram

The transitions among the three states of the RE RD^3 problem are shown schematically by Figure 3. At each time step, a choice has to be made between continuing research for another period, fully deploying the project, or abandoning it. Note that all choices are irreversible.

3.2 Finding the Optimal RE RD^3 Solution

3.2.1 Valuing RE RD^3 at Each Time Step

Extending the example shown in Figure 3, a full binomial lattice can be formed covering all time steps, and the optimal value of a RE RD^3 project can be computed as follows. First, for time period k, number of upward NRE cost movements i, and number of research increments r, the value of the RE RD^3 without deployment is $V(k,i,r)$, which can be estimated. For example, $V(1,1,0)$ represents the optimal value of the RE RD^3 project after one period has elapsed, there has been one upward movement in the NRE cost, no research increments have been made, and the RE technologies have been deployed.

Similarly, $W(k,i,r,j)$ is the value of the RE RD^3 with deployment given that the time period is k, the number of upward NRE cost movements i, the number of research increments r, and RE technologies were deployed in period $j \le k$.

The value of the RE RD^3 over the entire lattice is calculated recursively from the final time step backwards. Here, the terminal values are set to zero, $V(n,i,r) = 0 \ \forall\ i,r$ and $W(n,i,r,j) = 0 \ \forall\ i,r,j$, i.e., it is assumed to have no value once its time horizon elapses, although other terminal conditions would be possible.[7] The value at each previous node is determined via the following backward recursions:

with deployment

$$W(k,i,r,j) = (S(k,i) - C(k,r)) \cdot X(j,k) - M + \beta \cdot \{p \cdot W(k+1,i+1,r,j) + (1-p) \cdot W(k+1,i,r,j)\} \tag{2}$$

without deployment

$$V(k,i,r) = \max \begin{Bmatrix} -A; \\ W(k,i,r,k) - D; \\ -R - M + \beta \cdot \{p \cdot V(k+1,i+1,r+1) + (1-p) \cdot V(k+1,i,r+1)\}; \end{Bmatrix} \tag{3}$$

Note that equations (2) and (3) calculate the optimal values differently depending on whether the RE technologies have been deployed or not, respectively.

3.2.1.1 With RE Deployment

Deployment of the RE technologies invokes equation (2) as the recursion, and the value of the RD^3 project is now simply the present value of expected current and future cost savings. More precisely, the deployment of the RE technologies will result in immediate cost savings of $(S(k,i) - C(k,r)) \cdot X(j,k)$ minus any maintenance cost, M. Here $X(j,k)$ is the assumed maximum RE penetration into the national fuel mix in period k given RE deployment occurred in period j. Note that the market

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[7] This is a point where knowledge benefits could potentially enter the formulation.

penetration ceiling is an assumption in this formulation, without which RE would take over the energy supply if prices fell below NRE. Here, $C(k,r)$ is the RE cost, which has decreased from the starting value, $C(0,0)$, with the number of research increments granted to its RD^3 project. For the purposes of the example analysis, shown below, values of $C(k,r)$ were estimated, as is typical of DOE target setting; however, any functional form may be used that has the properties $\frac{\partial C}{\partial k} > 0$ and $\frac{\partial C}{\partial r} < 0$, e.g., $C(k,r) = C(0,0) \cdot e^{k-r}$. Furthermore, cost savings in future periods will also accrue, e.g., $W(k+1, i+1, r, j)$ in the next period if there is an increase in the cost of the NRE and $W(k+1, i, r, j)$ otherwise.

3.2.1.2 Without Prior RE Deployment

Absent prior RE deployment, three options are available in equation (3):

- *abandon* the RD^3 project completely at a cost of A
- *deploy* the RE technology at a cost of D and expected societal energy cost savings of $W(k,i,r,k)$[8]
- *continue the research* at a direct cost of R and a maintenance cost of M but with future expected energy cost savings of $V(k+1, i+1, r+1)$ if the NRE cost increases the next period or $V(k+1, i, r+1)$ if otherwise

Note that continuing the RE RD^3 has no immediate benefits, and incurs the additional costs of R and M but the value function's research index increases to $r+1$, lowering future RE costs and increasing prospects for subsequent economic deployment. The optimal value for $V(k,i,r)$ is simply the maximum of the three available choices multiplied by the discount factor β, which is just the present value of a continuous cash flow received one period in the future, $e^{-\alpha}$. Since the value of RE technologies

[8] While included here for generality, in the numerical examples below, both D and M are set to zero.

increases with NRE costs, both $V(k,i,r)$ and $W(k,i,r,j)$ are monotonically non-decreasing in i, the number of upward movements in the NRE cost (see the Appendix for a formal proof).

3.2.2 Computing Overall Value

After computing all of the $V(k,i,r)$ and $W(k,i,r,j)$, the overall value of the RE RD^3 project, $V(0,0,0)$, is:

$$V(0,0,0)=\max\left\{\begin{array}{c} -A; \\ (S(0,0)-C(0,0))\cdot X(0,0)-M-D+\beta\cdot\{p\cdot W(1,1,0,0)+(1-p)\cdot W(1,0,0,0)\}; \\ -R-M+\beta\cdot\{p\cdot V(1,1,1)+(1-p)\cdot V(1,0,1)\}; \end{array}\right\} \tag{4}$$

The $V(0,0,0)$ is, equivalently, the value of the RE technologies RD^3 under the real options framework.

3.3 Limitations of the Approach

There are, however, some significant limitations to this approach that will need to be explored in future work:

(1) As noted earlier, our extension of the Brennan and Schwartz (1985) approach using a binomial lattice method as developed here does not consider technical performance uncertainty associated with RD^3 investments. The current analysis approach used by the DOE ignores the real options implications of both market and technical risk. Here technical risk is overlooked to keep the real options solution method as transparent as possible. The focus is on market risk. Nonetheless, the technical risk involved in RD^3 is a crucial element that affects both the realized and options benefits and its presence cannot be overlooked in future work.

(2) Although the model developed here allows for the cessation of RD^3 spending, thereby exploring the timing options value of RD^3, it does not permit re-initiation of RD^3 at a later point, or funding level

adjustments. This simplification ensures maximum consistency with the current approach to RE RD^3 analysis, which compares a constant RD^3 funding stream to a world in which no equivalent RD^3 occurs.

(3) The Brennan and Schwartz (1985) mine problem is not analogous to the RE RD^3 problem in that once an RE technology is deployed, or RD^3 abandoned, no further decisions can be made. As a result: (a) after deployment, opportunities to reduce RE costs further through continued RD^3 cease, (b) once deployed, RE continues to be deployed in all future time periods even if RE no longer appears economic, and (c) a decision to abandon RD^3 forecloses any future option to reinstate the RD^3 programme or to deploy RD^3 technologies in the future. These restrictive assumptions are clearly not consistent with the RE RD^3 problem, but are employed here as a first step that will, over time, be enhanced stepwise towards a more realistic and comprehensive approach.

