

# **Evaluating the Impact of Government Energy R&D Investments through a Multi-Attribute Utility-based Decision Tool**

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Submitted to the System Design and Management Program  
in Partial Fulfillment of the Requirements for the Degree of

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## **ABSTRACT**

Government agencies characteristically face dynamic policy and investment environments yet frequently rely on ad-hoc decision-making methods in response to complexities inherent in their operating landscape. Additionally, standard decision making methods typically undervalue projects by ignoring difficult to value, non-monetary benefits. This presents a problem for public institutions, such as the Department of Energy (DOE), where goals relating to the environment and national security are difficult to quantify. As a result, it is especially challenging to accurately optimize the use of public funds.

The Department of Energy (DOE) is responsible for making significant investment decisions under extreme uncertainty with respect to the nation's public energy portfolio. Recently, leaders internal and external to the government have called for a comprehensive and structured approach to assess the DOE's portfolio of programs and initiatives (PCAST, 2010), (American Energy Innovation Council, 2011). Given the broad spectrum of the DOE's current portfolio, from basic R&D to demonstration and across every major energy technology, evaluating the impacts of its potential investments is complex. Within the Department of Energy's Planning Analysis and Evaluation (PA&E) team, a proposal was made to develop a first-of-a-kind decision tool that would provide rigorous analysis of cost and benefit trade-offs associated with the DOE's investments. The decision tool was designed to couple a state-of-the-art climate and energy model with sophisticated multi-attribute-based decision methods. The research described in this thesis illuminates the advantages and shortcomings of the initial decision tool structure, and

presents a second generation model that is tailored to the DOE's operational context. Finally, in order to expand its use for long-range strategy formation, an evolution of this second generation model is explored through the application of recent theoretical methodologies. The resulting decision tool is intended to play an informative role within a comprehensive portfolio review by enabling the enumeration of budgetary trade-offs that address high-level, strategy questions facing the DOE.

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Finally, a big thank you to my Mom and Dad. Who would have thought a little girl who insisted that reading books made her eyes burn would get a master's degree from MIT? You did. Thank you for always expecting my best and encouraging me to keep balance in my life.

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## **Chapter 1: Motivation and Background**

*“The United States is, in fact, at a historical point where the nation's energy innovation system is being examined, significantly expanded, and reshaped. As the country does this, it not only has a rare opportunity, but indeed a responsibility, to ensure that it improves the efficiency and effectiveness of this system to make sure that the country is getting the maximum payoff from its investments.”* - Institutions for Energy Innovation: A Transformational Challenge, Harvard Kennedy School, Venkatesh Narayanamurti, Laura D. Anadon, and Ambuj D. Sagar

The spring and summer of 2009 was an exciting and hectic time at the Department of Energy (DOE). With the instatement of the Obama Administration a turnover occurred of the entire DOE executive leadership resulting in a significant shift in strategic priorities. This shift was quickly followed by another major event, the passage of the American Recovery and Reinvestment Act in February 2009. The Recovery Act allocated \$32 billion in federal spending to the DOE, more than doubling their budget authority. As a result, there was great urgency within the Department to align the funds quickly and efficiently with new strategic priorities. To emphasize the need for action on issues such as energy independence, climate change, and American competitiveness, the new Secretary of Energy, Steven Chu, often quoted Martin Luther King Jr., “We are now faced with the fact, my friends, that tomorrow is today. We are confronted with the fierce urgency of now. In this unfolding conundrum of life and history, there is such a thing as being too late.”

In connection with these pressures internal to the government, leaders in academia and industry called for a more comprehensive approach to DOE portfolio assessment. The President's Council of Advisors on Science and Technology (PCAST) called for a DOE-Quadrennial Energy Review, in their 2010 energy report, stating that a review should include a systematic portfolio assessment that specifies the optimal deployment of resources, including the prioritization of financial resources and the resources of the national laboratories (PCAST, 2010). In addition, the American Energy Innovation Council, made up of leaders from the private sector such as Bill Gates and GE's Jeff Immelt, called for a similar in-depth assessment (American Energy Innovation Council, 2011).

Clearly, such an undertaking presented a complicated conceptual challenge. Policy, regulatory, and technology uncertainty as well as market dynamics specific to the energy sector form a landscape layered with complexities. It was apparent that a structured analytical decision tool would be of significant value in an overall portfolio assessment process.

The DOE's Chief Financial Officer's Program Analysis and Evaluation (PA&E) group, proposed developing a large decision tool aimed at assisting leadership with evaluating these deeply complex investment trade-offs. The decision tool was designed to generate benefits, linked with increases and decreases in funding levels to the DOE's core initiatives, and then evaluate those benefits using a Multi-Attribute Decision Analysis (MADA) framework. A large Integrated Assessment Energy and Climate model, MARKAL, was used to calculate the associated benefits. These benefits fed into ABC Software, which performed the Multi-Attribute Decision Analysis (MADA). The model is referred to internal to the DOE as the MADA model.

Examples of trade-offs this model was designed to provide guidance on included: 1) What yields greater combined public benefit – a heavier investment in building efficiency or basic solar R&D; and 2) How much more or less are the societal benefits associated with an increase in funding to the wind program, versus the fossil energy program?

By coupling traditional Multi-Attribute Decision Analysis with an Integrated Assessment Model and utilizing it to analyze long-term investment impacts in a dynamic global environment, the DOE attempted to develop a ‘first of a kind’ capability. As is typical with projects of a pioneering nature, however, many unexpected conceptual and technical issues arose.

Consequently, the initial MADA model did not produce results with the needed clarity and transparency. As a result, PA&E decided to abandon the MADA model and develop a less complex but more transparent second generation model, internally referred to as the Tradespace Evaluation model. This new model, based on Multi-Attribute Tradespace Exploration (MATE), a method evolved over the past decade at MIT’s Systems Engineering Advancement Research Initiative (SEARI), was successful in producing clear, understandable results. Recently completed, the Tradespace Evaluation model is planned for use as one component of a comprehensive DOE portfolio assessment process and for longer range strategy formulation.

This thesis provides an empirical study of the DOE’s decision tool development and explores the literature in order to determine the most appropriate application tailored to the DOE’s needs. It reflects on difficulties encountered and lessons learned. The thesis author had the fortuitous opportunity to work through an independent study arrangement for the DOE’s PA&E group from Cambridge, while completing her master’s degree. With the assistance of PA&E analysts, she

conducted the in-depth review process of the initial MADA model as well as designed and developed the second generation Tradespace Evaluation model.

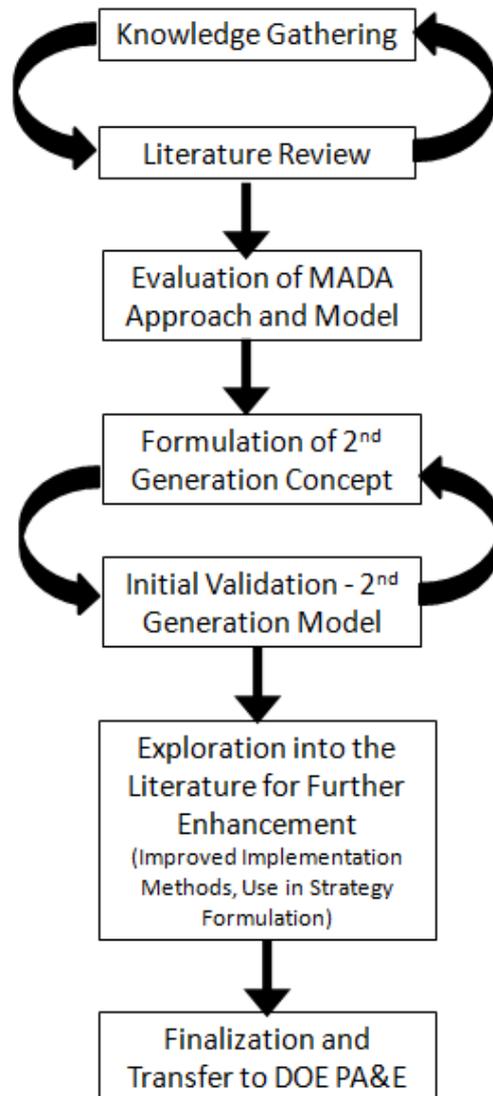
## **1.1. Research Approach and Questions**

Given that the DOE was committed to building a multi-attribute-based decision tool, the objective of this thesis was to investigate the most appropriate, tailored multi-attribute-based approach for the DOE's needs. The first step in the study was to review the initial MADA model, its structural and conceptual shortcomings as well as its methodological suitability for assessing problems relevant to the energy sector. This involved knowledge gathering from individuals at multiple levels of PA&E; a variety of analysts, managers and consultants involved in the MADA development effort as well as the final users of the model. As will be discussed in Section 3.3, a systematic review of the MADA model was conducted which included the following steps: 1) an enumeration of all core calculations within the MADA model, 2) a listing of major assumptions contained within each aspect of the model, 3) a sequential walk through of all core calculations for hypothetical budget portfolios, and 4) an identification of the top conceptual and structural shortcomings having the greatest impact on accuracy and transparency.

Next, an in depth literature review was conducted which explored application methods for multi-attribute-based decision analyses and their fit within the DOE's operating context. A review was conducted of MARKAL, its key functions, capabilities and limitations as well as comparable integrated assessment models. This research informed the design and build of an improved

second generation model, based on 1) the use of lessons learned from the MADA modeling effort, and 2) an investigation into the literature identifying multi-attribute-based approaches more suitable to the DOE's needs. The final step was to explore the further evolution of the second generation Tradespace Evaluation model. Recent methodological advancements in relevant systems research were explored for improved implementation methods as well as extension techniques for the model's use in strategy formulation. A visualization of this research approach is included below.

## Outline - Research Approach



**The thesis study was guided by three key research questions:**

- What were the key conceptual and structural shortcomings of the DOE's initial multi-attribute-based approach?

- Are alternative methodological approaches better suited for assessing the problems relevant within the energy sector and if so, how can they be applied in a framework which meets the DOE's requirements?
- How can the DOE's decision tool be further evolved and augmented to increase its utility to decision makers through the application of recent advancements in relevant systems engineering research?

## **Chapter 2: Literature Review**

A vast body of literature surrounding various application methods for multi-attribute-based decision analyses, easily numbers in thousands of relevant papers. This literature review conveys a glimpse of the potential variety of methods focusing-in on utility-based methods. As stated above, the DOE's investment decision tools, both the initial MADA model and the subsequent Tradespace Evaluation model, couple a multi-attribute decision method with an Integrated Assessment Model, MARKAL. A description and review of MARKAL's core functionality is provided as well as a comparison with similar Integrated Assessment Models.

### **2.1. Overview of Multi-Attribute Decision Methods**

#### **2.1.1. Decision Theory Overview**

The DOE's challenge clearly lies within the realm of decision theory and analysis, the modern origins of which emanate from the seminal work of von Neumann and Morgenstern (von Neumann, 1947). Decision theory, which is concerned with improving how people make decisions, is organized into three branches: normative, descriptive, and prescriptive (Raiffa, 1982). These areas consider, respectively; how people should decide given rational behavior, how people actually make decisions, and how to help people make better decisions. Generally, the prescriptive process of helping people make better decisions—the branch applied by this study to the DOE—is informed by both normative and descriptive decision theories.

### **2.1.2. Multi-Criteria Decision Analysis (MCDA)**

One broad class of decision tools that is applicable to the DOE is multi-criteria decision analysis (MCDA). This type of method is appropriate in situations where multiple criteria, some of which are non-monetizable, must be considered by one or many decision-makers. As detailed in (Ross, O'Neill, et al. 2010), multi-criteria problems are difficult to address with traditional valuation techniques, such as the net present value method or cost benefit analysis, and with traditional conceptualizations of single objective optimization.

The net present value (NPV) method, which is taught ubiquitously in engineering and business (Ross S., 1995), is used to evaluate the discounted net cash flow of single projects. In its simplest application, projects with positive net present value are deemed worthy of investment, and vice versa for an outcome of negative net present value. Using the most predominant assumptions for NPV, it is clear that the method is limiting in situations with uncertainty and non-monetizable criteria (Ross, O'Neill, et al. 2010). For one, it is assumed that the decision-maker has perfect information with respect to future cash flows and market rates of return. Secondly, value is only derived from net cash flow and desirability of different system attributes are assumed to be independent of one another. In the case of the DOE, significant uncertainty exists with respect to future project costs and technical details. Additionally, it would be difficult for decision-makers within the DOE to conceptualize some attributes, such as reduction in greenhouse gases as a revenue stream. Also, some of the attributes exhibit dependence, such as reduction of oil imports and greenhouse gases.

Cost benefit analysis (CBA) suffers from many of these same issues, as has been discussed in the economics of climate change literature (Ackerman, 2009). In general, CBA uses a single monetized metric of discounted net benefits: monetized benefits minus monetized costs discounted back to the present. It also relies on perfect information of system structure, parameters, and market behavior, effectively limiting the exploration of uncertainty. One improvement with respect to NPV, is that CBA does not focus strictly on costs and revenues. Costs, of course, are included, but benefits are taken to be broader than revenue. However, in order for benefits to be comparable to costs across time, as well as revenue, they must be converted to a monetary measure. Such conversions often require their own separate models and assumptions. For the decision-maker, this set-up can quickly lead to distrust of the model results.

Therefore, additional functionality is required in methods that are meant to analyze non-monetizable criteria. The umbrella term used for these methods, multi-criteria decision analysis (MCDA), can be broken into three categories: value measurement, goal level, and outranking (Belton, 2002).

In value measurement methods, value is placed on alternative actions, and the subsequent values are ordered based on a set of defined preferences. These methods have the benefit of imposing structure on the derivation of preference models, helping decision-makers understand and utilize their own values, and illuminating acceptable tradeoffs. Goal level methods define satisfactory or desirable outcomes and then seek out alternatives that fulfill them as much as possible. This MCDA category is useful when decision-makers express difficulty in specifying tradeoffs or

importance weights, but can describe a set of desirable outcome scenarios. Finally, outranking models involve pairwise comparison of different alternatives, such that incompatibilities, preferences, and indifferences are identified over time, rather than through an up-front elicitation of preferences (Belton, 2002).

### **2.1.3. Multi-Attribute Utility Theory (MAUT)**

Because the decision-makers at the DOE are able to express their preferences, this study focuses on the first form of MCDA, value measurement methods. Within this category resides multi-attribute utility theory (MAUT). MAUT, which was introduced by Keeney and Raiffa (Keeney, Raiffa, 1976), is an extension of expected utility theory introduced by von Neumann and Morgenstern (von Neumann, 1947).

The classic version of von Neumann and Morgenstern (VNM) utility theory maps the outcome of an action, as measured by a single attribute, to a subjective measure of value, utility. The theory states that under given assumptions with respect to rationality, an individual would select the action that maximizes expected utility. The rationality assumptions consist of four axioms, which define the preference relations among three hypothetical lottery outcomes  $H$ ,  $J$ , and  $K$ :

1. For two lotteries  $H$  and  $J$ , either  $H$  is preferred to  $J$ ,  $J$  is preferred to  $H$ , or the individual is indifferent between  $H$  and  $J$  (completeness axiom).
2. If  $H$  is preferred to  $J$  and  $J$  is preferred to  $K$ , then  $H$  is preferred to  $K$  (transitivity axiom).

3. If  $H$  is preferred to  $J$  and  $J$  is preferred to  $K$ , then a probability  $p$  exists such an individual is indifferent between  $pH + (1-p)K$  and  $J$  (continuity axiom).
4. For the three lotteries,  $H$  is preferred to  $J$  if and only if  $pH + (1-p)K$  is preferred to  $pJ + (1-p)K$  (independence axiom).

Extending classical VNM utility theory to MAUT then requires the addition of two other axioms relating to preference and utility independence (Keeney, 1993). Given elicited weights ( $\mathbf{k}$ ) on attributes ( $\mathbf{x}$ ), these axioms simplify the analysis of trade-offs among attributes. Furthermore, the general mathematical description of a multi-attribute utility function takes the form:

$$U(X) = u(\mathbf{x}, \mathbf{k}), \quad (1)$$

where  $U(X)$  is the multi-attribute utility function.