(4) The current approach does not consider perhaps the most interesting element of uncertainty in NRE costs, true regime switching, i.e., a change in the parameters that govern the underlying stochastic process. Intuitively, the idea that RE technologies should be developed because of the options value of their currently unexpected deployment is driven more by fears of a sudden regime change than by the orderly drift in prices implicit in the GBM formulation, especially since RE RD^3 might be justified as an investment over a distant time horizon. Consider again the history shown in Figure 1, which is repeated in Figure 4 with two key enhancements. First natural gas prices have been converted to real 2002 dollars, and second, a fuel price for power generation using this fuel has been estimated using historic data on the best available generating technology. Therefore, the series in Figure 4 now suggests the marginal cost of the best technology available for gas-fired generation. This thirty-year history exhibits two distinct regime changes: 1. the mid 1980s cost drop, which came about both because of the end of price regulation and the increased availability of combined cycle technology; and 2. the extreme price spike of 2000-2001, which may have ushered in a new era of high, rising, and volatile prices.

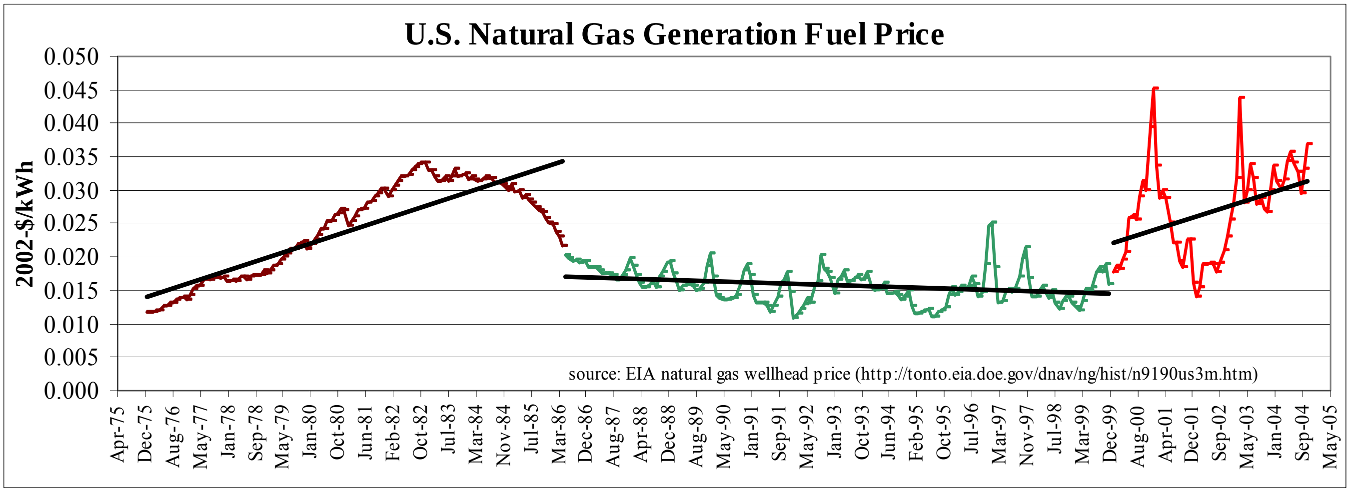

Figure 4. Real US Natural Gas Fuel Generation Fuel Prices (source: Energy Information Administration and Unger and Herzog (1998) for heat rates)

In addition to considering the movement of prices, an options model needs to also consider the possibility of such regime changes, or to put the issue a different way, the time period chosen on which to base the uncertainty of future prices can be critical. Quite obviously, a future regime change of particular importance would be the adoption of carbon emission limits, which currently only the US and Australia among the Kyoto Protocol Annexe 1 countries do not have.

(5) Note the importance in the problem formulation of the share of the overall energy supply available for RE to capture, $X(j,k)$. Necessarily, forecasting this parameter is crude and is not in keeping with good economics, which would naturally favour a formulation in which RE and a variety of different NRE technologies are competing for market share over time. Figure 5 shows the historic full levelised cost of historic coal generation, i.e., the equivalent to Figure 4 for coal, but with fixed cost recovery added in. One aspect of the difficulty of choosing the RE market share can immediately be seen here because, in contrast to natural gas generation, the cost of coal generation has been both stable and shows only one minor candidate regime switch.

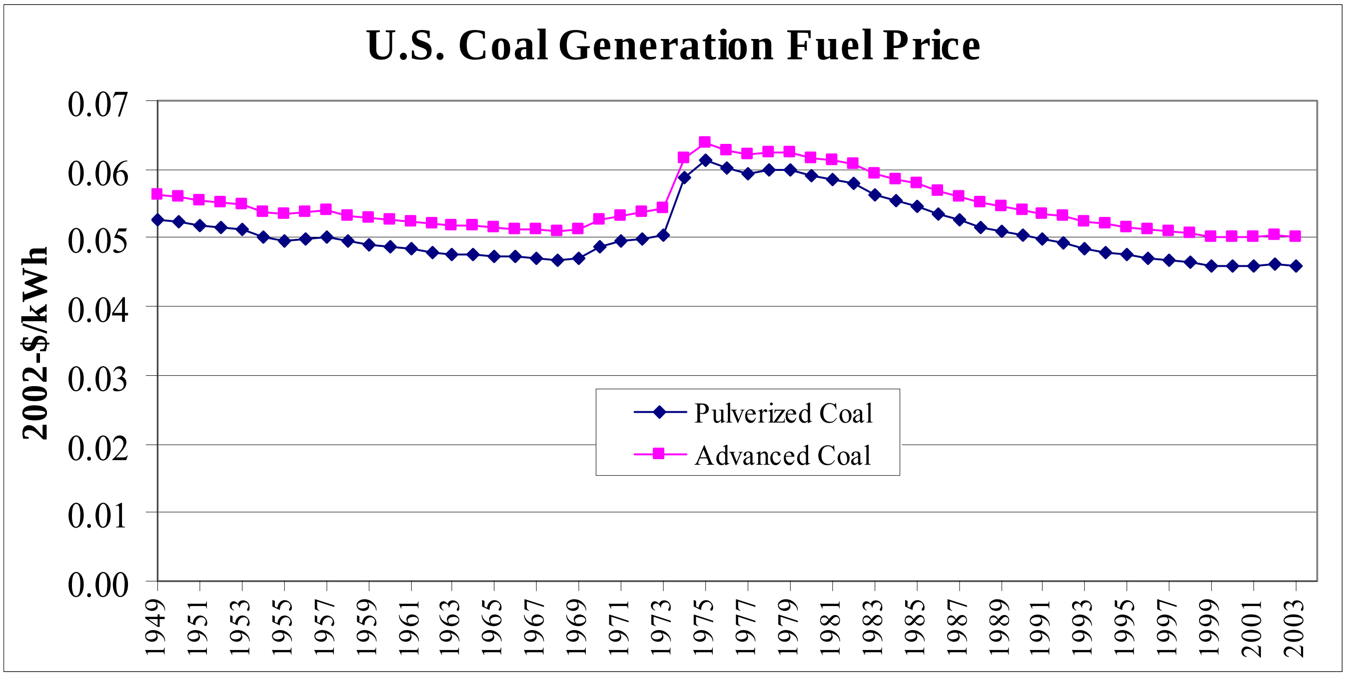

Figure 5. Real US Coal Fuel Generation Fuel Prices

If coal were considered the alternative to RE, then a quite different result would follow from the options value calculation, and given that lower market risk lowers options value, it must be lower, although of course the result also depends on the absolute trajectory of prices as well as its volatility. In other words, a true evaluation of the options value of RE should depend not just on a simple alternative technology, but on a complex competition between multiple alternatives, some currently available and potentially some that are not yet developed, but are the targets of competing RD^3 efforts.

Finally, to return to regime switching for a moment, it should be noted that if the United States decides to take aggressive action to reduce carbon emissions, the orderly future for coal generation that is indicated by its history in Figure 5 could be quite inaccurate.

4. Numerical Examples, Sensitivity Analysis, and Results

While the SDP developed here can be solved algebraically, the discrete time period lattice lends itself conveniently to both spreadsheet and traditional programming implementations. A simple numerical example has been coded and solved in both MATLAB® and Microsoft Excel. The MATLAB version of the model was used to execute a numerical example intended to give the reader an idea of how the options value framework might be applied and hopefully ultimately to derive some meaningful results.

4.1 Three-Case Simple Numerical Example

A stylised numerical example can provide insight into the importance of considering options value in RE RD^3 evaluation, and the sensitivity of that value to key assumptions is also illustrative of the policymaking and management decision making that might be supported by a real options model.

Table 1. Input Parameters for All Three Example Cases

Variable	Description	Unit	Case 1	Case 2	Case 3A	Case 3B
C(0,0)	initial cost of renewably generated electricity (RE)	¢/kWh	6	same as 1	same as 1	same as 1
C(n,0)	terminal cost of renewably generated electricity WITHOUT RD^3	¢/kWh	6	same as 1	same as 1	same as 1
C(n,n)	terminal cost of renewably generation electricity WITH RD^3	¢/kWh	5	same as 1	same as 1	same as 1
S(0,0)	initial cost of non-renewably generated electricity (NRE)	¢/kWh	4.5	same as 1	same as 1	same as 1
n	number of time periods	years	20	same as 1	same as 1	same as 1
α	risk free interest rate, average 3-month T-bill, 1984-2003	%	2.4	same as 1	same as 1	same as 1
β	discount factor		0.976	same as 1	same as 1	same as 1
σ	volatility parameter – standard deviation of historic percentage price movements	%	12	20	3	6
p	probability of a price increase in each period		0.571	same as 1	same as 1	same as 1
R	annual RD^3 expenditure	M$	250	same as 1	same as 1	same as 1
A	one-time abandonment cost	M$	250	same as 1	same as 1	same as 1
M	maintenance cost after deployment	M$	0	same as 1	same as 1	same as 1
X(j,k)	excess demand	TWh/a	see Figure 6	same as 1	same as 1	same as 1

This example is very loosely based on the Federal renewable energy RD^3 programme over approximately the next two decades. The key input variables appear in Table 1. The annual research budget is 250 M$, which is very approximately the current Federal RD^3 budget for technology development in wind, solar, biomass, and geothermal power generation, and it is further assumed that this effort lowers the real cost of RE from 6 ¢/kWh to 5 ¢/kWh with a simple linear decline over the twenty-year period beginning 2006. NRE costs 4.5 ¢/kWh at the outset, and its expected value rises in keeping with the model specification at the risk-free interest rate. Therefore, under expected conditions, RE becomes competitive with NRE and is deployed when the expected NRE cost exceeds the RE cost, which happens to occur in 2018 if no RE RD^3 is undertaken. Under the stochastic conditions, the value of RE will arise when the GBM of NRE costs rise to levels that greatly exceed the cost of RE. The background risk free interest rate is taken to be 2.4% per annum, which is based on a long history of three-month T-bill rates.