As outlined in Keeney and Raiffa (Keeney, Raiffa, 1976),  $u(\mathbf{x}, \mathbf{k})$  in Equation 1 can take many forms, the simplest of which is linear-additive:

$$U(X) = \sum_{i=1}^n k_i \cdot u(x_i). \quad (2)$$

In this form, the  $n$  values of  $k$  sum to one, and  $u$  is constrained to the range of zero to one. The Keeney-Raiffa function is a more sophisticated and generalized form of the linear-additive multi-attribute utility function:

$$K \cdot U(X) + 1 = \prod_{i=1}^n (K \cdot k_i \cdot U(x_i) + 1). \quad (3)$$

Here,  $K$  is a normalization factor, which takes the form:

$$K = -1 + \prod_{i=1}^n (K \cdot k_i + 1). \quad (4)$$

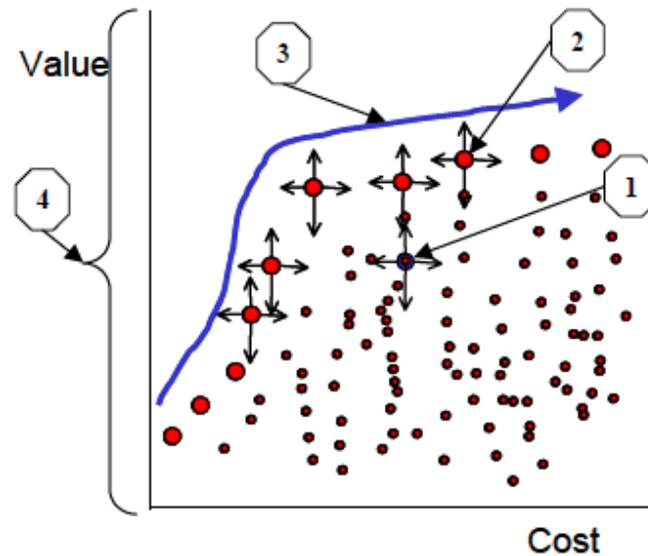
Equation 3 is flexible in that if the  $n$  values of  $k$  sum to one, then Equation 3 becomes the linear-additive function described in Equation 2. Otherwise, the Keeney-Raiffa becomes a multiplicative or inverse multiplicative function. Although Equation 3 presents a more general approach to capturing preferences, Keeney and Raiffa suggest that when a model has more than a few attributes, the linear-additive equation provides a good balance between simplicity and accurately approximating the decision-makers preferences—a recommendation adopted by this study.

#### **2.1.4. Tradespace Exploration**

Decision analysis requires both a measure of value and methods to illuminate the “best” options to decision-makers. In the case of a single-attribute problem, finding the best solution can be addressed through more traditional optimization methods. Moving to a multi-attribute space complicates the analysis, because no one single solution will optimize all attribute values.

Instead, a Pareto frontier (blue line labeled 3 in Figure 1) results. The points along this frontier

are such that value is maximized for each possible cost level. In practice, the Pareto frontier can be used to enable value trade-offs among design alternatives.



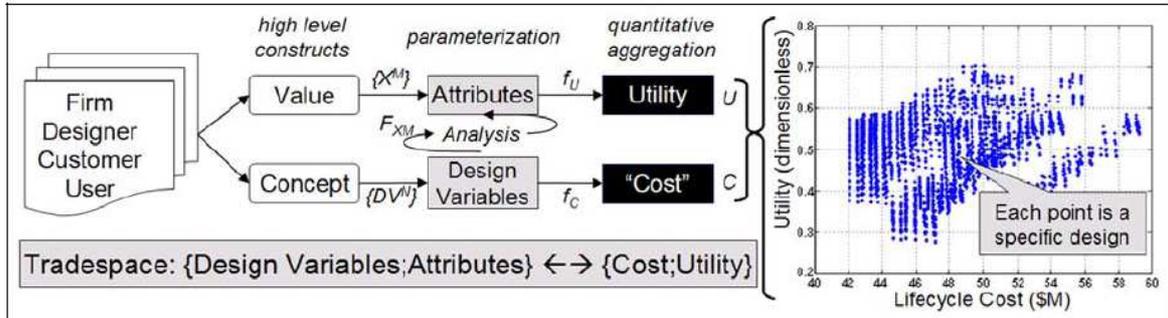
**Figure 1. Tradespace exploration. Label 1 = Local point solution trades. Label 2 = Multiple points with trades. Label 3 = Pareto frontier sent. Label 4 = Full tradespace exploration. (Ross, 2005)**

Finding the Pareto frontier of a multi-criteria problem involves a variety of optimization techniques, which are designed to efficiently search the space of all possible options (Jilla, 2002). Efficient identification of the frontier is important when the full space of options (Label 4, Figure 1) is too large to be computationally tractable or understandable. However, focusing on finding only the Pareto frontier obscures important information contained in other dominated solutions (Labels 1 and 2, Figure 1). For example, the DOE is comprised of multiple decision-makers, each of whom has different preferences and attribute weights, and therefore different tradespaces. When negotiating a consensus solution, it is to their advantage to have full

information of each other's tradespaces, because strict comparison of Pareto frontier sets may overly constrain possible outcomes.

### 2.1.5. Multi-Attribute Tradespace Exploration (MATE)

This thesis's inspiration for combining MAUT and tradespace analysis emanates from the Multi-Attribute Tradespace Exploration (MATE) method. MATE is a value-driven tradespace exploration method that has been evolved over the past decade by MIT's Systems Engineering Advancement Research Initiative (SEARI) (Ross, 2005) and has been applied in thirteen (mostly aerospace) case studies (Ross, McManus, et al., 2010). Table 1 below summarizes the MATE process.



**Table 1. Multi-Attribute Tradespace Exploration (MATE) (Ross, Rhodes, 2008)**

An example 48-step process for applying classic MATE can be found in (Ross, 2003). The steps can be grouped into three stages: need identification, design alternative enumeration, and design alternative evaluation. Need identification encompasses scoping decision-maker needs and eliciting attributes and preferences. Attributes are decision-maker designated metrics that

describe the performance characteristics of the system. These attributes, their associated utility curves, and preference weighting factors are elicited through formal stakeholder interviews. Single-attribute utility curves are then aggregated using a form of a multiplicative utility function. The second phase, design alternative enumeration, involves using the elicited attributes to compose a set of solutions for input to phase 3, design alternative evaluation. This is done through inspection of the attributes and proposal of various design variables. Design variables are quantitative parameters of the system, which taken together describe the system. Each possible combination of design variables makes up a design vector. This last phase entails the development of models to link design solutions to articulated value. A full-factorial sampling of the design space is enumerated, typically using parametric computer models, which take each design vector as input and return as output the attribute metrics and system costs. A utility function is then applied to the resulting attributes and cost versus multi-attribute utility plots can be generated, forming a tradespace (Ross, 2006).

Within the recent literature this classic form of MATE, described in (Ross et. al, 2004), has evolved to Dynamic MATE (Ross, 2006). The distinguishing characteristic of Dynamic MATE is the use of network analysis to create a series of tradespaces, which incorporate time-dependent context variables and span time. In order to generate this depiction, Epoch-Era Analysis is employed. In this method, a system's lifecycle, or era, is divided into a set of discrete epochs (Ross, 2006), (Ross, Rhodes, 2008). Further details, benefits, and challenges of this approach are discussed further in Section 6.6.

## **2.2 MARKAL/TIMES - Integrated Assessment Model**

MARKAL is a flexible modeling framework, which in its simplest form, has the capability to identify the least cost structure of an energy system over time. The detail and scale of the represented energy system is dependent on user needs and fidelity of available input data. Typically, users create a relatively comprehensive system representation that includes the costs of fuel extraction all the way to specific types of end-use demand for energy, such as electricity for lighting and steam for heating. In between these two ends of the energy chain are technologically rich descriptions of the economic and technological attributes and linkages among various conversion and production technologies, such as the conversion of crude oil to gasoline and electricity produced by coal-fired generation (U.S. EPA, 2007). Thus, it is a very technology-centric model, much like NEMS (U.S. EIA, 2009), IMAGE (PBL Netherlands EAA, 2011), CIMS (Simon Fraser University EMRG, 2011), and MESSAGE (IIASA, 2011).

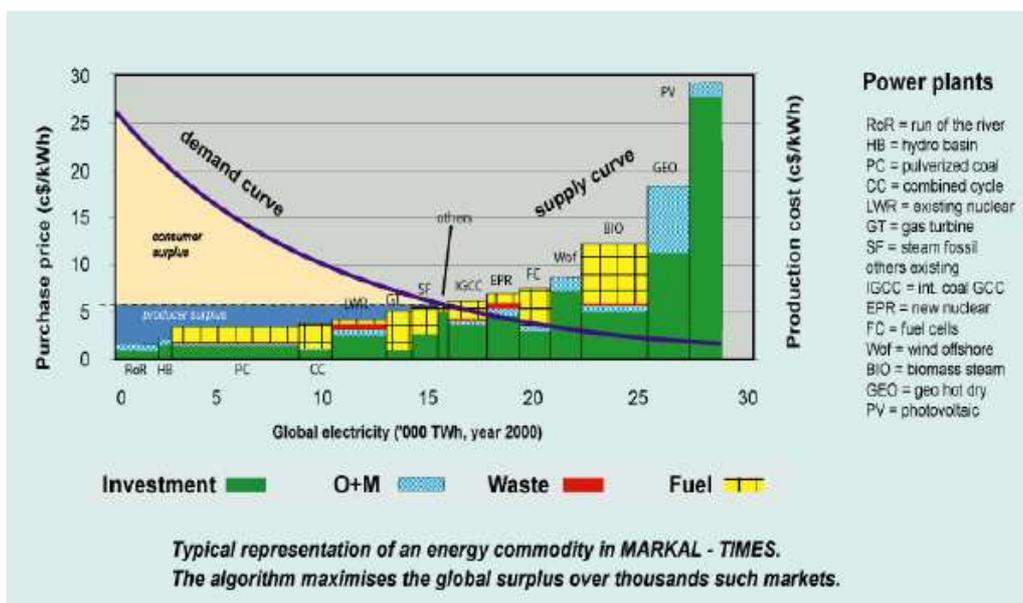
NEMS, IMAGE, CIMS, and MESSAGE are a sampling of the most well known Integrated Assessment models that compete with MARKAL. NEMS, CIMS, and IMAGE are not structured to compute optimal energy system configurations, but add the ability to more richly describe the behavioral aspects of the penetration of energy technologies (Mendaca et al., 2010). While MESSAGE is conceptually similar to MARKAL, it does not have the same long-standing international commitment to ongoing development and use of the model.

Because of its flexibility, MARKAL has been used at the global scale by the IEA, EIA, ETSAP, and EFDA, as well as at the regional scale (European Community, EPA-ORD, BNL, NESCAUM, China ERI, ASEAN, and SEE), national scale (UK DTI/ERC, US BNL/EPA-ORD,

numerous EU countries (Germany, France, Italy, Spain, Switzerland, Denmark, Norway, Sweden, Belgium, Russia, China, India, South Africa, APEC, and Colombia), and the sub-national scale (California, Colorado, Massachusetts, New Jersey, Ohio, Texas, New York City, Geneva, and Toronto) (International Resources Group, 2009). It is particularly popular in policy analysis because its explicit representation of the economic *and* technical details of the energy system allows for the study of regulatory policies (such as a renewable portfolio standard or a restriction on trade of fuels or technologies), R&D investments, and market-based policies (such as a carbon tax or cap-and-trade scheme). Given input data of appropriate detail, MARKAL gives an analyst the ability to compare policy impacts through investigation of model outputs such as: total discounted system cost, resource levels and marginal costs, technology levels of total installed capacity, annual investments in new capacity and expenditures, annual fixed and variable operating and fuel costs, annual and season/time-of-day (for power plants) utilization, energy consumed by each technology (sector), marginal price (by season/time-of-day for electricity), and emission level by resource/sector/technology for each period (International Resources Group, 2009).

The useful detail of MARKAL's output, however, must be considered in tandem with the implications of MARKAL's structural assumptions. From a mathematical perspective, MARKAL is a mixed integer linear programming model whose objective function is the present-value cost of the energy system (U.S. EPA, 2007). This choice of methodology translates into very specific assumptions about how actors in the energy system make choices. For one, it assumes that all individuals possess the information, cognitive abilities, and control to make decisions that lead to a least-cost configuration of the energy system. Implicit in this setup is that

individuals make decisions only with regard to monetized incentives and that they are perfectly responsive to any changes in these incentives. As shown in Figure 2, this leads to an equilibrium price for energy, given demand and attributes of the energy system. This is an especially important detail when considering the efficacy of market-based versus regulatory policy instruments.



**Figure 2. Graphical Representation of Equilibrium Energy Price Determination (International Resources Group, 2009)**

It is possible within MARKAL to relax these behavioral assumptions by introducing various constraints on the model behavior or modifying input data. However, these changes are often ad hoc and difficult to parameterize. For example, one might be interested in how market barriers impede the effectiveness of government R&D investments on the penetration of renewable technologies. In MARKAL, this would typically be addressed by including a constraint on the

rate of technology penetration, because it is difficult to explicitly represent in an optimization model many of the processes that cause market barriers. However, adding this constraint might be capturing other impedances of technology adoption that are difficult to separate from those specific to market barriers and government R&D investments. Therefore, additions to MARKAL that stray from its core assumptions of system optimization must be carefully constructed to avoid giving erroneous or opaque results to decision-makers. Other models such as IMAGE, NEMS, and CIMS avoid some the issues inherent to MARKAL by adding more behavioral elements of consumer decision-making (Mundaca et al., 2010). However, as a tradeoff they give up much of the ability to estimate how least-cost changes in the energy system resulting from different R&D investment portfolios.

## **Chapter 3: Initial MADA Model**

The MADA model concept was originally proposed and by XYZ Consulting, a leading management consulting firm. It was jointly implemented by the DOE PA&E office, XYZ Consulting and ABC Software Company, a boutique consulting firm. This chapter starts at the beginning with a summary of XYZ Consulting firm's initial proposal and described expected outcomes. The proposal is then contrasted with a description of the actual outcome, the implemented MADA model. Next, an account is provided of the in-depth review of the MADA model, which was conducted at the request of PA&E leadership. Concerns are detailed surrounding the model's ability to produce accurate results with the transparency needed to significantly inform the DOE's portfolio assessment process. Finally, key lessons learned by DOE PA&E from the modeling effort are discussed.

### **3.1. Initial MADA Proposal**

The development of a Multi-Attribute Decision Analysis (MADA) tool was proposed by XYZ Consulting to the DOE's PA&E group over the course of several presentations and meetings held in the summer of 2009. The thesis author's residency within the DOE's PA&E group allowed for the compilation of the below observations with respect to the original model proposal and outcomes anticipated by PA&E.

### **Proposed Vision of MADA Model Functionality and Deliverables:**

As shown below, XYZ Consultancy's pitch appeared to deliver a targeted solution to some the most pressing problems faced by the DOE.

*“The Department of Energy (“DOE” or “Department”) faces an increasingly complex financial and strategic decision environment where it must justify its need for resources, demonstrate the benefits derived from its expenditures, and improve the efficiency of its strategic investment decision processes. In this spirit, the Department would benefit from a strategic investment decision support and portfolio management methodology for the Program Analysis and Evaluation (PA&E) office, Office of the Chief Financial Officer (CFO). XYZ Consulting proposes a Multi-Attribute Decision Analysis Tool to assist the Office of the CFO in making complex budget and investment decisions. MADA provides an industry-accepted approach to decision-making and when combined with risk analysis and portfolio optimization methodologies it offers a transparent and comprehensive method to resource allocation.” (XYZ Consulting, 2009)*

The proposed MADA tool was describe by XYZ Consulting as having applicability to multiple strategic objectives, capable of addressing funding increments and decrements, capable of addressing multi-year programs and funding deferrals, possessing risk analysis capability, able to address program and project interdependencies, and having the ability to evaluate early stage scientific research. Its characteristics were described as; accurate, defensible, transparent, complete, practical, accepted, easy to use, internally consistent and robust.

Additionally, the benefits the DOE could gain from the MADA model were expressed as; providing a clear methodology, linking the budget to agency objectives and priorities, providing justification for tough choices, enabling stakeholder collaboration and confidence, allowing for greater accountability, enabling performance gains, and leveling the playing field

A list of challenges facing the DOE was described in detail, of which the MADA tool was proposed as a solution. Those challenges included; multiple strategic objectives, divergent activities, and diverse stakeholders. Specific DOE financial objectives were described as; effectively direct incremental and decremental spending, terminate ineffective programs, and gauge multi-year cost commitments and optionality of go-forward opportunities. Strategic and non-financial DOE objectives were described as; to support national objectives for long-term economic growth and stability, ensure energy security, mitigate climate impacts, and compete with and exceed international peers.