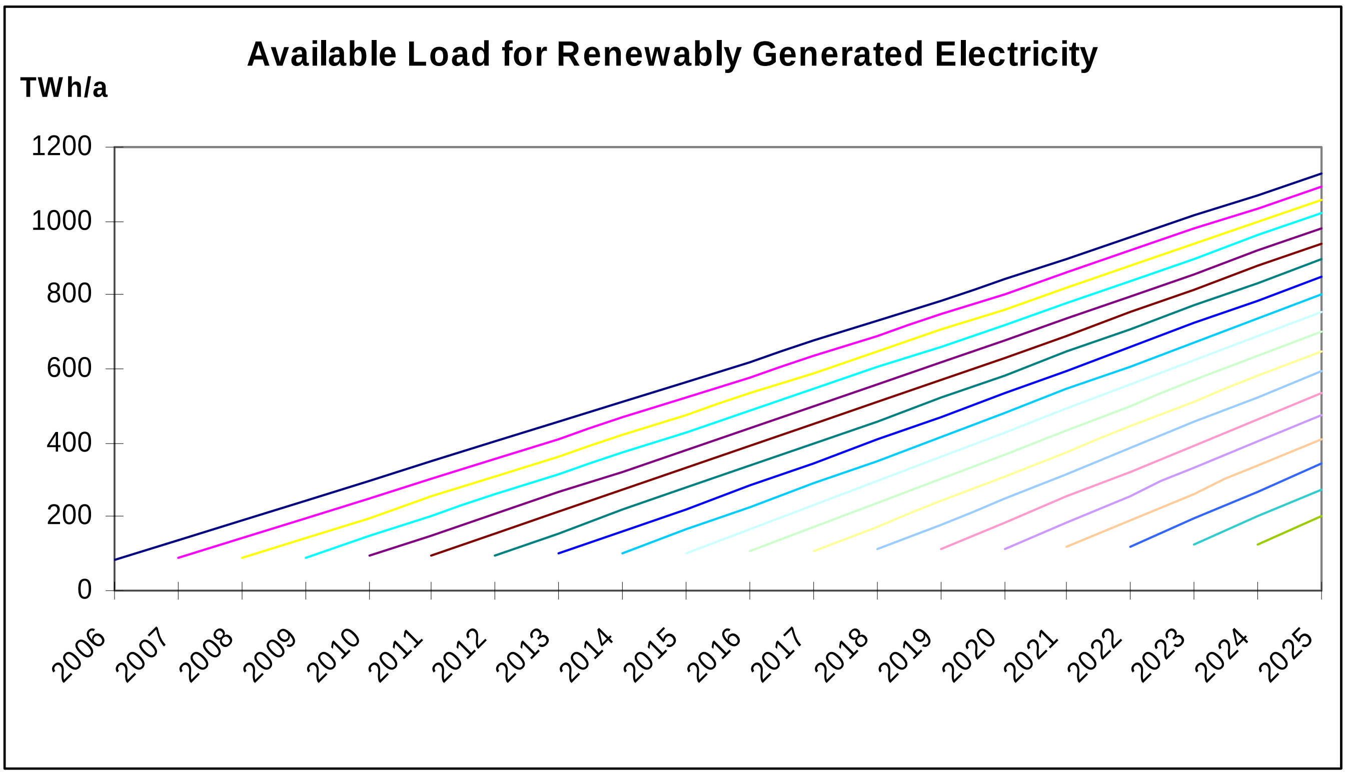

Figure 6. Available Load for Renewably Generated Electricity [$X(j,k)$]

The available load for RE to serve, i.e., $X(j,k)$ or the market penetration of RE, is shown as a family of curves in Figure 6. There is a separate curve for each year in which deployment might occur, i.e., the uppermost curve shows the available load if RE were deployed in the first possible year, 2006, reaching 1131 TWh in 2025. If deployment occurs in 2007, the penetration in 2025 is 1095 TWh, etc. These values are based on AEO 2004 forecasts and the following assumptions: 1. the initial share of RE in year 0, 2005, is 1.25% of US electricity generation, and absent RE RD[3] this fraction holds steady, and 2. once deployed, RE can only increase its penetration by a maximum of 2% of the total NRE share annually, which is taken to be total forecast coal, oil, and natural gas generation. Under these assumptions, if deployment takes place in 2006, it rises to serve about 19.5% of US generation in 2026, whereas if it is never deployed, it continues to serve just the initial 1.25%.

The key parameter is NRE price volatility, i.e., the standard deviation of annual price movements in NRE costs. This is the only variable that differs across the three cases, as follows:

Case 1: The volatility parameter is set to 12%, which is an estimate of natural gas generation cost variation over the two decades after the price fall of 1985. In this case, therefore, RE competes head-to-head with natural gas whose price has the same volatility as in this historical period.

Case 2: This is a high natural gas price volatility case, with the parameter set to 20%, which has roughly been our experience over the five years to 2004, i.e., following the possible regime switch.

*Case 3A:*This case brings in the possibility that the competing fuel to RE may not be natural gas alone. The NRE alternative here is a blend consisting of 75% coal and 25% natural gas. Because of the very low historic volatility of coal prices, this blend has a volatility parameter of only 3% based on the same historical period as Case 1.[9]

Case 3B: This case only differs from Case 3A in that the NRE blend consists of 50% coal and 50% natural gas, which results in a volatility parameter of 6%.

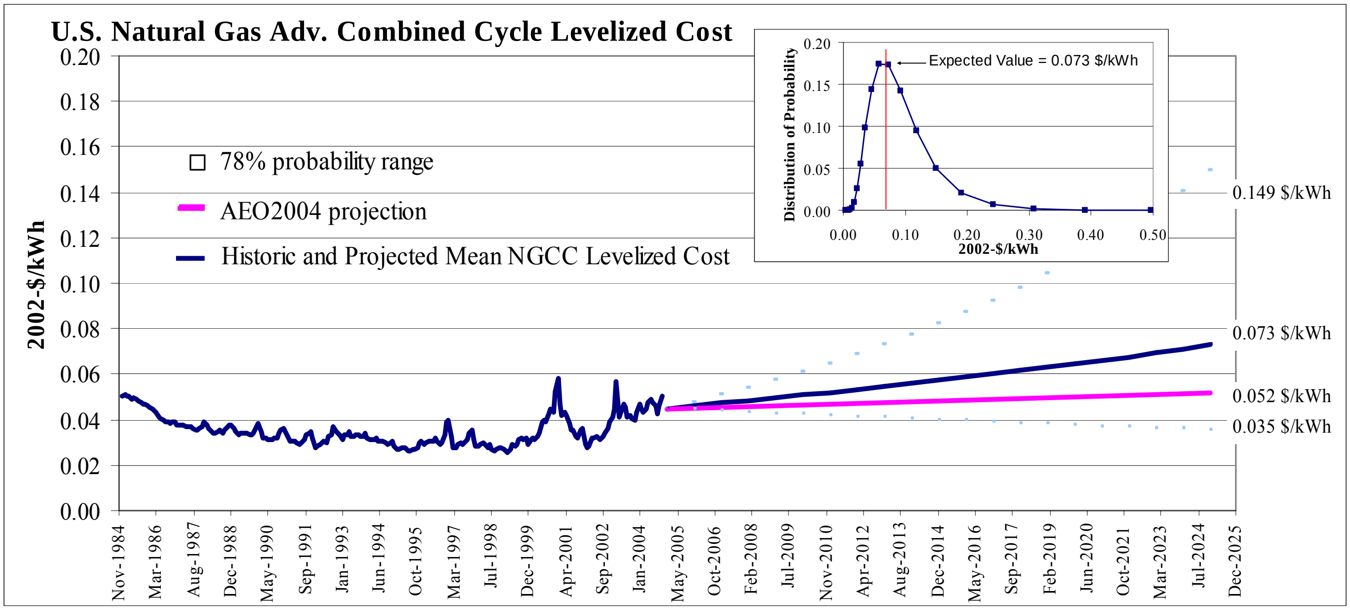

Figure 7. The Implied Forecast of NRE Costs and Historic Data

Figure 7 shows the implications of the Case 1 assumptions. The left half of the graphic shows a series that takes the now familiar post-1984 data from Figure 4 and further enhances it by adding an estimated fixed cost to the historic fuel cost to yield an estimate of the historic levelised cost of the best available natural gas fired technology. In Case 1, this is the technology that is assumed to be in direct competition with RE. The right-hand side of the graphic shows the path of the mean levelised cost. It rises from its starting point of 4.5 ¢/kWh in 2005 to 7.3 ¢/kWh in 2025. The insert shows the log-normal probability distribution of prices in 2025. On the main graphic, the shaded area encompasses about 78% of the

[9] Since the correlation in the prices of these two fuels is close to zero, it is assumed zero in calculating the blend volatility parameter. However, the latter is not sensitive to changes in the correlation because the volatility of coal prices is very low at 0.6% over the twenty years to 2002.

probability in this distribution. For comparison, the much lower equivalent implied natural gas generation cost from the AEO 2004 is also shown.

4.2 Example Results

4.2.1 Basic Results

The results obtained for the four cases appear in Table 2. The estimated current options value ranges over the four cases from 36 to 104 billion 2002 US$. Remembering that the total RD^3 expenditures are only 250 M$/a over twenty years, and at first blush, these results seem suspiciously high. The reason for this is in large measure because the options value captured by these results represents the *full options value* of RE technology available for deployment throughout the forecast period. This implies that they encompass the options value of existing RE technology as well as that resulting from the RD^3 whose benefits are sought. In the remainder of this section, an analysis is presented that attempts to disaggregate these gross results in a way that will enable the derivation of a truer estimate of the options value added by the RD^3 rather than that of the entire technology.

Table 2. Real Options Results (billions of 2002 US$)

Cases	Total Real Options Value
Case 1: low gas volatility	70
Case 2: high gas volatility	104
Case 3A: 75% coal-25% gas	36
Case 3B: 50% coal-50% gas	46

4.2.2 Non-Stochastic Basis for Comparison

In order to facilitate a better understanding of the real options model and its valuation of RE RD^3, results can be usefully compared to a deterministic DCF benefit estimate. In this formulation, NRE costs are not stochastic, but are nonetheless forecasted to increase at the continuously compounded risk-free interest rate. An approximation is then derived of how RE technologies and subsequent RD^3 efforts would be valued under the following three alternative conditions:

(1) RD^3 is never permitted. In this instance, the *value of existing RE technologies*, which are available to meet available load at a cost of 6 ¢/kWh, is the NPV of meeting the residual load exclusively with NRE technologies minus the NPV with the option to deploy existing RE technologies at any point when the cost of RE is lower than the expected cost of NRE.

(2) RD^3 is mandatory until RE technology deployment, if any. That is, the *value of existing RE technologies along with future RE RD^3 enhancements* is the difference in the NPV of meeting the residual load exclusively with NRE technologies minus the NPV of meeting the same load with the option to deploy RD^3-improved future RE technologies any point. Therefore, the *value of future RE RD^3* is determined by subtracting the *value of existing RE technologies* from *value of existing RE technologies along with future RE RD^3 enhancements*.

(3) RD^3 is mandatory as before, but now the abandonment option[10] is also available. Thus, the *value of existing RE technologies along with future RE RD^3 enhancements and RE RD^3 abandonment flexibility* is the difference in the NPV of meeting the residual load exclusively with NRE technologies minus the NPV of meeting the same load with the option to *abandon* or deploy RD^3-improved RE technologies at any point. As before, the *value of RE RD^3 abandonment flexibility* is determined by subtracting the *value of existing RE technologies along with future RE RD^3 enhancements* from *value of existing RE technologies along with future RE RD^3 enhancements and RE RD^3 abandonment flexibility*.

Table 3. DCF Approximation Results (2002 billion US$)

Value of Existing RE Technologies	Value of Future RE RD^3 Enhancements	Value of RD^3 Abandonment Flexibility

[10] This allows the RD^3 programme to be abandoned at any point with the remaining available load to be met by NRE.

1.4	-2.5	0.85

The results in Table 3 indicate while the existing RE technologies are modestly valuable, as shown in the left-hand column, continued enhancements to them via RD^3 should not be undertaken, as shown by the centre column, and having the option to abandon is an improvement, but not enormously so. Consider the left-hand column first. In this purely deterministic framework, the forecasted NRE cost increases above 6 ¢/kWh in 2018. At that time, it becomes optimal to deploy RE technologies to meet available demand. Consequently, the value of the existing RE technologies reflects the difference in the future forecasted NRE costs and the initial RE cost of 6 ¢/kWh, a cost which goes unchanged in this no RD^3 allowed future. Because there is no RD^3 expenditure and NRE costs eventually exceed the unchanging RE cost, a positive benefit accrues. In the centre column by contrast, any RE RD^3 has a negative value because it lowers RE cost by at most 1 ¢/kWh over twenty years while a total PV of approximately US$4 billion is spent on RD^3. Indeed, the RD^3 expenditure outweighs not only the value of reducing RE costs from 6 ¢/kWh to 5 ¢/kWh, but also the savings over the NRE costs, resulting in a negative result. Finally, the right-hand column reveals that the flexibility to abandon the RD^3 is only slightly valuable. Indeed, instead of conducting mandatory RE RD^3, which does not provide any benefit, the abandonment option limits one's losses to an unavoidable first year RD^3 investment of US$0.25 billion. As a result, it adds US$0.85 billion relative to the value of existing RE technologies and mandatory RE RD^3.

4.2.3 Disaggregated Results

As indicated in Table 2, the combined Case 1 total real options value of the existing RE technologies and the flexibility to conduct or abandon RD^3 is US$70 billion, with the other cases showing aggregate benefits of US$36 billion to US$104 billion.

Table 4. Disaggregated Options Value Results (2002 billion US$)

Cases	Total Real Options Value	Value of Existing RE Technologies	Value of Future RE RD^3 Enhancements	Value of RD^3 Abandonment Flexibility
Case 1: low gas volatility	70	63	7.4	0.22
Case 2: high gas volatility	104	97	6.2	0.34
Case 3A: 75% coal-25% gas	36	21	15	0.00
Case 3B: 50% coal-50% gas	46	35	11	0.06

Most of this benefit reflects the benefit from existing RE technologies, which can be deployed to meet residual demand at a cost of 6 ¢/kWh along all price paths that lead to prices higher than this baseline, which includes the mean trajectory. Table 4 disaggregates the results for all cases presented earlier in Table 2, estimated in the same manner as their deterministic equivalents in Table 3. The total options values are dominated by the value of the existing RE technology, while the value of enhancements to RE technologies from future RD^3 is a modest 10% of the total, and the value of the abandonment option is insignificant. These results help bring the overall picture into much clearer focus. The value of future RD^3 enhancements column provides the result of primary interest. At US$6 billion to US$15 billion, inclusive of the US$4 billion RD^3 investment, the incremental value of the RD^3 programme is not insignificant. As importantly, whereas the deterministic analysis shows a negative value to RE RD^3, use of real options demonstrates that such investment may provide significant value.