XYZ Consulting stated the goal of the model is to enumerate the efficient frontier of portfolio options. Key results were described as; the identification of where to cut in order to maximize cash (short-term) and value (long-term), the clarification of which projects to invest in and at what level, the clarification of which projects to defer or cut and incurred “opportunity cost”, the creation of a holistic portfolio view, and improvement of strategic and organizational alignment of projects.

### **Proposed Technical Architecture:**

At the time of the original concept proposal, the technical architecture of the MADA model as well as the internal calculations were yet to be specified. The conceptual description of the

model was proposed as a combination of MADA methodology, risk analysis techniques, portfolio optimization methodologies and appropriate software.

It was recommended that the DOE model be centered on a web-based modeling platform that was described as able to address the MADA requirements as well as provide for risk analysis, portfolio optimization, multi-users, security controls, customizable modeling logic and management reports. Based on XYZ Consulting's previous modeling experience, they recommended the use of ABC Software platform, provided by ABC Software Company - a boutique consulting firm. This platform was described as the option which most completely addressed the requirements of the DOE, was priced at the lower end of sophisticated portfolio optimization tools, and provided functionality, flexibility and scalability at the upper end of comparable products. Additionally, the proposed MADA model was to take into account current PA&E and CFO budgeting tools, and to provide for scalability for possible future versions or extensions.

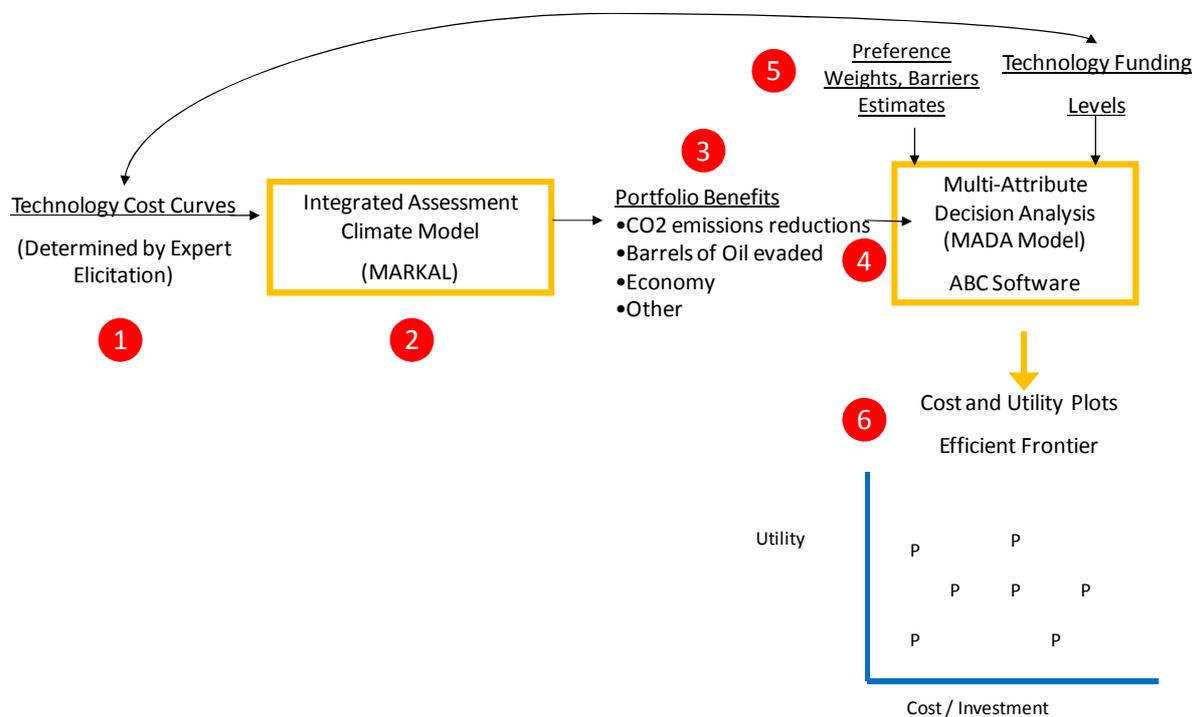
#### **Post-Implementation Observations:**

Due to a variety of limitations that surfaced during the build of the MADA model, promised capabilities described in the proposal process above proved difficult to realize. Fully reflecting upon the initial vision is important to understanding the gap between what the MADA tool actually delivered and what it was expected to deliver. Additionally, the reflection process is an important step in enabling the DOE to identify early-on key limitations that have the potential of rendering any large systems project ineffective. Lessons learned from this process are discussed in Section 3.4.

### 3.2. Actual Implementation of MADA Model

This section provides a basic overview of the implemented MADA model, including the model’s structure and core calculations. A visualization of the MADA model is shown in Figure 3.

**Core Calculations:** Numbered items correspond to preceding descriptive paragraphs.



**Figure 3. Author’s Depiction of MADA model Framework.**

1. The first step of the MADA model is to generate technology cost curves that are sensitive to DOE funding adjustments. The curves are generated through an expert elicitation process. Experts are asked hypothetical questions like, “If funding for the DOE’s Wind Program was canceled, how would that effect the cost curve for various wind technologies; what if it was

increased to very high levels?” Each potential DOE budget portfolio is therefore linked to a set of technology cost curves.

2. These curves are then fed into MARKAL, an integrated climate and energy assessment model. Taking into account the given cost curves, as well as other standard assumptions of demand growth, market barriers, and energy policy, MARKAL finds the least cost (i.e. optimal) energy system.
3. The benefits associated with each DOE budget portfolio are output from MARKAL. Benefits are measured out through 2050 and include total CO<sub>2</sub> emissions reductions, total barrels of oil evaded, total reduction in deployment barriers, and total reduction in cost of the energy system.
4. Each singular MARKAL run requires a significant amount of time and resources to complete. Because of this limitation, only a select number of budget portfolios are run through MARKAL. The MARKAL output from these runs is recorded and the benefits associated with the various technology funding levels are isolated. These results are input into ABC Software, which recombines the isolated funding levels to estimate the impact of “new” portfolio scenarios. This allows the impact of a larger number of combinations of funding levels for different DOE technologies to be evaluated without having to spend the resources to run MARKAL for each conceivable portfolio. This process and conceptual problems associated with it are explained in more detail in Section 3.3.5.

5. Through an additional expert elicitation process, stakeholder preference weightings for each benefit are gathered. For example, one stakeholder could be more concerned about energy security, and as a result, would weight barrels of oil evaded very high and CO<sub>2</sub> emissions reductions low. As a counter-example, a stakeholder who is more concerned about the environment would assign opposite weights.
  
6. These major inputs—technology funding levels, resulting benefits, and stakeholder weightings—are then fed into ABC Software. ABC Software performs three major tasks. First, it calculates the total benefit associated with the reduction of “barriers”. The definition of barriers in this context, the calculation of benefits associated with reducing barriers, as well as conceptual issues with this calculation are discussed in Section 3.3.6. Second, ABC Software converts the benefits associated with each funding level into weighted dollars. This “dollarization” process and its associated problems are described in Section 3.3.7. Finally, ABC Software generates potential budget portfolios through a recombination of the benefits associated with each funding level. It then searches for an “optimal” portfolio by selecting the portfolio with the highest total benefit for a given cost.

The equation below depicts the benefits function,  $B$ , calculated within the MADA model.

Benefits are measured in terms of weighted dollars and include - total energy systems savings, greenhouse gas emissions reductions and barrels of oil saved. The barrier impediment term is added in as a negative amount. It represents the total magnitude of all barriers associated with a specific portfolio. Finally, the barrier reduction term is added in as a positive amount. It equates to the reduction in total barriers resulting from the portfolio’s investments.

$$B = B_{\text{energycost}} + B_{\text{GHG}} + B_{\text{oil}} + B_{\text{BarReduct}} + B_{\text{BarImped}}$$

**Figure 4. MADA Model Benefits, B, Calculation**

### **Management Framework:**

Design, development and testing of the MADA tool was jointly managed by XYZ Consulting firm and PA&E's modeling and analysis team. MARKAL runs were completed by a third consulting company with expertise in integrated assessment modeling. The development and testing of the core model was contracted out to ABC Software Company, with oversight from both XYZ Consulting firm and PA&E. Totaling to four separate organizations involved in the decision tool development process. The existence of multiple parties was a challenge for model integration and management coordination.

### **3.3. In-depth Review of MADA Model**

Upon conclusion of the MADA development process, it became clear to PA&E leadership that the model was failing to provide results which met the needed level of fidelity and transparency to guide the DOE's portfolio assessment process. Several issues, within the MARKAL model itself and the ABC Software portion of the model, were identified.

Confusion existed among decision makers about the precision of the MARKAL outputs. For example, it was unclear whether differences among various portfolios constituted meaningful contrasts or were within the error window associated with MARKAL outputs. Compounding

this mistrust were questions over the impact of running MARKAL with various policy options. For example, if MARKAL were run with a cap on carbon emissions then no matter what the funding levels for the various technologies – total emissions measured and therefore associated greenhouse gas reduction benefits would be the same. Additionally, due to the computational intensity associated with running MARKAL, there exists little opportunity to familiarize decision makers with its core assumptions or calculations.

However, not all of the blame can be placed on the MARKAL model. Much mistrust of the results emanated from the complex and confusing ABC Software output, a lack of transparency around ABC Software's internal calculations, and conceptual problems with specific methodologies. Decision makers and DOE analysts especially found problematic the presentation of benefits in unintuitive units of weighted dollars. Additionally, the handling of non-monetary barriers, which relied heavily on expert opinion, was complex and opaque. A final constraint was PA&E's heavy dependence on ABC Software Company to run and make adjustments to the model. This reliance made the change process lengthy and expensive. Consequently, the model was not flexible to PA&E's quickly changing analytical needs.

The compound result of these concerns was a perception by the decision makers that the model was a 'black box', which they instinctively put little trust in. Consequently, PA&E leadership requested an in-depth review of the MADA model, which was undertaken with the assistance of two PA&E analysts. The systematic review process included the following sequence:

1. Enumeration of all core calculations through creation of a calculation sheet.
2. Listing of major assumptions fed into each aspect of the model.

3. Sequential walk through of all core calculations. For one hypothetical portfolio, walk through entire modeling process, from original input data to output from the ABC Software.
4. Identify conceptual and implementation errors in the model calculations.
5. Single out the issues having the greatest impact on accuracy and transparency.

After the review process, the team came to three major conclusions. First, the MADA model's initial proposal promised capability beyond what is practically feasible, in large part due to the lack of model fidelity available with today's state-of-the-art Integrated Assessment Models, such as MARKAL. Second, the MADA model's core calculations contain systematic errors that produce conceptually inconsistent and nontransparent results to the decision maker. Finally, the observed problems do not point to fundamental inadequacies of applying a multi-attribute based decision methodology to the DOE's investment questions. Rather, they point to shortcomings in the execution of the model. The review team found that, if executed correctly, MADA holds large potential to provide useful and much needed guidance to decision makers. Consequently, the recommendation was made to not abandon the original concept. These conclusions are elaborated on in the sections below.

### **3.3.1. Conceptual Framing – Scope of Deliverables and Granularity of Data**

#### **Available from MARKAL**

MARKAL is a high-level model of the entire energy system that takes as input data that often has a non-trivial degree of uncertainty. Additionally, the nature of the model structure does not

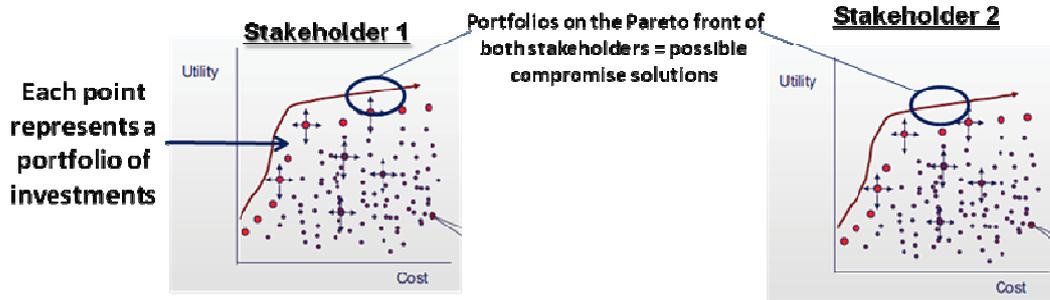
always translate well to certain scenario experiments. As a result the interpretation of results due to small adjustments of any of the model parameters can be difficult to distinguish in a meaningful way. For example, small DOE funding level adjustments have minimal measurable impact within the overall economy because the private sector portion of investment dwarfs the DOE's level of investment. Thus, although the model will certainly indicate impacts from a 10% increase or decrease to a DOE budget line item, drawing definitive conclusions from the result can be problematic. As a consequence, many capabilities of the MADA model assumed to exist by XYZ Consulting were not practically feasible. Unfortunately, comparable integrated assessment models possess identical limitations, so replacing MARKAL in the MADA framework does not present a solution.

It was found that only very large increases in DOE funding could be meaningfully evaluated. As a result, the MADA scenarios specified three discrete funding levels for each technology: zero funding for an entire DOE initiative (low), current funding levels (target), and an arbitrary increase in funding level identified through expert elicitation (high). Because values used for the 'high' scenarios varied across technologies, rather than a set percentage above the target value, interpretation of the results by decision-makers was hindered.

### **3.3.2. Conceptual Framing – Optimization versus Tradespace Exploration**

One of the key questions PA&E leadership posed during this review process was, "What should the ideal output from a multi-attribute based model look like?" As the literature review on this topic shows (Chapter 2), the answer to this question has evolved over time.

MADA's initial output identifies a single-point, optimized budget portfolio and focuses the decision maker towards that data point. MADA has the capability to generate a benefits versus cost graph for the Pareto front but it is not malleable, allowing for a deeper investigation of trade-offs. An alternative to this approach is Tradespace Exploration which is not an optimization technique but an enumeration of a multitude of options that then become the basis for analysis and negotiation (Ross, Hastings, Diller, 2003). When exploring a variety of DOE budget portfolios, no single portfolio can realistically be identified as "optimal". This is due to the fact that multiple stakeholders exist with interest and authority over the DOE's final budget allocation. These stakeholders have contrasting preferences in terms of the overall size of the budget and the importance of its associated benefits. Tradespace Exploration is discussed in the literature review, Chapter 2. The advantage of multi-attribute analysis used in conjunction with tradespace analysis, as proposed within the MATE framework (Ross, Hastings, Diller, 2003), is that it captures those different preferences and displays them in tradespaces associated with each stakeholder - enabling negotiation and allowing compromise solutions to be found. A discussion of the utilization of MATE for negotiation can be found in (Ross et. al, 2010). See below Figure 5 for depiction. The proposal that a single optimized budget portfolio does not exist is especially relevant within the energy sector, where preferences for generation and transportation technologies are highly politicized and polarized amongst the major stakeholders.



**Figure 5. Tradespaces for Multiple Stakeholders**

### **3.3.3. Conceptual Framing – Monetizing Benefits versus Utility**

This section explores the question of selecting a value metric (e.g., dollars, utils) appropriate for the MADA application. No method is entirely complete in capturing value, but the selection of the most appropriate one involves a matching between the benefit being valued and assumptions that are acceptable to the particular decision maker. The term “value” holds inherent ambiguity. It refers to measuring or creating “goodness”. In order to use this concept for quantitative evaluation, the term must be unambiguously understood (Ross, O’Neill, et al. 2010).