4.3 Deterministic and Real Options Results Compared

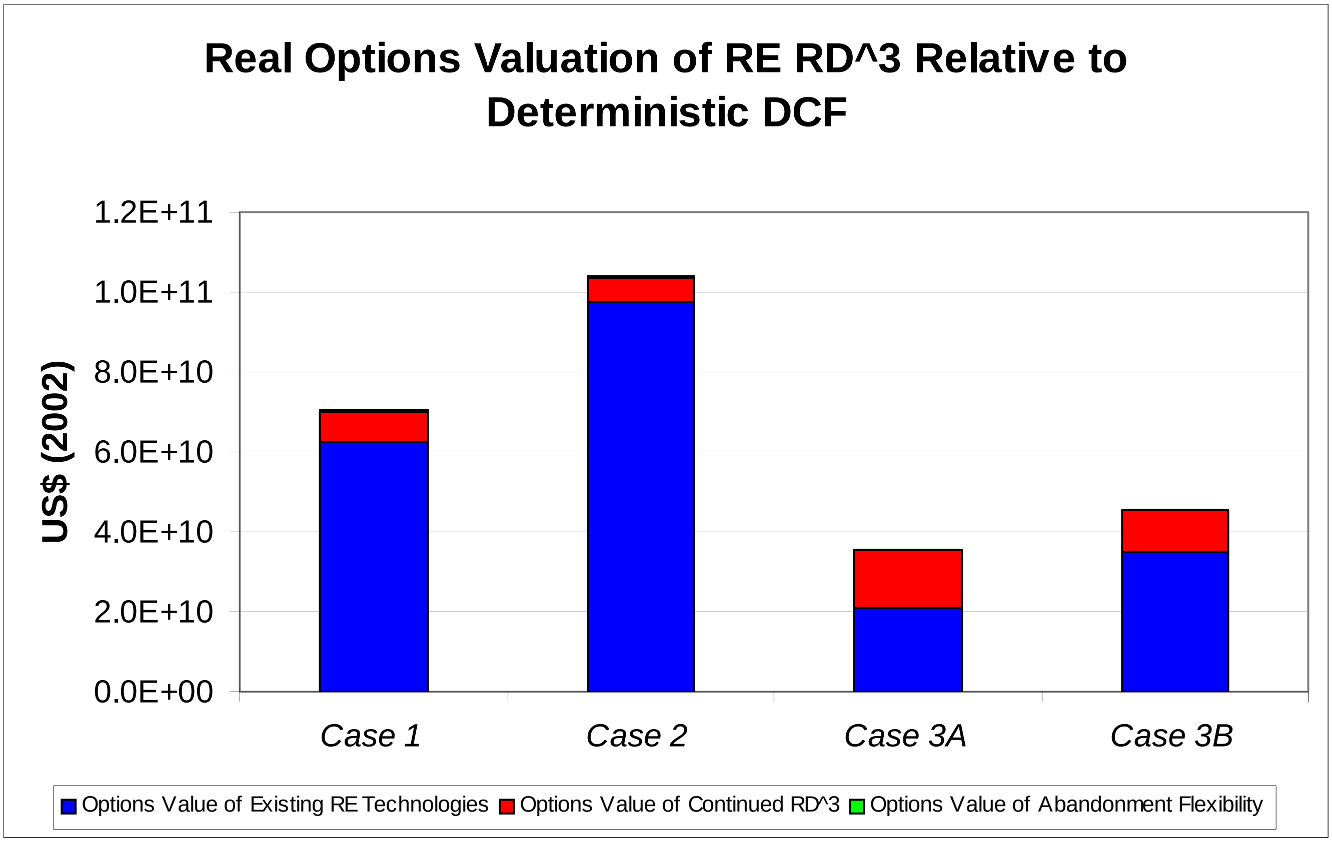

Figure 8. A Comparison of Real Options and Deterministic Results

Compared across the cases, some clear patterns emerge. Figure 8 shows the results for each of the four cases, with the options value disaggregated as in Table 4.

(1) The total options value, the heights of the bars in Figure 8, agree with standard financial options theory and are completely intuitive, i.e., greater volatility in NRE costs increases the options value of RE technologies.

(2) As volatility increases, the contribution of existing RE technologies to the total real options value also increases. This is because this component measures the difference between the NRE cost and the initial RE cost 6 ¢/kWh. As fossil fuels get more volatile, this difference increases, thereby raising the value of the existing RE technologies.

(3) The twenty-year RD^3 programme adds modestly to the total as expected. However, counterintuitively, this value actually decreases with NRE cost volatility. The explanation is that the RD^3 expenses do bring down the RE costs, but this continued effort can lower the RE cost by at most 1 ¢/kWh over twenty years, which is swamped by the huge savings *vis à vis* the NRE cost increases. In other words, RD^3 has little opportunity to generate benefits because RE is quickly attractive and quickly deployed, thereby choking off any opportunities for RD^3 benefits to accrue because the model assumes that once deployed, RD^3 efforts cannot continue (in other words, when volatility is high, RE is deployed early, before the benefits of RD^3 in reducing RE costs are shown). By contrast, when NRE cost volatility is low, continued RD^3 can provide more substantial potential benefits because there is little chance for RE technologies to be adopted when they cost 6 ¢/kWh. This outcome is entirely due to the model simplification that prevents RD^3 after RE deployment, and this is an area of needed model improvement.

(4) Finally, the incremental options value of the abandonment option is insignificant as predicted. Interestingly, it too covaries positively with the NRE cost volatility. The value of this option is derived from protecting against downside risk, i.e., if NRE cost becomes extremely low and the potential for RE tech deployment is almost foreclosed, then it is cheaper to abandon the RD^3 programme completely. However, in a world with low NRE cost volatility, there is not much chance of a downside (or upside), so the abandonment option will never be exercised.

The value of ongoing RD^3 in Davis and Owens (2003) amount to US$4.3 billion, or approximately 14% of the total real options value of RE technologies, a figure that is again similar to the 10.5% share from our Case 1 results in spite of the fact that we do not consider technical risk. Using our model, we explain this partition in terms of the difference between NRE costs and the initial RE cost as well as the difference between the initial RE cost and RD^3-enhanced RE cost. Indeed, while the model is limited in not permitting RD^3 after RE deployment, its transparency, nevertheless, allows the RD^3 programme manager to disentangle the components of overall RE technology value. Furthermore, the sensitivity analysis with the NRE cost volatility enables a pattern to emerge in the values of these components.

5. Conclusions and Next Steps

Securing future energy supply at minimum cost is a vital national concern and public expenditures to this end are clearly justified. Technologies to harness indigenous renewable energy sources efficiently have a major advantage over technologies powered by conventional fuels because they are less vulnerable to the negative consequences of volatile fuel prices (or future environmental regulations). In the routine Federal government research funding process, methods for evaluating the potential benefits of RD^3 programs are essential public policy tools. Unfortunately, current methods used in evaluating RE RD^3 do not capture the important insurance value of these efforts. In the field of energy research, additional analytic methods are needed that can capture the benefits of RE technologies in avoiding reliance on energy sources with uncertain future prices.

Prior approaches to this problem have been developed in the literature based on standard options value methods, and a new one has been explained here. This approach, using a binomial lattice structure for the underlying NRE cost, allows estimation of the options value of RE technologies that potentially accrues by avoiding dependence on technologies fired by fuels with volatile prices. The approach also allows determination of the potential options value of RE RD^3 abandonment. Ultimately, it will be important that these estimates be derived using standard forecasts consistent with those used in other aspects of the public research funding budget process. Developing methods to incorporate options value routinely into the Federal budget development and review process is a worthy area for further research. In a worked example loosely based on Federal renewable energy research, the options value is estimated to be significantly greater than when using a DCF approach with deterministic input assumptions. This worked example also suggests that the option value of existing RE technology is sizable, with the incremental option value of a twenty-year RD^3 effort adding to that already-significant value. The option value of RD^3 abandonment, however, is relatively modest, suggesting that future efforts should be focused on refining the estimation of RE RD^3 option value in the face of market risk.