As described in Section 3.3.7, the MADA model calculates a single benefit metric,  $B$ . The benefit metric is calculated by converting the benefits associated with each portfolio from their unit of measure to dollars, weighting the resulting monetized benefits based on stakeholder preferences, and summing the results. This produces a benefit metric,  $B$ , in terms of weighted-dollars. The original motivation for using dollars was that it is a unit with which decision makers are familiar. Consequently, the experts should find it easier to communicate their preference weightings for benefits such as GHG emissions and barrels of oil saved. The problem with this

rationale is that the benefits of concern within the energy sector are not easily monetized. A barrel of oil is worth some dollar value today, but that value is much more difficult to predict fifty years into the future (the timespan of MADA model runs). Additionally, that market value does not contain the added benefits of increased national security due to less dependence on foreign oil, as well as ancillary benefits such as a domestic economy not subject to large swings in energy prices. An even more challenging problem is assigning a monetary value to greenhouse gas emissions reductions, considering that today's market currently assigns a value of zero dollars to carbon. Sources vary widely on what the social cost of carbon should be. In a review of the literature, (Tol, 2005) reports a 5 to 95 percentile range of 10 to 350 dollars per ton of carbon. Thus, this conversion process adds a large amount of uncertainty into the results.

Ross and O'Neill state:

*“In order to turn value into a dollar figure, one must have a consistent “measure” of both value and dollars. Possible violations of this consistency include: the existence of multiple perceivers of value, with distinct perspectives (e.g., the problem of aggregating across individual preferences mentioned earlier), temporal considerations (e.g., the difference between achieving value today versus tomorrow), and constraints on types of dollars expended (e.g., the “colors of money” problem where budget allocations put constraints on how dollars can be spent up to certain limits). If a consistent measure for both dollars and value does not exist, then a consistent transformation from one to the other is not possible.” (Ross, O'Neill, et al. 2010)*

The specific application of MADA in question entails a violation of all three factors mentioned.

After budget portfolio benefits are converted to dollars they are multiplied through by a weighting factor dependent on stakeholder preferences. The result is that the key output from the MADA model, the benefit metric  $B$ , exists in units of weighted-dollars. In contrast of its original intent, this unit is confusing to decision makers and presents a nontransparent result.

The question of what is the best representation of value for the DOE (e.g., dollars, utils) really comes down to what assumptions the decision makers are comfortable with making. The assumptions required to be made in the case of evaluating the impact of energy technologies are quit large and do not lend themselves well to a monetized value unit. An alternative is the use of Multi-Attribute Utility Theory (MAUT), which is commonly used in MATE applications. Multi-Attribute Utility Theory is described in more detail in the literature review, Chapter 2. While utility is not necessarily a “better” metric than weighted-dollars, it is often chosen because the decision maker is not comfortable with making some of the assumptions (i.e., the curve of the social cost of carbon for the next fifty years) required by other valuation methods. As is concurred by (Ross, O’Neill, et al. 2010), “The motivation for using MAUT in the valuation of engineering systems is due to it being the more appropriate alternative to value functions, for the ranking of alternatives based on multiple sources of non-monetary value under uncertainty. This motivation is further substantiated given the inherent inability for stakeholders to assign a monetary value to an outcome (or set of outcomes) in the first place.”

### **3.3.5. Structural Issues - Treatment of MARKAL Runs as Independent**

The MADA model treats the benefits associated with each MARKAL run as if they are independent, and can therefore be independently recombined in order to estimate the benefits of a portfolio that was not calculated by MARKAL. This assumption of independence, which underlies the entire MADA model structure, is a systematic error that produces misleading results to the decision maker. Because of its complexity, the impacts of this incorrect assumption of independence are best demonstrated through a simplistic example (below).

#### **Simplified Demonstrative Example:**

Problem: Calculate ABC Software's weighted benefits metric,  $B$ , for the following portfolio:

Wind – high level of funding, Nuclear – high level of funding, all other technologies – zero funding. No carbon cap assumed in MARKAL.

ABC Software's General Steps:

1. Reference the MARKAL run with Wind at high and everything else at zero.
2. Calculate  $B$ , benefits, associated with Wind at high.
3. Reference the MARKAL run with Nuclear at high and everything else at zero.
4. Calculate  $B$ , benefits, associated with Nuclear at high.
5. ADD  $B$  associated with Wind at high to  $B$  associated with Nuclear at high (as if the two are independent).
6. Result: the new portfolio's  $B$  metric

The benefits associated with Wind and the benefits associated with Nuclear are not independent and thus cannot be added together. Future energy demand is a fixed curve (excluding efficiency impacts). Wind generation and Nuclear generation compete to fill this demand in the market place. Therefore the benefits of Wind are much less if Nuclear is simultaneously funded at high levels, and vice-versa. When these two MARKAL runs are completed separately and then added together, the result is a larger benefit than would occur in reality, and in some cases, than what is realistically possible. This problem is compounded if MARKAL is run with a carbon cap.

### **3.3.6. Structural Issues - Misleading Handling of Barriers**

Barriers, in this context, constitute - market, financial, regulatory, and technological impediments to commercialization faced by a specified technology. These barriers are in addition to market adoption constraints imposed by technology cost curves. For example, a barrier to massive renewables deployment is the requirement for some combination of enhanced electric transmission capacity, storage, back-up capacity, and demand control.

An unanticipated issue arose when it was identified that MARKAL does not explicitly model all of the major barriers to technology deployment and adoption existing within the energy sector today. Some of the barriers are incorporated into the MARKAL framework and others are not. Because of this MARKAL will underestimate benefits of DOE funding that reduce barriers and overestimate benefits of funding that invest in technologies that retain deployment barriers.

The majority of the DOE's Program Offices have tandem goals: to reduce the cost of their specified technologies as well as to reduce critical barriers to deployment and adoption. Thus the DOE's full efforts are not accurately measured by impacts on technology cost curves alone. Initiatives such as the Loan Guarantee Program cannot be measured by their impact on lowering technology cost curves because the Program focuses instead on the reduction of financial barriers. This presents a complex challenge when attempting to enumerate and forecast the impact of DOE funding adjustments.

An approach to address this challenge was developed after-the-fact and incorporated into the core MADA calculations. The process consists of the identification of the magnitude of barriers through an expert elicitation. Next, the impact DOE funding has on reducing those barriers is estimated through the same expert elicitation. The resulting total impact on reducing "barriers" associated with a single investment in a technology is termed a benefit and added into the core benefits,  $B$ , function. Below is a discussion of the problems associated with this process.

## Uncertainty within the Elicitation Process

As with any expert elicitation process, large uncertainties result due to disagreement among experts as well individual expert uncertainty with respect their own estimates. The figures below display excerpts of the questionnaires given to experts in order to obtain estimates on four elements: the type of barriers effecting deployment, the magnitude of the barriers, the potential barrier reduction given X dollars of funding, and the timing of the barrier reduction. These questions are extremely subjective and difficult to estimate even for an “expert”, but are treated in the model with the same validity as other benefits that are more rigorously calculated in MARKAL. Obtaining more precise estimates would require a larger, expensive elicitation process.

### How significant are the non-cost deployment barriers facing this technology?

*This scale shows the magnitude of barriers to deployment faced by a specified technology, absent any DOE funding. These barriers are in addition to cost effects and any explicit deployment constraints in MARKAL.*

1: Scoring Scale for Barrier Magnitude		
Score	Definition	Scaling value
0	This technology experiences no barriers to deployment (other than costs and constraints simulated in MARKAL).	0
1	This technology experiences relatively insignificant barriers to deployment. The technology's ability to capture market share is retarded by less than 5% due to existing barriers.	3
2	This technology experiences moderate barriers to deployment. The technology's ability to capture market share is retarded by 5% to 25% due to existing barriers.	15
3	This technology experiences strong barriers to deployment. The technology's ability to capture market share is retarded by 26% to 50% due to existing barriers.	38
4	This technology experiences very strong barriers to deployment. The technology's ability to capture market share is retarded by 51% to 90% due to existing barriers.	75
5	This technology experiences overwhelming barriers to deployment. The technology's ability to capture market share is retarded by more than 90% due to existing barriers.	95

Indicate those barriers that apply for this technology and rank them (e.g., 1, 2, ...).

For which factors will the funding alternative produce a significant impact?	Rank
<b>Market barriers</b>	
Availability of prerequisite & complementary technologies	
Institutional inertia/resistance	
Availability of capable labor	
Demand behavior (free riders, buyer's risk benefits perception, consumer rebound effects, transaction costs, incomplete and imperfect information, misplaced incentives)	
Infrastructure (access, capital stock turnover)	
<b>Financial barriers</b>	
Misplaced incentives	
High upfront capital costs (related to credit strength, access to capital, loans & loan guarantees, cost recovery)	
Liability	
<b>Regulatory/policy/legal</b>	
Liability	
International cooperation	
Tech demos (international, co-funding)	
Labeling and information dissemination	
Uncertain or counterproductive policies (cost recovery, taxes/tax incentives & subsidies, land use priorities, key decision makers, procurement policies, codes & standards, property rights)	
Mandates	
Siting/permitting	
Resource availability	
Competing priorities/models	
Health, safety & environment	
Intellectual Property	
<b>Other (describe below)</b>	

Description (if you checked "other").

How effective will the program's activities be at addressing the technology's deployment barriers, under the specified funding level?

2: Scoring Scale for <u>Impact</u> on Barriers		
Score	Definition	Scaling value
5	The funding level will nearly eliminate (more than 90%) the most critical (non-cost) deployment barriers	0.95
4	The funding level will produce a major (roughly 51-90%) reduction to the most critical (non-cost) deployment barriers	0.7
3	The funding level will produce a large (roughly 21-50%) reduction to the most critical (non cost) deployment barriers	0.38
2	The funding level will produce a significant (roughly 6-20%) reduction to the most critical (non cost) deployment barriers	0.13
1	The funding level will produce a small (1- 5%) reduction to the most critical (non cost) deployment barriers	0.03
0	The funding level will have little or no effect on deployment barriers	0

How quickly will the program's activities reduce the technology's deployment barriers, under the specified funding level?

3: Scoring Scale for <u>Time</u> of Barrier Reduction		
Score	Definition	Scaling value
5	Within a year	Function of the date the barrier is reduced and the specified discount rate
4	1 – 5 years	
3	6 – 10 years	
2	11 – 20 years	
1	More than 20 years	

Consequently, the functional form used to calculate the benefit of reducing barriers requires expert estimation of multiple point estimates that involve great uncertainty. This methodology presents a seemingly arbitrary result to the decision maker.

### **Misleading Incorporation of Barriers into Benefit Function**

At a very basic level it is known that barriers stunt the speed of adoption, reduce market size, and thus reduce the overall benefits associated with each technology,  $B$ . For example, in the left panel of the graphic below, offshore wind market share might increase smoothly over time. In the right panel, the existence of a market barrier such as lack of storage technologies, significantly delays adoption of the technology.



**Figure 6. Stylized Example of the Effect of Market Barrier on Technology Adoption.**

The treatment of barriers within the MADA model, however, does not mimic this behavior and presents an unintuitive result to the decision maker. It tacks on a negative benefit associated with the impact of a barrier and a positive benefit associated with the reduction of that barrier. A more appropriate representation of the impact of barriers to deployment would be to directly

reduce the overall benefits associated with greenhouse gas reductions, barrels of oil saved, and reduction in the totally energy system.

$$B = B_{\text{energycost}} + B_{\text{GHG}} + B_{\text{oil}} + B_{\text{BarReduct}} + B_{\text{BarImped}}$$

**Figure 7. ABC Software Benefits Function,  $B$ .**

### **Incorrect Treatment of Barrier Reduction as Independent**

Because market dynamics are complex, it is incorrect to assume that a reduction in barrier magnitude will result in a proportional increase in benefits,  $B$ . Barriers, once removed, may be trumped by additional barriers. For example, recent advances in hydraulic fractionation have drastically reduced the supply limitation of natural gas. However, increased regulatory oversight could impose a more significant barrier, which threatens to eliminate the gains made by hydraulic fractionation. Additionally, these technologies do not operate in a monopolistic market. If, for example, all non-cost barriers to the deployment of a specific technology were removed, but associated deployment costs are not competitive, the technology will not be adopted within the market place. However, within the MADA framework the benefits associated with this reduction in barriers will inaccurately be added into the benefits metric. These market dynamics are extremely important and have a large impact on realizable benefits associated with the DOE's investments. Contrastingly, if modeled directly into MARKAL, the resulting impact of barrier removal would be more transparent to decision makers. The MADA model, however, attempts to measure and incorporate the impacts of these barriers outside of the MARKAL.

### 3.3.7. Arbitrary “Dollarization” method

The MADA model’s method for monetizing benefits through a “Dollarization” process adds unnecessary complexity and significant levels of uncertainty. This uncertainty has a multiplicative effect across the benefit function,  $B$ . The method attempts to generate a factor that converts non-monetary benefits, such as mega tons of CO<sub>2</sub> and units of barrier reduction, into units of weighted dollars. The factor performs two functions: converting the non-monetary benefits to dollars and weighting the expert’s value of that benefit. If it is determined that benefits are best measured in monetary terms, multi-attribute based models will typically convert benefits to dollars using some sort of market equivalent, and then hold a separate expert elicitation of the benefit weightings. In contrast, the MADA approach combines the two queries, increasing the cognitive requirements placed on the experts. This complex process is difficult to decode, and thus significantly reduces the end transparency of model results.

Experts were asked difficult to conceptualize questions such as:

*“Which would you value more, a one time savings in 2017 of \$500 or a onetime CO2 emissions reduction of 10 mtCO2 in 2017, or eliminating in year 2017 nearly all the barriers to deployment for a technology that is predicted by MARKAL to capture and maintain a significant (10%) market share but that is known to currently face very strong deployment barriers (50% retardation of potential market share) that are not captured by MARKAL. And how much more do you value those choices over each other?”*

Additionally, these questions represent a single scenario, and as a result, are likely to not capture the richness of the expert's preferences.

### **3.4. Summary and Discussion of Key Learnings**

The creation of a portfolio assessment tool of this complexity was an enormous undertaking, and perhaps more demanding than initially realized. The combined need to examine investment questions at a global scale yet through detailed technology, market, and economic analyses presented an unprecedented challenge. As is natural with first-of-a-kind projects – certain shortfalls with the initial iteration became apparent. The top six shortfalls having the largest impact on decision tool transparency and accuracy were identified and discussed in this chapter.

The associated successes and failures of this extensive effort led to a rich learning process. As will be discussed in Chapter 4, those learnings form the basis of a second generation decision tool. In this way, the MADA modeling effort moved the DOE in a critical and positive direction. The attempt significantly increased the expected level of sophistication and rigor of the DOE's budget evaluation process. Additionally, it provided core PA&E analysts with greater insight into energy market dynamics and complexities as well as a deep working knowledge of key climate models.

A preliminary discussion of lessons learned is provided in this section. Many of these learnings can be generalized and applied to the development of any complex decision tool. A preliminary lesson learned was the importance of conducting an extensive *internal* literature review of

potential methodological approaches. When this initial step is conducted by a consulting firm, as was the case in the MADA effort, the consulting firm has the tendency to steer solutions towards their previous experience, rather than fully exploring the academic landscape for solutions tailored to the client.

The proposal process involving the selection of a firm to develop a complex modeling tool can be overwhelming with multiple back and forth meetings. The customer's ability to look for and identify 'red flag' commitments, which stand-out as not practically feasible, is important in assessing proposal validity. A post contract review of the original MADA proposal identified a few of these red-flags, such as a promised but realistically unachievable capability to "assess the future impacts of early-stage R&D". In this situation, enlisting a trusted third party, such as an internal DOE climate modeling expert, could aid in evaluating proposal reasonableness.

Additionally, it was learned that not only is it important to perform a holistic needs analysis, which XYZ Consulting firm delivered in their original proposal, but it is also equally important to translate those needs into specific model requirements – to which the developer is held responsible for delivering. Typically, over the course of a complex project, unexpected issues arise and resulting attempts to scale back promised capabilities are made. When this occurs, maintaining and measuring to a clearly defined requirements list is essential.

It was observed that conducting an early detailed review of the proposed model architecture might have assisted in preventing some surprises. This could have produced beneficial actions such as: 1) Performing a rigorous assessment of limiting factors and capabilities of core model

components prior to committing to deliverables; 2) Requiring a detailed sketch of the proposed decision tool's technical architecture prior to committing to development project; 3) Requiring a roadmap of all core calculations and major assumptions; and 4) Building a scaled-down model to test key assumptions, calculations, and applicability of data to decision maker needs.

As a project progresses, organizations tend to feel locked in to seeing the project through with its current direction. However, in the case when an issue that is unable to be resolved arises and drastically hinders model accuracy, such as the realization that benefits associated with each MARKAL run cannot be treated as independent, it is better to abandon the project rather than put more resources into a poor product.