The options model and worked example provided here are first, crude steps in developing an approach that serves the needs of the RE RD^3 community. Future work will expand the approach to accommodate more forecast details and to analyse the RE RD^3 problem better. The key limitations with the extension of the Brennan and Schwartz (1985) mine problem to the RE RD^3 case will be addressed. Specifically, using the Brennan and Schwartz (1985) framework, once RE technologies are deployed or RE RD^3 is abandoned, then no further decisions can be made in subsequent time periods. This is a fundamental problem in the way the current model is structures, and model improvements will eliminate these restrictive assumptions. Furthermore, future work will consider the possibility of step changes in the underlying cost of NRE that might, for example, be caused by stringent carbon regulations. Finally, the model may be extended to better account for RD^3 timing flexibility and technology performance risk. The creation of a comprehensive real options model is not, however, the goal of this work. Therefore, in modifying and improving the model, care must be taken to create a model that could realistically be used by the DOE in its future efforts to evaluate RE RD^3.

6. Acknowledgements

This work described in this paper was funded by the Office of the Assistant Secretary of Energy for Energy Efficiency and Renewable Energy, Office of Planning, Budget and Analysis of the US Department of Energy under Contract No. DE-AC03-76SF00098. The lead author is also grateful to the generous support of the Business Research Programme of the Michael Smurfit Graduate School of Business at University College Dublin. The authors wish to thank Mark Bolinger, Etan Gumerman, and

Kristina Hamachi LaCommare of Berkeley Lab for their valuable research assistance. Also beneficial were discussions with Conall O'Sullivan of University College Dublin, who shed insight into numerical methods for options pricing, and Ben Hobbs of Johns Hopkins University, who provided some general counselling on RE RD[3]. We also gained greatly from other work being conducted by Doug Norland of the National Renewable Energy Laboratory and Russell Lee of Oak Ridge National Laboratory, who are also pursuing approaches to options value estimation for US DOE along other paths. All remaining errors are the authors' own.

7. Bibliography

Awerbuch, S and M Berger (2003), *Energy Security in the EU: Applying Portfolio Theory To EU Electricity Planning And Policy-Making*, International Energy Agency Report EET/2003/03, Paris, France.

Baker, E, L Clarke, and J Weyant (2004), "Optimal Technology R&D in the Face of Climate Uncertainty," *Annual Meeting of the International Energy Workshop*, International Energy Agency, Paris, France, June (available at http://www.ecs.umass.edu/mie/faculty/baker/Hedge.pdf).

Black, F and M Scholes (1973), "The Pricing of Options and Corporate Liabilities," *Journal of Political Economy* 81(3): 637-654.

Boyle, PP (1977), "Options: A Monte Carlo Approach," *Journal of Financial Economics* 4(3): 323-338.

Brennan, MJ and ES Schwartz (1977), "The Valuation of American Put Options," *Journal of Finance* 32(2): 449-462.

Brennan, MJ and ES Schwartz (1985), "Evaluating Natural Resource Investments," *Journal of Business* 58(2): 135-157.

Cohen, L, and R Noll (1991), *The Technology Pork Barrel*, The Brookings Institution, Washington, DC, USA.

Cortazar, G (2001), "Simulation and Numerical Methods in Real Options Valuation," in *Real Options and Investment Under Uncertainty: Classical Readings and Recent Contributions* (ES Schwartz and L Trigeorgis, eds), MIT Press, Cambridge, MA, USA: 601-620.

Cox, JC, SA Ross, and M Rubinstein (1979), "Option Pricing: A Simplified Approach," *Journal of Financial Economics* 7(3): 229-263.

Davis, G and B Owens (2003), "Optimizing the Level of Renewable Electric R&D Expenditures Using Real Options Analysis," *Energy Policy* 31(15): 1589-1608.

Deng, S-J and SS Oren (2003), “Incorporating Operational Characteristics and Startup Costs in Option-Based Valuation of Power Generation Capacity,” *Probability in the Engineering and Informational Sciences* 17(2): 155-182.

Frey, HC, RJ Lempert, G Farnsworth, DC Acheson, PS Fischbeck, and ES Rubin (1995), *A Method for Federal Energy Research Planning: Integrated Consideration of Technologies, Markets, and Uncertainties*, Lawrence Livermore National Laboratory Report, Berkeley, CA, USA.

Grenadier, SR and AM Weiss (1997), “Investment in Technological Innovations: An Option Pricing Approach,” *Journal of Financial Economics* 44(3): 397-416.

Hostick, DJ, DM Anderson, D Belzer, KA Cort, JP Dion, JA Dirks, and SC McDonald (2004), “Scenario-Based R&D Portfolio Analysis: Informing the Tough Decisions,” *ACEEE 2004 Summer Study on Energy Efficiency in Buildings*, Asilomar, CA, USA, 22-27 Aug.

Huchzermeier, A and CH Loch (2001), “Project Management Under Risk: Using the Real Options Approach to Evaluate Flexibility in R&D,” *Management Science* 47(1): 85-101.

Lee, R, G Jordan, PN Leiby, B Owens, and JL Wolf (2003), “Estimating the Benefits of Government Sponsored Energy R&D,” *Research Evaluation* 12(3): 183-195.

Longstaff, FA and ES Schwartz (2001), “Valuing American Options by Simulation: A Simple Least-Squares Approach,” *The Review of Financial Studies* 14(1): 113-147.

Luenberger, DG (1998), *Investment Science*, Oxford University Press, Oxford, UK.

McVeigh, J, D Burtraw, J Darmstadter, and K Palmer (2000), “Winner, Loser, or Innocent Victim? Has Renewable Energy Performed as Expected?” *Solar Energy* 68(3): 237-255.

Merton, RC (1973), “Theory of Rational Option Pricing,” *Bell Journal of Economics and Management Science* 4(1): 141-183.

National Research Council of the National Academy of Sciences (NRC) (2000), *Renewable Power Pathways: A Review of the US Department of Energy’s Renewable Energy Programs?*, National Academy Press, Washington, DC, USA.

NRC (2001), *Energy Research at DOE: Was it Worth It?*, National Academy Press, Washington, DC, USA.

President’s Committee of Advisors on Science and Technology (PCAST) (1997), *Federal Energy Research and Development for the Challenges of the Twenty-First Century*, Executive Office of the President of the United States, Washington, DC, USA.