A final lesson learned involved the management and coordination of such a complex development project. Four separate organizations were responsible for various aspects of the MADA model. This was a major challenge for model integration. Accountability for fixing specific issues was sometimes a question. The project may have ran smoother with a contract structure giving a single, main consulting firm total responsibility over key deliverables.

## **Chapter 4: Evolving an Enhanced Approach**

Upon review of the advantages and shortfalls of the initial MADA modeling effort, a consensus emerged among PA&E leadership that the initial concept of coupling multi-attribute decision analysis to an integrated assessment model still held significant promise. Additionally, PA&E leadership came to the conclusion that the shortcomings of the initial MADA model could be learned from to develop an improved, second generation model. As added motivation for preserving the current conceptual direction, the implementation of a multi-attribute-based portfolio assessment tool, the National Oceanic and Atmospheric Administration (NOAA) had recently developed a model based on a similar approach and found it useful to decision makers (Moynihan et al., 2009).

This second generation model incorporated a simplified design that could be quickly developed and tested for its utility to decision makers. To allow for quick development and test, the technical architecture was significantly down-scaled by replacing ABC Software with simple Excel spreadsheets. Several conceptual and theoretical advancements discussed in this chapter were undertaken which made this scaled-down approach feasible while simultaneously improving the accuracy and transparency of modeled results. The proposed quick turn-around for the second generation model was seen as a low-risk proposition for PA&E. The organization had just spent significant time and resources developing the MADA model and was questioning the suitability of a multi-attribute approach.

The second generation modeling concept was formulated and developed with PA&E analysts as part of an independent study conducted by the thesis author. The model was referred to

internally at the DOE as the Tradespace Evaluation model. Its theoretical basis in the literature, technical architecture, results and associated limitations are discussed below.

#### **4.1. The Move Toward a Multi-Attribute *Tradespace Exploration* Based Model**

As was identified through an analysis of the literature, the core concepts of Multi-Attribute Tradespace Exploration (MATE), developed at MIT and currently evolved by MIT's Systems Engineering Advancement Research Initiative, provide a good fit to the problems the DOE needs to investigate and the functionality the DOE requires from a decision tool (i.e., quick assessment of trade-offs and an understanding of multi-stakeholder perspectives). Therefore core MATE concepts were selected and utilized for the design of the DOE's second generation, Tradespace Evaluation model.

##### **4.1.1. The Selected Use of Multi-Attribute Utility**

Upon review of the characteristics of the DOE's portfolio evaluation challenge, it was identified in Section 3.3.3 that the use of multi-attribute utility, rather than dollarized benefits, provided an improved metric of not easily monetizeable benefits, such as those at the DOE. The monetary value of benefits such as reduced greenhouse gas emissions strongly varies within the scientific literature (ToI, 2005). Additionally it was identified that multi-attribute utility theory provided a particularly good fit when dealing with diverse stakeholders that perceive and value benefits resulting from the DOE's investments very differently. As an example, a conservative leaning congressional stakeholder may place a much larger value on reduced barrels of oil consumed

than the current market price of oil, because of a perceived additional benefit relating to an increase in national security. As a consequence, the use of multi-attribute utility as a metric was incorporated into the new, adapted model.

#### **4.1.2. The Selected Use of Tradespace Exploration**

The DOE's portfolio assessment process demands the quick assessment and visualization of cost and benefit trade-offs amongst major investments. Often senior, congressionally-appointed leadership involved in the decision-making process require speedy results to trade-off questions. As a consequence, the value of a potential investment model is linked to how quickly trade-off questions can be answered and visualized in real-time. As was the case with the MADA model, no malleable tradespace existed. In order to visualize trade-offs a day or more was required for analysts to adjust and re-run the model.

Taking this problem into account, it was identified that the concept of Tradespace Exploration, discussed in Chapter 2, could provide significant insight for DOE decision makers, where preferences for generation and transportation technologies are highly politicized and polarized amongst the major stakeholders. Additionally, a significant benefit of Tradespace Exploration is that compromise solutions can be found, enabling negotiation between key stakeholders. This ability to identify compromise solutions proves hugely beneficial in the context of the DOE's budget process where heavy negotiation occurs.

### **4.1.3. Conceptual Basis on Multi-Attribute Tradespace Exploration**

As discussed above, multi-attribute utility theory and tradespace exploration both posed significant advantages within the context of the DOE's decision making process. These two concepts make up the core of Multi-Attribute Tradespace Exploration (MATE), see Chapter 2 for literature review. Therefore the academic literature detailing theoretical and methodological advancements surrounding MATE, was acutely relevant to this study and heavily relied upon.

## **4.2. Refining Model Scope**

A key lesson from the MADA modeling effort was that it is necessary to fully evaluate and understand the components of the modeling system, their associated limitations, and capabilities. This assessment should be done prior to committing to deliverables, so that the initial model proposal does not over-promise and decision makers do not expect more than what is practically possible.

The number and scope of questions the MADA model initially proposed to answer was larger than practically feasible given the granularity of data available from MARKAL, a key limitation. Taking this into account, the breadth of questions that the second generation model proposed to answer was reduced. As has been noted, MARKAL does not produce noticeable differences between portfolios when small funding level adjustments (5-25% depending on the technology) are made to the DOE's programs. However, MARKAL does produce clear shifts in technology deployment with larger funding blocks, as well as with policy adjustments. Therefore the proposal for the new Tradespace Evaluation model limited the scope of deliverables to enabling

higher-level strategic decision making and broader investment trade-offs, rather than promising the capability to evaluate small funding adjustments.

While the number of questions was scoped down, new capabilities introduced by tradespace analysis enabled the addition of questions such as, how to identify compromise solutions between stakeholders. In contrast, the initial MADA model did not yet have the capability to evaluate perspectives from multiple stakeholders. The Tradespace Evaluation model was built to initially incorporate two major stakeholders—one representing a historically conservative viewpoint and the other a more liberal viewpoint—with the ability to easily expand the model. Using an easy user interface, two separate tradespace plots were created for these hypothetical stakeholders. This setup allows for quick selection of multiple portfolios, evaluation of respective utilities, and identification of compromise solutions.

### **4.3. Addressing Key MADA Shortcomings**

As was discussed in Chapter 3, the in depth review of the MADA model identified three conceptual and three structural issues. The issues surrounding the conceptual framing of the model were the granularity of MARKAL data, the optimization to a single portfolio versus the creation of a manipulatable tradespace, and the monetization of benefits to measure value versus the use of utility. These were addressed within the Tradespace model through three tactics. First, the reframing of the model scope and promised deliverables (Section 4.2) ensured that the Tradespace model only delivered results that were within the limitations of the MARKAL data. Second, the application of multi-attribute utility theory employed a measurement of value, more in line with the characteristics of the DOE's landscape. Last, the model's main output is a user

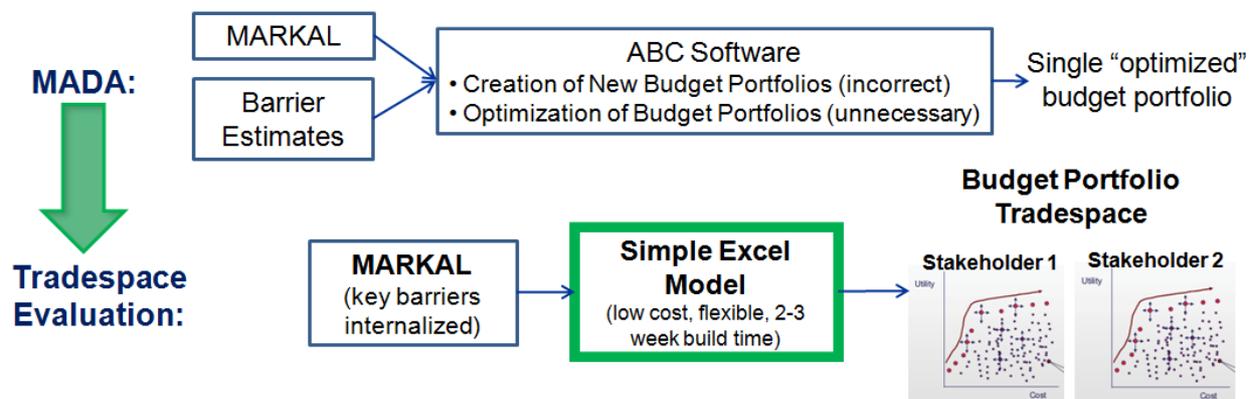
interface with two manipulatable tradespaces: one associated with a more environmentally conscious stakeholder and one associated with a more energy security conscious stakeholder. As a result, the misleading implication that a single optimal portfolio exists was removed, and a platform was provided to identify compromise portfolios to use as inputs for negotiation. Additionally, the new Tradespace model did not have to work through a computationally intensive optimization algorithm, which enabled its simpler and more flexible design in Excel. The model's ability to instantly calculate and display trade-off results was also enabled by this lack of a computation-heavy core.

Three structural problems which were identified during the MADA review process were the treatment of MARKAL runs as independent within ABC Software, the handling of "barriers", and the process for dollarizing benefits. In order to address MADA's inappropriate treatment of MARKAL runs as independent, the proposed Tradespace model eliminates ABC Software and instead feeds MARKAL data directly into the Excel model. Each MARKAL run is treated as a complete unit which cannot be spliced and recombined with other runs. As will be discussed in the limitations Section 4.6, this reduces the number of portfolios that can be analyzed and requires a new MARKAL run for each portfolio. However, the results from the Tradespace model no longer contain this key structural error.

The MADA model's approach to handling barriers was complex, containing multiple point estimates with large associated uncertainty. Consequently, an unintuitive result was presented to decision makers. To simplify, it was recommended that key barriers to technology adoption and deployment be modeled directly into MARKAL. Doing so allows their impact to be more accurately assessed. The downside to this approach is that the modeling of barriers within

MARKAL takes time and computational resources. However, PA&E determined that the effort was worth the increased accuracy provided. For increased clarity, only the barriers with the largest expected impact were modeled directly into MARKAL. The Tradespace Evaluation model clearly lists the remaining barriers not modeled directly into MARKAL on its user interface, improving transparency and trust of model results.

Finally, MADA’s complex dollarization process, which in one stroke converts benefits to dollars and weights them, was replaced with a multi-attribute utility metric. To improve transparency, attribute weightings are displayed directly on the user interface. A visual summary of the transformation of the original MADA approach to the Tradespace evaluation can be seen below.



**Figure 8. MADA Model Structure versus Tradespace Evaluation Model Structure**

#### **4.4. Technical Architecture and User Interface - Tradespace Evaluation Model**

The MADA model was difficult for PA&E to rapidly manipulate without significant time and assistance from ABC Software Company’s consulting team. This type of rigid model structure

did not mesh well with the DOE's frequent need for quick turn-around and high visibility analysis, the specifics of which regularly change due to political whims. Learning from this, the Tradespace model's structure was based in Excel in order to allow for quick and relatively easy manipulation, as well as future expansion.

Early on in the MADA design process several integrated assessment climate, energy and economic models were evaluated in conjunction with MARKAL. It was determined that the basic functions of these models were the same, but MARKAL had an advantage because of its ability to assess investment impacts in shorter five year timespans, which matched more closely with the DOE's budget assessment periods. Also, significant resources had already gone into running multiple budget portfolios in MARKAL, so it was kept as the main input for the Tradespace model. The benefits (attributes) associated with each portfolio remained the same: reduced greenhouse gas emissions, barrels of oil saved, and total energy system cost savings.

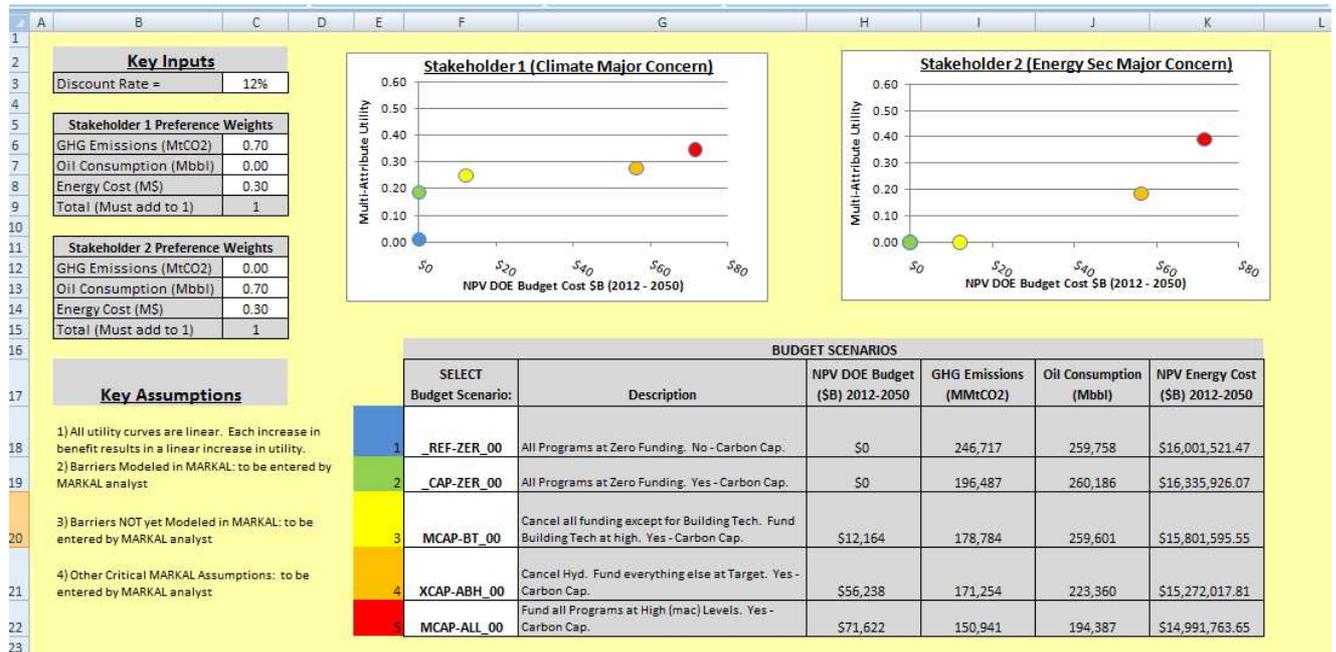
The internal Excel structure was designed to be as simple as possible, with three core spreadsheets: an input sheet that contains model runs from MARKAL (Figure 9), a utility calculation sheet (Figure 10), and a user interface sheet which displays outputs (Figure 11). These sheets were linked together through the appropriate equations and lookup functions. To avoid the previous MADA model's challenging aspect of time consuming data entry of MARKAL results, the input sheet was specifically designed for easy drop-in of MARKAL output.