Rendleman, RJ and BJ Bartter (1979), “Two-State Option Pricing,” *Journal of Finance* 34(5): 1093-1110.

Ross, SM (1999), *An Introduction to Mathematical Finance: Options and Other Topics*, Cambridge University Press, Cambridge, UK.

Schock, RN, W Fulkerson, ML Brown, RL San Martin, DL Greene, and J Edmonds (1999), "How Much is Energy Research & Development Worth as Insurance?" *Annual Review of Energy and the Environment* (24): 497-512.

Sharpe, WF (1978), *Investments*, Prentice Hall, Englewood Cliffs, NJ, USA.

Smit, HTJ and L Trigeorgis (2001), "Flexibility and Commitment in Strategic Investment," in *Real Options and Investment Under Uncertainty: Classical Readings and Recent Contributions* (ES Schwartz and L Trigeorgis, eds), MIT Press, Cambridge, MA, USA: 451-498.

Taylor, J (1999), *Energy Efficiency: No Silver Bullet for Global Warming*, The Cato Institute, Cato Policy Analysis No. 356, Washington, DC, USA.

Taylor, J and P Van Doren (2002), *Evaluating the Case for Renewable Energy: Is Government Support Warranted?*, The Cato Institute, Cato Policy Analysis No. 422, Washington, DC, USA.

Tseng, C-L and G Barz (2002), "Short-Term Generation Asset Valuation: A Real Options Approach," *Operations Research* 50(2): 297-310.

Unger, D, and H Herzog (1998), *Comparative Study on Energy R&D Performance: Gas Turbine Case Study*, MIT Energy Laboratory Report EL98-003, Cambridge, MA, USA.

Appendix: Proof of Value Function Monotonicity

Proposition:

The value functions are monotonically non-decreasing in upward NRE cost movements, i.e.,

$$V(k,i+1,r)\geq V(k,i,r)\forall\ k,i,r$$

and

$$W(k,i+1,r,j)>W(k,i,r,j)\forall\ k,i,r,j\ .$$

Proof:

The terminal conditions on the value functions imply $V(n,i,r)=0\ \forall\ i,r$ and $W(n,i,r,j)=0\ \forall\ i,r,j$. Therefore, the value functions in year $n-1$ with i upward NRE cost movements are:

$$V(n-1,i,r)=\max\begin{Bmatrix}-A;\\ W(n-1,i,r,n-1)-D;\\ -R-M+0;\end{Bmatrix} \tag{A1}$$

$$W(n-1,i,r,n-1)=(S(n-1,i)-C(n-1,r))\cdot X(n-1,n-1)-M+0 \tag{A2}$$

Furthermore, the value functions in the same year corresponding to $i+1$ upward NRE cost movements are:

$$V(n-1,i+1,r)=\max\begin{Bmatrix}-A;\\ W(n-1,i+1,r,n-1)-D;\\ -R-M+0;\end{Bmatrix} \tag{A3}$$

$$W(n-1,i+1,r,j)=(S(n-1,i+1)-C(n-1,r))\cdot X(n-1,n-1)-M+0 \tag{A4}$$

In comparing equations (A2) and (A4), since $S(k,i+1)>S(k,i)\ \forall\ k,i$, it follows that $W(n-1,i+1,r,j)>W(n-1,i,r,j)\ \forall\ i,r,j$. Consequently, because the first and third options are equal in equations (A1) and (A3), $V(n-1,i+1,r)\geq V(n-1,i,r)\ \forall\ i,r$. Now, suppose that these relations hold for all periods greater than or equal to some k^*, i.e., we have:

$$V(k,i+1,r)\geq V(k,i,r)\ \forall\ k\geq k^*,i,r \tag{A5}$$

$$W(k,i+1,r,j)>W(k,i,r,j)\ \forall\ k\geq k^*,i,r,j \tag{A6}$$

Via the definitions of the value functions in period k^*-1, we obtain:

$$V(k^*-1,i,r)=\max\begin{Bmatrix}-A;\\ W(k^*-1,i,r,k^*-1)-D;\\ -R-M+\{pV(k^*,i+1,r)+(1-p)V(k^*,i,r)\};\end{Bmatrix} \tag{A7}$$

$$\begin{aligned}W(k^*-1,i,r,k^*-1)=&(S(k^*-1,i)-C(k^*-1,r))\cdot X(k^*-1,k^*-1)-M\\ &+\{pW(k^*,i+1,r,k^*-1)+(1-p)W(k^*,i,r,k^*-1)\}\end{aligned} \tag{A8}$$

$$V\left(k^*-1,i+1,r\right)=\max\begin{cases} -A; \\ W\left(k^*-1,i+1,r,k^*-1\right)-D; \\ -R-M+\left\{pV\left(k^*,i+2,r\right)+(1-p)V\left(k^*,i+1,r\right)\right\}; \end{cases} \tag{A9}$$

$$\begin{aligned} W\left(k^*-1,i+1,r,k^*-1\right)=&\left(S\left(k^*-1,i+1\right)-C\left(k^*-1,r\right)\right)\cdot X\left(k^*-1,k^*-1\right)-M \\ &+\left\{pW\left(k^*,i+2,r,k^*-1\right)+(1-p)W\left(k^*,i+1,r,k^*-1\right)\right\} \end{aligned} \tag{A10}$$

In comparing equations (A8) and (A10), we find that $W\left(k^*-1,i+1,r,j\right)>W\left(k^*-1,i,r,j\right)\forall\, i,r,j$ because of equation (A6) and the fact that the NRE cost is monotonically increasing in i. By induction, it then follows that $W\left(k,i+1,r,j\right)>W\left(k,i,r,j\right)\forall\, k,i,r,j$.

As for equations (A7) and (A9), they differ in their second and third options. Since the former refers to $W\left(k^*-1,i+1,r,j\right)>W\left(k^*-1,i,r,j\right)\forall\, i,r,j$, in order to prove $V\left(k^*-1,i+1,r\right)\geq V\left(k^*-1,i,r\right)\forall\, i,r$, we need to show only the following:

$$\begin{aligned} &-R-M+\left\{pV\left(k^*,i+2,r\right)+(1-p)V\left(k^*,i+1,r\right)\right\}\geq -R-M+\left\{pV\left(k^*,i+1,r\right)+(1-p)V\left(k^*,i,r\right)\right\} \\ &\Rightarrow pV\left(k^*,i+2,r\right)+(1-p)V\left(k^*,i+1,r\right)\geq pV\left(k^*,i+1,r\right)+(1-p)V\left(k^*,i,r\right) \end{aligned}$$

The latter follows, however, from the induction hypothesis, i.e., $V\left(k,i+1,r\right)\geq V\left(k,i,r\right)\forall\, k\geq k^*,i,r$. Hence, again by induction, we obtain $V\left(k,i+1,r\right)\geq V\left(k,i,r\right)\forall\, k,i,r$.