	A	B	C	D	E	F	G	H	I	J	K	L
1	<b>Input Sheet - MARKAL Output Data</b>											
2	Discount Rate =	12%										
4	Portfolio Identifier:	_REF-ZER_00	Portfolio Description: All Programs at Zero Funding. No - Carbon Cap.									
5		Total	2010	2015	2020	2025	2030	2035	2040	2045	2050	
6	GHG Emissions (MMtCO2)	246,717	5599.756	5748.222	5859.203	6055.202	6156.724	6399.531	6605.673	6961.592	7405.516	
7	Oil Consumption (Mbbbl)	259,758	6367.056	6709.773	6696.713	6560.722	6597.779	6623.932	6579.688	6754.292	6948.462	
8	Energy Cost (M\$)	94,917,476	1332443	1755511	1987974	2203818	2397661	2593584	2804067	3026663	3274420	
9	NPV Energy Cost:	\$16,001,521.47										
10	Total DOE Investment (M\$)	0										
11	NPV of DOE Invest	\$0.00										
13	Portfolio Identifier:	_CAP-ZER_00	Portfolio Description: All Programs at Zero Funding. Yes - Carbon Cap.									
14		Total	2010	2015	2020	2025	2030	2035	2040	2045	2050	
15	GHG Emissions (MMtCO2)	196,487	5609.448	5568.767	5438.742	5390.966	5096.46	4968.649	4666.184	4594.64	4082.618	
16	Oil Consumption (Mbbbl)	260,186	6365.467	6707.377	6681.176	6545.014	6585.242	6653.985	6642.865	6828.798	6888.754	
17	Energy Cost (M\$)	100,118,733	1332714	1774538	2015839	2249516	2483427	2710836	2989575	3302982	3746938	
18	NPV Energy Cost:	\$16,335,926.07										
19	Total DOE Investment (M\$)	0										
20	NPV of DOE Invest	\$0.00										
22	Portfolio Identifier:	MCAP-BT_00	Portfolio Description: Cancel all funding except for Building Tech. Fund Building Tech at high. Yes									
23		Total	2010	2015	2020	2025	2030	2035	2040	2045	2050	
24	GHG Emissions (MMtCO2)	178,784	5609.45	5259.522	5056.343	4839.299	4486.604	4366.382	4131.331	4120.673	3934.448	
25	Oil Consumption (Mbbbl)	259,601	6370.035	6695.017	6658.934	6515.719	6565.532	6638.438	6625.295	6786.476	6956.438	
26	Energy Cost (M\$)	94,393,086	1333155	1741252	1945664	2156917	2371401	2544194	2774901	3057064	3394862	
27	NPV Energy Cost:	\$15,801,595.55										
28	Total DOE Investment (M\$)	57622.5										
29	NPV of DOE Invest	\$12,164.30										
31	Portfolio Identifier:	ZCAP-WN_00	Portfolio Description: All but WN, H2 and FCV MAC scenarios w/ CO2 Limit									
32		Total	2010	2015	2020	2025	2030	2035	2040	2045	2050	
33	GHG Emissions (MMtCO2)	160161.0516	5609.417	5124.09	4728.007	4420.266	3860.5	3591.251	3521.157	3552.59	3488.421	
34	Oil Consumption (Mbbbl)	219116.1333	6318.092	6387.929	6047.409	5913.337	5622.288	5328.863	5107.196	5099.988	5092.319	
35	Energy Cost (M\$)	85191843.25	1328382	1695713	1867418	2013405	2149632	2298226	2454211	2619021	2816265	

Figure 9. Snapshot of Input Sheet

	A	B	C	D	E	F	G	H	AF	AG	AH	AI	AJ	AK	AL	
1	<b>Stakeholder 1 Climate Major Concern</b>								<b>Stakeholder 1 = Energy Sec Major Concern</b>							
	Sum of Weights = 1								Sum of Weights = 1							
2	ATTRIBUTE:	GHG Emissions	Set Range:	Min (Happiest) =	50,000	Max (Unhappiest) =	250,000		ATTRIBUTE:	GHG Emissions	Set Range:	Min =	50,000	Max =	300,000	
3	UNITS:	MtCO2	Set Curve:	Linear (all curves initially set at linear)												
4	DESCRIPTION:		Stakeholder Weight (0-1) =	0.70					DESCRIPTION:		Stakeholder Weight (0-1) =	0.00				
7	ATTRIBUTE:	Oil Consumption	Set Range:	Min =	150,000	Max =	300,000		ATTRIBUTE:	Oil Consumption	Set Range:	Min =	150,000	Max =	250,000	
8	UNITS:	Mbbbl	Set Curve:	Linear												
9	DESCRIPTION:		Stakeholder Weight (0-1) =	0.10					DESCRIPTION:		Stakeholder Weight (0-1) =	0.70				
12	ATTRIBUTE:	Energy Cost	Set Range:	Min =	9,000	Max =	13,000		ATTRIBUTE:	Energy Cost	Set Range:	Min =	9,000	Max =	13,000	
13	UNITS:	\$B	Set Curve:	Linear												
14	DESCRIPTION:		Stakeholder Weight (0-1) =	0.20					DESCRIPTION:		Stakeholder Weight (0-1) =	0.30				

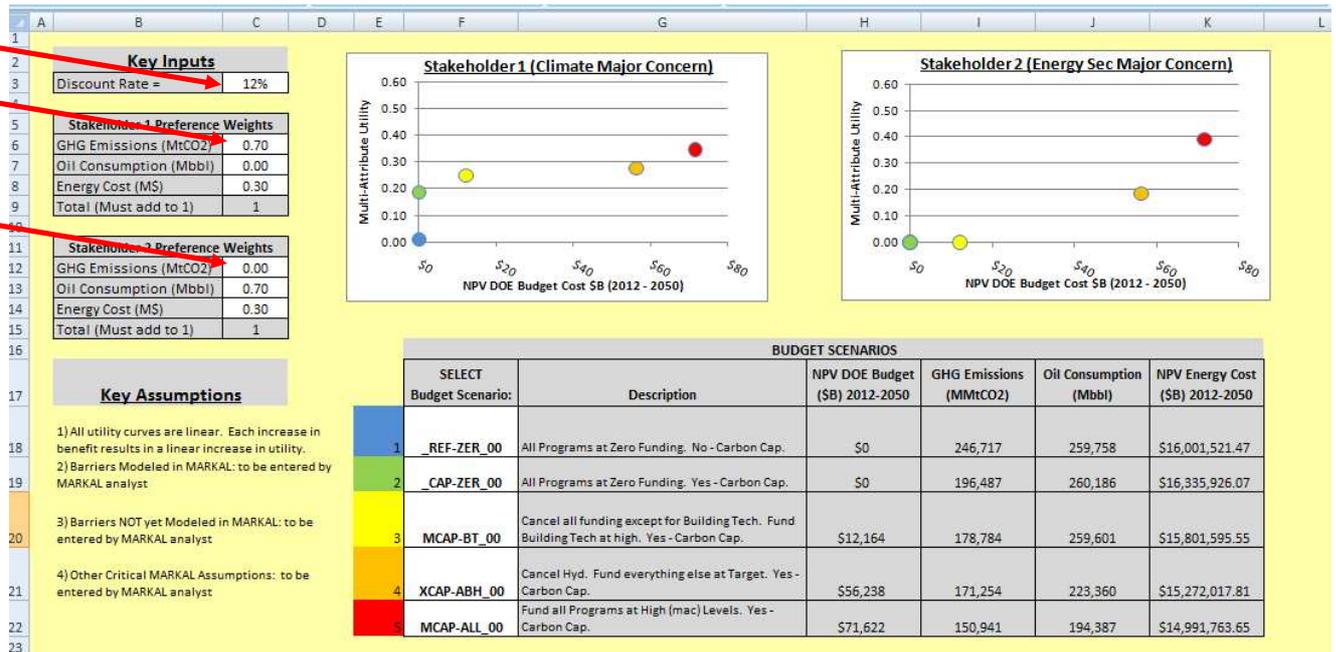
Figure 10. Snapshot of Utility Calculation Sheet



**Figure 11. Snapshot of Output Sheet with Tradespace Plots**

A significant difficulty with the MADA model was that decision makers did not trust its results. This was mainly due to the non-transparency and complexity of the model's internal calculations, which resulted from a combination of a complicated dollarization and benefits weighting scheme, barriers calculations with significant uncertainty, and a complex search and optimization algorithm. Additionally, the MADA model results were displayed in such a way that the major assumptions going into the model were difficult for decision makers to recognize. In the context of the DOE's budget, where decision makers are making impactful investments with taxpayer funds, the stakes are high. Thus, analytical transparency and accuracy are of critical importance. Understandably, decision makers want to fully comprehend and trust the information that is feeding their final investment decisions.

Based on this guiding principle, several technical decisions were made to keep the internal calculations of the Tradespace model as simple and clear as possible while still providing the needed value. Utility curves were initially set to be linear but with the ability to easily switch to more complex curves in the future. Within the Tradespace model, each increase in benefit results in a linear increase in utility. Preference weightings, which had been buried within the MADA model and were difficult to decipher due to the “dollarization” approach, were brought forward onto the user interface of the Tradespace model. The weightings were then built-in as inputs that could be instantly altered in order to assess their direct impacts on the tradespace. The determination of the appropriate discount rate is often contentious, so it was included as an input that could be changed to assess the results. Finally, in order to foster transparency, all major assumptions concerning which barriers were modeled and not modeled into MARKAL are listed directly on the user interface. As shown in the below snapshot (Figure 12), the user interface consists of white cells where preference weightings and the discount rate are typed in by the user. When changed, the tradespace reflects the alterations instantly. For example, if the security conscious decision maker decides he/she cares less about barrels of oil saved and more about the total cost of the energy system, those preferences can be changed and the utility associated with the displayed portfolios will respond in real-time.



**Figure 12. Tradespace Evaluation Model User Interface – Adjustable Inputs**

At the time of the build of the Tradespace model, one hundred and twenty five portfolios, each with varying levels of investment for DOE programs, had been run through MARKAL. In order to limit the cognitive demand on decision makers, the user interface was designed to only display five portfolios at any one point in time. Although, through a drop down box (Figure 13), any one of the one hundred and twenty five could be automatically selected to display in the two tradespaces.

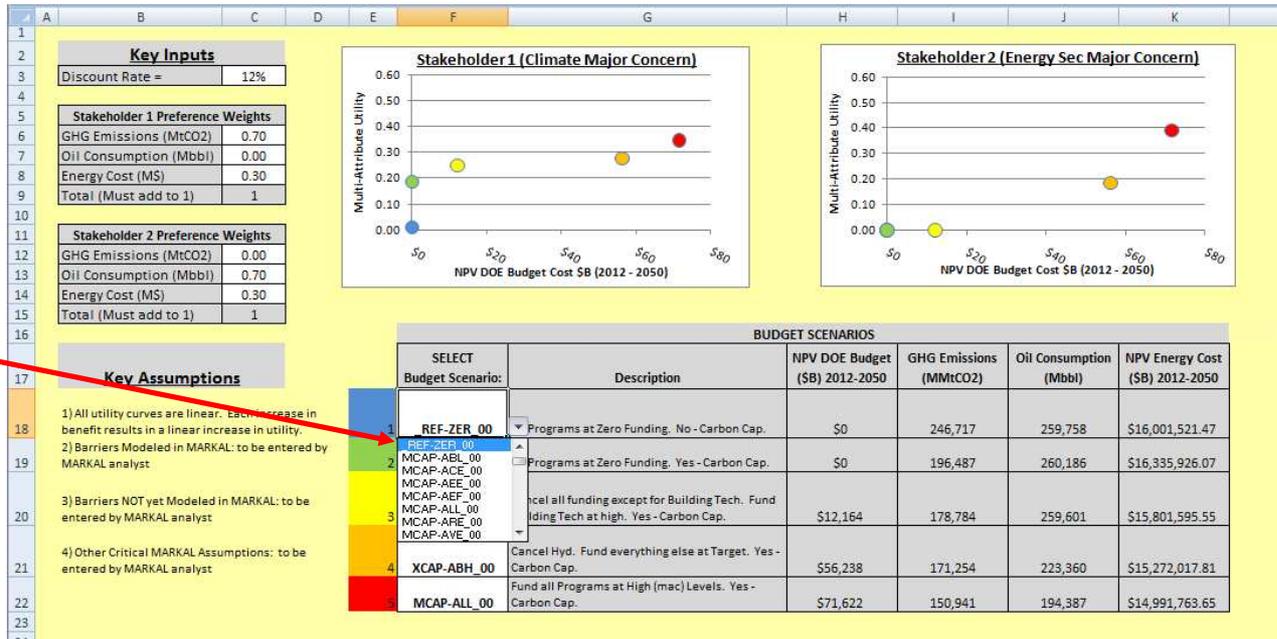
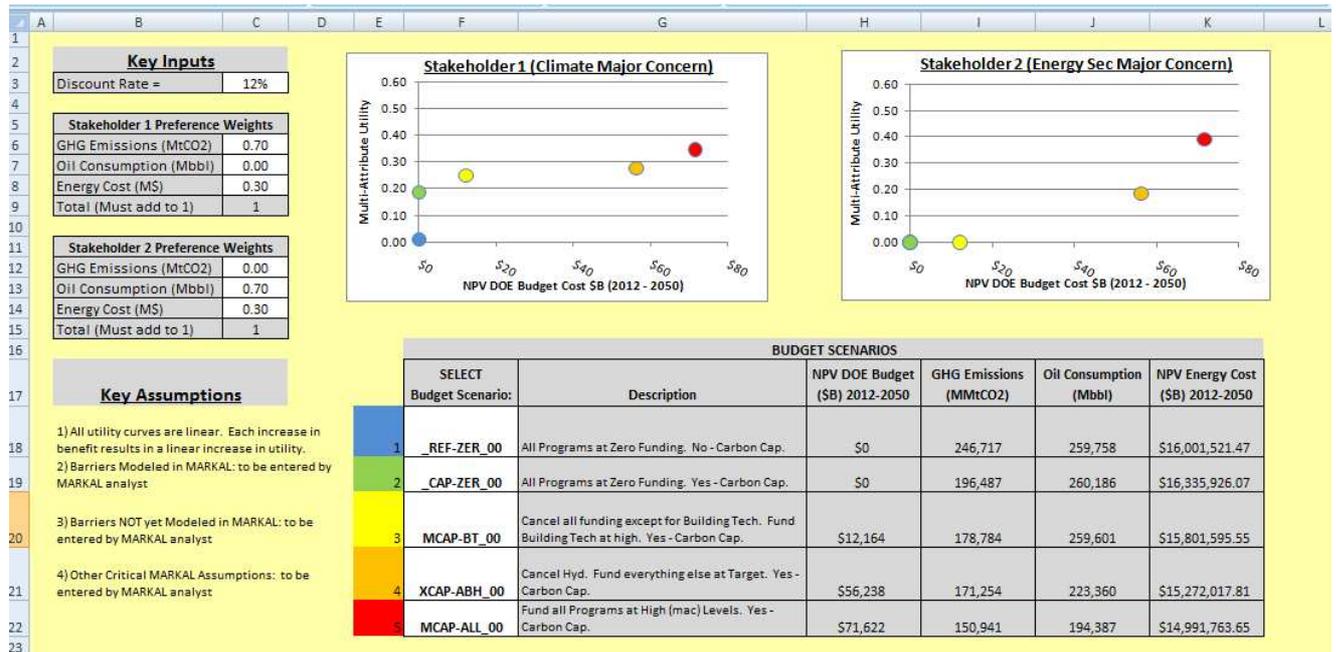


Figure 13. Tradespace Evaluation Model User Interface – Portfolio Drop-Down Box

#### 4.5. Tradespace Evaluation Model Walk Through

This section provides a summary of five selected portfolios in order to demonstrate how they might be analyzed within the Tradespace model. First the stakeholder preference weightings would be set by the analyst, decision maker, or stakeholders investigating the benefits and costs of each investment portfolio. For this example, the stakeholder more concerned with climate change weights GHG emissions savings at 70% and the total cost of the energy system at 30%. In contrast, the stakeholder more concerned about energy security weights barrels of oil saved at 70% and the total cost of the energy system at 30%. The discount rate is placed at 12% for this example to reflect the riskiness of investments in early stage energy technologies.

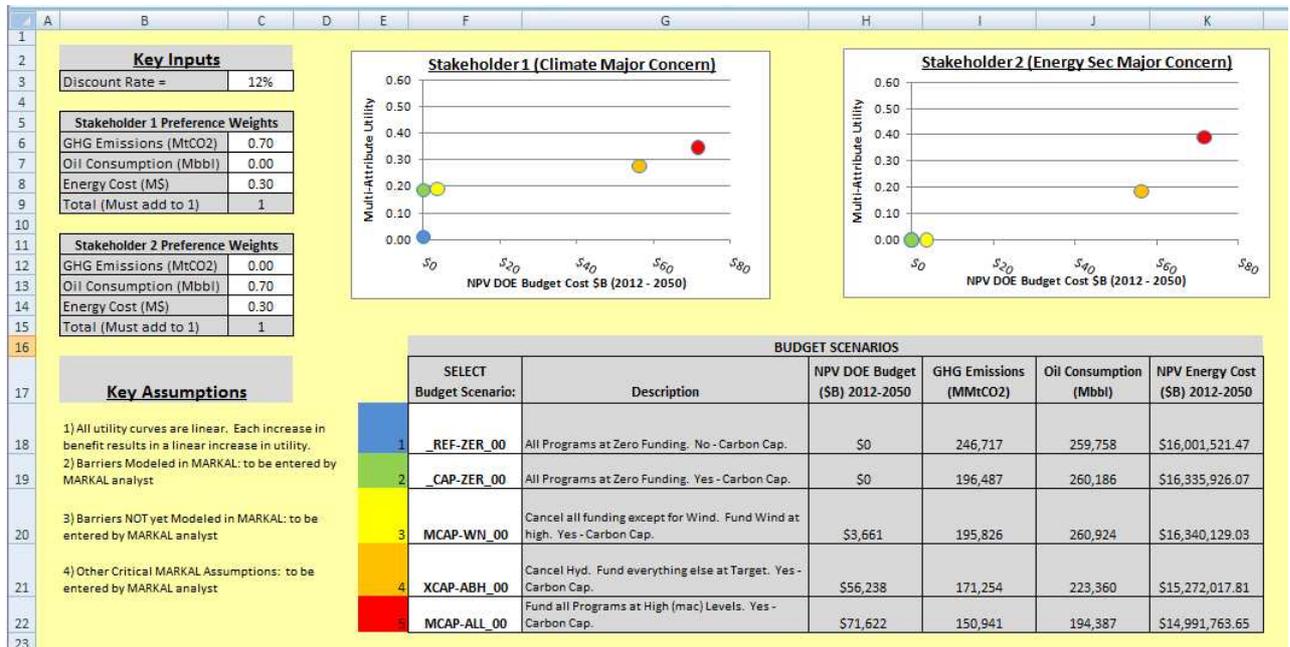


**Figure 14. Tradespace Evaluation User Interface – Displaying Five Portfolios for Analysis**

The first portfolio selected (blue) is the business as usual reference case under which zero DOE programs are funded. As is shown, it provides a near zero utility for both stakeholders as well as a zero cost to the DOE. The second portfolio (green) still funds all DOE programs at zero but institutes a cap on carbon emissions. This scenario provides much greater utility for stakeholder 1, who weights greenhouse gas reductions most heavily. However, it provides zero additional utility for stakeholder 2, who has weighted greenhouse gas emissions reductions at zero. The third portfolio (yellow) funds all DOE programs at zero, except for the Building Technologies program, which is funded at a high level. A jump in utility can be seen for stakeholder 1, but overall utility remains the same for stakeholder 2. This is because the Building Technologies program focuses on technologies that reduce energy use, the generation of which mainly comes from non-oil sources. Thus, the funding of the program does not significantly impact barrels of

oil consumed. The fourth portfolio (orange) funds all DOE programs at the current level of funding and continues that level of funding into the future. This adds significant overall cost to the DOE and provides greater utility to both stakeholders. The final portfolio (red) funds all DOE programs at a high level. This portfolio provides the greatest utility to both stakeholders but also at the greatest cost to the government.

Different combinations of portfolios can be selected and viewed in this tradespace format. As a further example of the type of strategic analysis that can be completed with this model, consider the snapshot of the user interface below (Figure 15). The third portfolio (yellow) that previously provided zero funding for all DOE programs except Building Technologies, which was funded at high, has now been swapped for a portfolio which provides zero funding for all DOE programs, but funds the Wind Program at high. Funding just the Wind Program at high provides much less utility than funding only the Buildings Program at a high level. This makes intuitive sense because wind technologies are currently very mature, with the cost of wind being competitive under the right environmental conditions. This is a success story partly attributed to the DOE's Wind Program. Because of its maturity, further R&D investments have a smaller impact on bringing down the cost curve. Investigations of this nature can help inform strategy, such as when to move R&D funding from a mature and successful technology to earlier stage technologies of greater need.



**Figure 15. Demonstration - Third Portfolio (yellow) Adjusted to Fund Wind Program at High Levels**

## 4.6. Remaining Limitations

### 4.6.1. Lack of Capability to Evaluate Small Funding Shifts

As was discussed previously (Section 4.2), the Tradespace model did not promise nor possess the analytical capability to assess the impacts of small shifts in DOE funding levels. This limitation, of both the MADA and Tradespace Evaluation models, is significant because a large portion analytical questions posed to PA&E staff involve the evaluation of 5-20 percent increases or decreases in funding levels. Upon the original build of MADA, the hope was to be able to address those questions with this type of model. Today's state-of-the-art integrated assessment models do not hold the capability to perform analysis at that level of detail. This limitation leaves a gap in the spectrum of PA&E's analytical capabilities. The Tradespace Evaluation

model can, however, provide significant insight and assistance when investigating broader strategic questions to help inform the DOE's strategy. Rather than being used as the basis of the DOE's integrated portfolio assessment process, as MADA was proposed to do, the Tradespace Evaluation model should be used as one component of a broader, more holistic portfolio assessment approach.

#### **4.6.2. Increased Number of MARKAL Runs Required**

Due to an inappropriate assumption of independence, the MADA model required a much smaller amount of MARKAL runs to produce analysis for a large amount of budget portfolios. In order to correct this error the Tradespace model requires an individual MARAL run for each budget portfolio to be analyzed. The downside to this requirement is that MARKAL is expensive to setup and run.

#### **4.6.3. Remaining Weak Link between Funding Level and Impact on Technology Cost Curves**

The original expert elicitation, which determined the impact of various funding levels on the cost curve of each energy technology, has its associated weaknesses and uncertainties. It should be bolstered and redone to include a larger number of experts from different domains. However, that process is lengthy and expensive. A research team in conjunction with the DOE's Policy Office is, at the time of the publication of this thesis, conducting an extensive elicitation of this nature, which presents an opportunity to revisit the elicitation in the near future. For now, the

results of the elicitation process will be left as-is. A discussion, regarding this weakness, should be held with decision makers who utilize the Tradespace model.

#### **4.6.4. Remaining Limitations Associated with MARKAL Data**

When combining several model types together for the purpose of decision analysis, one must be cognizant of the limitations of the information produced as output of one model that is subsequently used as input into another. A general weakness of integrated assessment models is that in order to ensure model tractability, many simplifying assumptions about the economy and the energy sector must be made. MARKAL, as well as most other integrated assessment models, is based on the assumption that the market always adopts the efficient allocation of resources (or least-cost solution), given present and future technology cost-curves and demand. The least-cost solution is achieved by assuming there is a single representative decision maker—akin to a centralized planner—that has perfect foresight and the analytical ability and influence to make optimal decisions over time. However in actuality, organizational players and consumers within the energy market do not have perfect foresight or knowledge. Additionally, market decisions by these actors are driven by a multitude of factors – not simply monetary factors.

Therefore it is important for the DOE to understand the disparity between the resulting MARKAL calculations, and how the outcomes of the DOE's programs and investments will unfold in the real world. Given that this simplified consideration of market dynamics results in an idealized future energy sector structure, final results from the Tradespace Evaluation model—if taken purely at face value—could lead to misguided recommendations. Resultantly, a

complementary in-depth understanding of market dynamics and how MARKAL deviates from observed outcomes in each domain of the energy market is essential. Fortunately, the DOE employs experts within each energy technology segment that understand the market dynamics which are not fully considered in integrated assessment models. Below is a brief overview of the types of market dynamics that DOE PA&E analysts should be aware of.

### ***The Importance of Considering Market Dynamics not Captured by MARKAL***

A useful way to think about how idealized model results might differ from reality is to examine observed phenomena in the energy market such as technology cycles, social influences, market feedback loops, and limiting effects. These phenomena can be grouped under the term market dynamics. Market dynamics are defined as the interaction between forces of demand and supply and the pricing signals they generate (Weil, 2009).

The DOE's multi-attribute decision approach seeks to evaluate the costs and benefits of multiple technologies competing in various segments of the energy market. Consumer adoption trajectories and subsequent commercial success of these technologies are determined by market dynamics such as network and bandwagon effects, attitudes towards things which are new, characteristics of early adopters, windows of opportunity for innovation, incentives and capability to innovate, technology performance versus user requirements, competition among varying generations of a technology, *perceptions* of benefits vs. costs and risks, and others. Contrastingly, MARKAL simplifies these complexities and assigns technology cost curves and their intersections as the major driver of technology adoption. Dynamics in technological,

business and social arenas are difficult to handle in models like MARKAL, because what is being modeled is an aggregate approximation of ideal system behavior. Advances within MARKAL have been made by including aggregate dynamics like endogenous technological change (i.e., cost learning curves), but much work remains in capturing the many underlying firm-level processes.

### ***Understanding Energy Market Dynamics through Feedback Loops***

Feedback loops are a simplified construct for understanding and depicting market dynamics and help describe why and how markets behave in a nonlinear fashion. A feedback loop is defined simply as the sequence that leads from the initial signal to the subsequent modification of the initiating event. A positive feedback loop seeks to increase the event that caused it. For example, an increase in global temperatures contributing to the melting of northern tundra, thus resulting in the release of greenhouse gasses, which in-turn increases the global temperature causing the further melting of northern tundra. It is also known as a *self-reinforcing* loop. A negative feedback loop seeks to reduce the original input signal, and is also known as a self-correcting or *balancing* loop (Senge, 1990).

Below are examples of major feedback loops currently at work in the energy market. When reading through these examples, consider how these reinforcing cycles could positively or negatively affect the impact of major DOE investments - how can the Department of Energy take advantage of possible positive feedback loops and counteract negative ones in order to achieve

the best result for the public? *Consider how a better understanding of market dynamics could assist in strategy formulation.*

#### *Energy Efficiency Feedback Loop...*

The energy efficiency feedback loop is a well known and interesting area of study. As energy efficiency increases two phenomena could occur; energy demand could decrease or more unintuitively, energy demand could increase. If energy demand decreases, this causes a decrease in demand for new peak-load generation. Renewables are typically built to satisfy peak-load demand, as base-load demand is met by dirtier, cheaper, existing infrastructure such as coal. A reduction in peak-load demand hurts demand for clean energy thus slowing the drop in manufacturing costs associated with clean energy which in turn cycles back and reduces demand for clean technologies further. Thus a negative feedback loop can be drawn between increase energy efficiency and the adoption rate of renewables. On the other hand, increases in energy efficiency could ultimately result in increased demand because increased efficiency “frees up” energy that can then be used for other activities—also widely known in the literature as the take-back effect (Grubb, 1990).

#### *Social Feedback Loops...*

Social dynamics such as trust, bandwagon effects, peer pressure, etc. are critical in determining how a market responds to innovation especially in the areas of distributed generation, energy efficiency, and transportation with greater direct consumer interaction. As an example of a possible future social feedback loop, one could consider an innovation where advanced metering made it possible to post real-time household energy use on a social networking sight such as

Facebook or Twitter. That visualization of consumption would in turn generate peer pressure to increase energy efficiency. Resultantly, energy use would decrease and peer pressure would increase, thus causing more consumers to post energy consumption rates on Facebook, thus causing energy use to decrease. This is an example of a positive feedback loop. Transportation is another area in which the bandwagon effect has been seen to be especially strong (Weil, 2009). These kind of dynamics have the impact of speeding up the rate of technology adoption, faster than what would be modeled in MARKAL.

#### *Enabling Technologies Feedback Loop...*

The positive feedback loop between increased enabling technologies such as the national grid and energy storage, and the development of renewable energy is also a known and often discussed phenomena, the impact of which is not fully captured via MARKAL. A quick description is as follows: as transmission to renewable resource rich areas increases, development of renewables increases; as development of renewable increase, costs of renewables decrease; and finally as costs of renewables decrease, demand for renewables increases, thus cycling back and increasing the demand for new transmission to resource rich areas. Consequently the DOE's investment in the grid and other enabling technologies can have an enormous impact on the potential benefits delivered by other DOE programs. The potential benefit, as modeled in MARKAL, depends on the version used.

#### *The Commoditization Feedback Loop...*

Commoditization is well understood as a basic market dynamic that impacts almost every sector of the economy. While technology cost reduction is modeled in MARKAL, the dynamics that

affect the speed of commoditization are not. The rate of commoditization is driven by herd behavior, a proliferation of competitors, persistent excess capacity, over-estimation of demand growth, lapse of financial constraints, and sometimes dysfunctional regulation (Weil, 2009). This typically results in price slashing and a subsequent collapse of margins. In some segments of the energy market commoditization could be beneficial to the American public, such as the lithium ion battery industry. If driven too quickly, however, specific DOE investments could be ruined by commoditization dynamics. A recent example of commoditization dynamics at play in the energy industry, was seen in the US biofuels market.

*“ The biofuels revolution that promised to reduce America's dependence on foreign oil is fizzling out. Two-thirds of U.S. biodiesel production capacity now sits unused, reports the National Biodiesel Board. The global credit crisis, a glut of capacity, lower oil prices and delayed government rules changes on fuel mixes are threatening the viability of two of the three main biofuel sectors -- biodiesel and next-generation fuels derived from feedstocks other than food. Critics of the biofuels boom say government support helped create the mess in the first place. In 2007, biofuels including ethanol received \$3.25 billion in subsidies and support -- more than nuclear, solar or any other energy source, according to the Energy Information Administration” (Davis, 2009).*

### ***Additional Market Dynamics Impacting the Energy Industry***

Below is a quick discussion of several commonly analyzed market phenomena that influence large-scale initiatives undertaken by the DOE. As was stated before, it is crucial that decision

makers at the DOE understand the workings of dynamics, such as these, when analyzing funding trades within the Tradespace Evaluation model and utilizing it for strategy formulation.

#### *Reluctance of Incumbents to Cannibalize...*

When innovation enables a new generation of products or services, such as clean energy technology, the dominant companies often are complacent and slow to react. Fear of cannibalization leads them to protect legacy products and business models. Their initial reaction often is dismissive – “*It’s inferior, only a niche market*” (Weil, Utterback, 2005). A recent example of this is telecom’s reaction to wireless communication. This type of behavior, if mirrored by the big utilities, could cause a much slower development and adoption rate of clean energy generation than expected. Understanding the mindset of large incumbent utilities can assist the DOE in crafting strategies to alter it.

#### *The Impact of Disruptive Innovation...*

Disruptive innovations change the way people use a product or service, enable new business models and architectures, challenge the existing industry structure, cause shifts in market leadership, and often trigger or accelerate commoditization (Weil, Utterback, 2005). The DOE, as a strong funder of research of disruptive innovations needs to understand the entirety of their impact on the market place and focus dollars towards segments of the energy market where disruptive innovation could have the greatest impact.

Several other dynamics include the impact of international cooperation and competition specifically from within large consumer societies such as China, the impact of complex regional

policy scenarios on the market dynamics of the U.S. as a whole, the influence of deregulation on competition, innovation, and pricing, the elasticity of demand which can be considered depending on the version of MARKAL.

### *Dynamics of Innovation...*

MARKAL's representation of technological change is to some extent technology-centric, while the study of market dynamics puts more emphasis on the firms' role and inefficiencies associated with human decision-making. Entries of firms into a market, and the subsequent exit of competitors, are central to the dynamics of innovation and technological cycles. A "lemming effect" often reinforces the impression that this must be "the new big thing", contributing to the proliferation of initial players. The subsequent large number of firms generates a high rate of experimentation and innovation which in turn drives improvements in cost and performance, increases the willingness of consumers to switch, resulting in the accelerated adoption of the new technology (Weil, Utterback, 2005). As the market becomes more crowded, the intensity of competition is increased. A dominant design and standards emerge, waves of companies leave the market, there is a shift from technological innovation to process innovation, and survivors pursue economies of scale resulting in the commoditization of the product or service (Weil, Utterback, 2005). One can observe a narrative similar to this when looking back over the past decade and a half at the traditional photovoltaic energy sector.

### ***Incorporation of Market Dynamics in the Tradespace Evaluation Model***

It is evident that enumerating and incorporating an understanding of these significant energy market dynamics is time and resource intensive. Section 6.2 talks about the use of scenario

planning as an approach to structure this analysis through the mapping out of possible future scenarios. Section 6.5 discusses how a new methodology, Epoch-Era Analysis, can be used in conjunction with the Tradespace Evaluation model to assist in scenario planning.

#### **4.7. Summary and Future Use**

The Tradespace model was tested and positively reviewed by PA&E management. As of the publication date of this thesis, it has been assigned to an incoming manager who will be responsible for developing new MARKAL runs and scenarios for strategy analysis and support. Chapter 5 discusses how the Tradespace Evaluation model could be used in conjunction with temporal analysis techniques like Epoch- Era Analysis to develop information rich scenarios for strategy formulation.

## **Chapter 5: Improving the DOE's Multi-Attribute-based Approach Using Relevant System of Systems Research**

Multi-Attribute Tradespace Evaluation (MATE), the core concepts of which are applied within the DOE's Tradespace Evaluation model, is typically used for evaluating decisions within a single system, project, or program. For example, MATE has been applied to conducting trade-offs between various satellite designs as well as between transportation system designs (Nickel, 2010). In expanding the use of MATE principles to evaluate the complex energy market and its effects on the global climate system, the DOE is developing a 'first of a kind' analytical capability for a system of unprecedented complexity. This new use involves challenges not present with more traditional and mature approaches.

A body of academic research exists exploring the application of MATE methods to System of Systems (SoS). A System of System is defined as a system that is composed of other systems that are value producing in their own right and whose constituents have a sense of independence after being assembled into the SoS (Shah, Hastings, & Rhodes, 2007). Maier (1998) discusses five principal characteristics that distinguish single systems from true systems-of-systems; 1) operational independence of system elements, 2) managerial independence of system elements, 3) evolutionary development, 4) existence of emergent behavior, and 5) geographic distribution of system elements.

The use of multi-attribute analysis at the Department of Energy is more of an application onto an enterprise, rather than a SoS in the strict sense of the definition. However, many interesting

parallels between the DOE's organizational structure and the structure of a SoS can be made, and thus recommendations for improvements can be gleaned from the body of SoS research. This section seeks to adapt insights from the SoS field to the DOE and its use of the Tradespace Evaluation model, in order to improve the decision making process.

The Department of Energy is composed of constituent Program Offices and initiatives, such as ARPA-E and the Loan Guarantee Program, that are value producing in their own right. SoS's are described as having the ability to generate stakeholder value beyond that which can be delivered by a single system or even a collection of systems (Chattopadhyay et al., 2009). This property can be seen at the Department, where the complimentary interaction between each Program Office produces a unique value to the American public than would have occurred if each Program Office was a separate agency.

The Department, viewed as an enterprise comprised of semi-autonomous programs and initiatives similar to a System of Systems, displays three significant characteristics that are different from more simplified tradespace analyses: (1) the dynamic interactions between the various programs and initiatives, (2) the composition of both legacy and new programs, and (3) the multi-level stakeholder value proposition required by the Department. These differences were also identified, by Chattopadhyay et al. 2009, as drivers for modifying MATE for use on SoSs and similarly should be taken into account through appropriate enhancements to DOE's use of the Tradespace Evaluation Model.

## **5.1. Internal Characteristics Specific to the DOE when Conducting Funding Trades**

First, the dynamic interactions among the programs and initiatives at the DOE make conceptual portfolio design decisions more complex than compared to traditional design. Benefits analyzed should attempt to understand emergent value created through exchanges between the Programs, especially in cross-cutting technology areas. As an example, cuts to the Solar Program may affect one of Solar's subprograms, Grid Integration. An emphasis within Grid Integration is the critical improvement of inverter reliability, efficiency, and life-cycle-costs. Inverters are a cross-over technologies essential to wind and solar integration, as well as other applications. Thus Solar's investment, or potential lack of investment, effects value beyond the solar industry.

Additionally, critical dependencies exist between Program Offices; high-level funding trades may not capture these. One example is the Office of Electricity's ability to affect the successful deployment of technologies in the Solar and Wind Programs. Such symbiotic relationships enable the adoption rate and impact-level of each Program's respective technologies. These types of internal relationships provide the DOE with the ability to produce value beyond what would occur if the Programs operated autonomously. It would be beneficial for PA&E to thoroughly enumerate these dependencies prior to making funding trades which might unknowingly slash cross-cutting initiatives.

Unlike traditional MATE applications where analysis is performed and completed in the early lifecycle phases, in an enterprise like the DOE there is a need for continuous exploration as programs start-up and retire, or major priority shifts occur. The budget portfolio designer may have limited control over the structure and operational characteristics of existing programs and

initiatives and much greater control over newly created ones (Chattopadhyay et al., 2008).

While the Secretary of Energy may desire greater support of alternative energy sources, his options are limited because of the heavy legacy of the weapons programs. The combination of a constrained tradespace of legacy programs and the relatively unconstrained tradespace of newly created programs results in a complicated evaluation.

In the case of the Department of Energy, the new administration's shift in focus away from nuclear, weapons-based security programs and towards renewables programs poses a challenge for the budget portfolio planner. When considering funding trades within the construct of the Tradespace Evaluation Model, PA&E should enumerate and be aware of hurdles for a smooth transition, such as sunken costs of facilities and capital equipment specifically designed for out-dated goals. If drastic trades are made that result in reorganization of any particular area, there are hidden costs associated with reorganization such as; overhead, productivity losses, and possible mismatching of personnel expertise. Additionally, decision makers should consider how to avoid sunken costs and hurdles by designing flexibility into the organization. Flexibility could be in the form of renting capital facilities rather than owning, increasing the number of contract personnel versus federal employees, and others.

## **5.2. The Importance of Coupling an In-Depth Stakeholder Analysis with the Tradespace Evaluation Model**

Compared to more typical multi-attribute based analyses, the Department of Energy has a large amount of stakeholders at each level of the organization. Internally; the DOE headquarters, the

Program Office's, and National Labs each have their own set of stakeholders with varying motives. Additionally multiple external stakeholders exist; OMB, Congress, Industry, the American public, and others. Resultantly, the selection of a portfolio of investments is made more complex by the need to consider value preferences of local as well as global stakeholders (Chattopadhyay et al., 2008).

Unlike the typical corporation, the DOE does not have final approval authority over its own budget. In order to achieve funding objectives the Department must not only match those objectives with the current administration's priorities, but simultaneously placate members of Congress with entrenched interests. Congressional approval or disapproval may reflect concern over jobs in a home state, a special tie to an industry group, or a misunderstanding of the DOE's true objectives. These types of unique motivations—which could lead to outside agents having power to alter the DOE's objectives through a change in funding – could be better enumerated through an in-depth stakeholder analysis. When conducting trades within the construct of the Tradespace Evaluation model, decision makers with an understanding of entrenched stakeholder interests would be adequately armed, resulting in the formulation of tactical moves for pushing the DOE's optimal portfolio design through to final Congressional approval. The Tradespace Evaluation model looks at tradespaces associated with two proxy stakeholders. Given its Excel format it can easily be expanded to include additional stakeholders.

## **Chapter 6: Augmenting the Tradespace Evaluation Model for use in Strategy**

### **Formulation**

The structure of the Tradespace Evaluation model is innovative, and aims to apply the latest academic research and state of the art modeling tools to the massive global energy challenge.

While in its current state the model provides value, there exists a particularly appealing opportunity to expand its use for more robust strategy formulation. This chapter seeks to utilize the pertinent academic literature, to further illuminate possible theoretical and practical enhancements in this vein.

#### **6.1. Motivation**

The Department of Energy operates within a sphere that is in a constant state of flux. Federal administrations have the possibility of changing every four years, and the dynamics of the economy and energy sector change at an even quicker pace. Despite its place in a complex, changing environment, the results produced by the DOE's Tradespace Evaluation model currently represent an evaluation conducted in terms of a static context. The DOE's different budget portfolios are run within MARKAL under a single future scenario. The lone alteration to that scenario occurs when MARKAL is run with a carbon cap versus no carbon cap. In this aspect, the DOE is employing the traditional, static approach to executing multi-attribute tradespace exploration. Recent research suggests that portfolios which are overly optimized for a single future scenario are fragile in the face of changing external contexts (Carlson & Doyle, 2000).

As an organization broadens its investments—placing bets across market segments and

technologies—they increase their vulnerability to market, technological, and political shifts.

This is the case with the Department of Energy. Given the DOE's broad technology portfolio, which spans basic R&D to demonstration and deployment, investments are extremely susceptible to external change. In fact, the only certainty is that massive change will occur in the landscape in which the DOE plays. Examples of these shifts include change in administration, passage of a cap and trade bill, spike in oil prices, and technological breakthroughs that drastically lower the price of a single resource. Many of these factors are not typically considered, though they may significantly affect the capacity of a portfolio of programs to deliver value.

Several historic examples exist of market and policy shifts that dramatically affected the DOE's ability to supply value to the public. One such example is the DOE's investment in the Synthetic Fuels Corporation (SFC), a public-private entity which was charged with producing 500,000 barrels of oil per day by 1987. Initial cost-benefit estimates were determined to be economical in the static context of the day, however when gasoline prices dropped—changing the external environment—the project became uneconomical and was viewed by the public as a “government boondoggle” (Taylor & Van Doren, 2007). A more robust initial analysis of possible changing futures, as related to market dynamics, could have potentially prevented such an outcome.

*“The troubles of the synfuels industry deepened last month when the U.S. House of Representatives voted 312 to 111 to eliminate all funding for the Synthetic Fuels Corporation, which has financed several large-scale projects. The bill provides only \$500 million for a Department of Energy program of synfuels research.”* (Wierzynshi, 2005)



**Figure 16. Ruins of the German Synthetic Petrol Plant in Police, Poland**  
(Source: Remigiusz Jozefowicz, May 2007)

External contextual shifts do not always have a negative effect on the DOE's programs and overall mission; occasionally they can form large opportunities that the Department could use to its advantage. A recent example is the drastic drop in natural gas prices, and the significant increase in long-term supplies due to the use of hydraulic fractionation. Anticipatory analysis of potential scenarios, such as this one, could enable the DOE to be better prepared with possible responses and strategies.

## **6.2. Summary of Benefits to Scenario Planning**

The complex dynamics of the world energy market make it virtually impossible to clearly map the contours of the future and select today's investments accordingly. However, modern strategic planning and evaluation methods are imperatives for all countries and organizations that have a stake in the energy industry (ECSSR, 2005).

*“The advantages of scenario planning are clear: since no one base case can be regarded as 100% probable, it’s necessary to develop plans on the assumption that several different futures are possible and to focus attention on the underlying drivers of uncertainty.” (Dye, Sibony Viguerie, 2009)*

As complex energy systems and programs are increasingly typified by long development timelines (e.g., future gen), extended operational lifetimes (e.g., nuclear facilities), and interdependencies with other systems and infrastructures (e.g., grid connection), front-end scenario planning has grown in importance (Roberts et al., 2009).

### **6.3. Scenario Planning Methodology Overview**

Scenario planning refers to a set of methods used by organizations to make decisions in the case of uncertainty. Generally, approaches can be divided into two classifications, narrative and computational-based. Narrative-based approaches are informed by trends where as computational-based approaches rely more heavily on quantitative characterizations of future states. Both approaches rely heavily on domain experts (Roberts et al., 2009).

#### ***Narrative-based Approaches***

Pioneered at Royal/Dutch Shell in the 1970’s, the narrative-based approach to scenario planning involves producing a few focused, qualitative storylines which are informed by an in-depth study of the pertinent stakeholders and indicators. Because this approach is time-intensive, the constructed scenarios tend to focus on extreme outcomes so that the entire space of future uncertainty is covered. Once the storylines of the stakeholder expectations and indicators are

made, analysts can then evaluate portfolio strategies. An advantage to this approach is that the constructed scenarios are informative and assist analysts in understanding key uncertainties and making more effective decisions. A disadvantage is that since the scenario product is qualitative, subsequent portfolio analysis is also qualitative (Roberts et al., 2009).

### *Computational Approaches*

Computational-based approaches can be viewed as an extension of a narrative-based exercise. The next key step is to parameterize the narrative information into discrete variables. For example, if evaluating an investment in a specific energy technology, then scenarios of future energy demand and oil prices might be two variables quantified as the result of scenario planning. This allows for a more exhaustive enumeration of key uncertainties rather than a limited focus on the extremes, like the narrative approach. The computational approach, while still prohibitively time-intensive, allows for a reduction in biases due to more specific enumeration of possible futures (Roberts et al., 2009).

## **6.4. Challenges of Traditional Scenario Planning Techniques at the Department of Energy**

The execution of narrative or computational-based scenario planning at the DOE would be extremely challenging for several reasons. First, the DOE historically and currently has a broad set of technology investments in every major (and minor) energy channel. These programs and initiatives cover the spectrum of technological maturity—from basic R&D to demonstration. Second, the DOE is a weighty player in the energy sector due to the size of its budget, Recovery

Act funds, and the loan guarantee program. Resultantly, it has the ability to shape market dynamics and drive future scenarios. In combination, these factors produce a large, complex landscape of uncertain future outcomes that would need to be approximately represented by scenarios. This poses a much more complicated task than performing scenario analysis for an organization with investments in one or two areas of the energy sector.

### **6.5. Augmenting the Tradespace Evaluation Model with Epoch- Era Analysis to Assist in Scenario Planning**

As mentioned above, scenarios describing long-term projections of the energy sector contain a considerable amount of uncertainty. It is particularly difficult to foresee how existing technologies might evolve or what new technologies might emerge as market conditions change. As uncertainty increases, scenario planning becomes more complex as the number of variables and possible range of plausible outcomes explode. The heart of scenario planning consists of crafting a number of strategies for different outcomes. As those scenarios multiple, increased demands are placed on analysts in terms of gathering information, exploring policy, regulatory and market possibilities, and understanding latent dynamics. (Dye, Sibony, Viguerie, 2009).

Evolving the DOE's use of the Tradespace Evaluation model to conduct Epoch-Era Analysis, a recent advancement in the literature, may be an approach to reducing the cumbersome nature of scenario planning. Epoch-Era Analysis is described in detail in Section 6.6. In brief, it is a framework for utilizing tradespace analysis, like that generated within the Tradespace Evaluation model, to construct and explore a variety of future scenarios. The use of Epoch-Era Analysis allows for the abstraction of multiple complexities, thus simplifying the analysis and allowing

the decision-maker to grasp trade-offs between investments and their impact on the future. In this way, the Tradespace Evaluation tool could be used to advance scenario planning techniques through parameterization and ordering of potential future contexts. Taking this approach would assist in the development of more rigorous alternative futures as well as provide a process for evaluating portfolio evolution strategies over time (Ross, 2006).

Coupling Epoch-Era Analysis with the Tradespace Evaluation model has the potential to provide the DOE with a process for performing scenario planning that is tailored to fit within the organization's current analytical tool set. Importantly, this approach would inform the development of strategic and tactical moves based on a data-driven analysis whose framework is rooted in academic research.

*“Despite the challenge of operating in a highly uncertain climate, the strategic-planning process need not be an exercise in anxiety or futility. Developing scenarios in greater depth, monitoring strategies more rigorously, and remaining focused on the long term will all help strategists boost the odds of creating plans that lead their companies through turbulence.”* (Dye, Sibony, Viguerie, 2009)

## **6.6. What is Epoch-Era Analysis?**

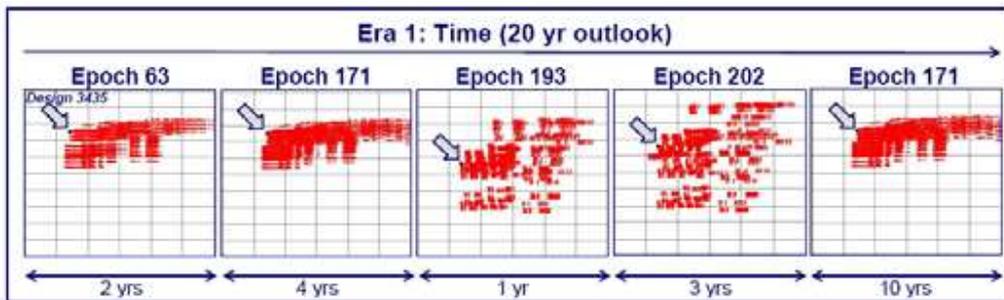
Epoch-Era Analysis is an approach, developed at MIT's Systems Engineering Advancement Research Initiative (SEARI), that expands upon traditional tradespace exploration, as is executed within the DOE's second generation Tradespace Evaluation model. It provides a structured framework for visualizing and evaluating portfolios across changing contexts. One of the

objectives is to identify “value robust” portfolios. Value robustness is a term used to describe portfolio options that will continue to perform well in the face of changing environments (Ross, Rhodes, Hastings, 2009).

Each epoch is defined to contain a static context and typically spans a shorter time period of one to ten years. For example, one epoch could span five years and consider a fixed set of subsidies and incentives for energy efficiency; another epoch could span the next five years and set an alternative case of subsidies and incentives. Within these epochs a tradespace is constructed for the budget portfolio options. Multi-attribute utility is determined during each epoch. This is because perception is context dependent and varies with time. These epoch tradespaces can then be strung together into a series to create possible future scenarios. One string of epochs is referred to as an Era—thus the term Epoch-Era Analysis. The decision maker can then observe how each portfolio’s performance, as viewed in cost vs. utility tradespaces, evolves over time. The advantage of the epoch-era construct is that it parses a complex problem into a series of simpler ones (Ross, 2006).

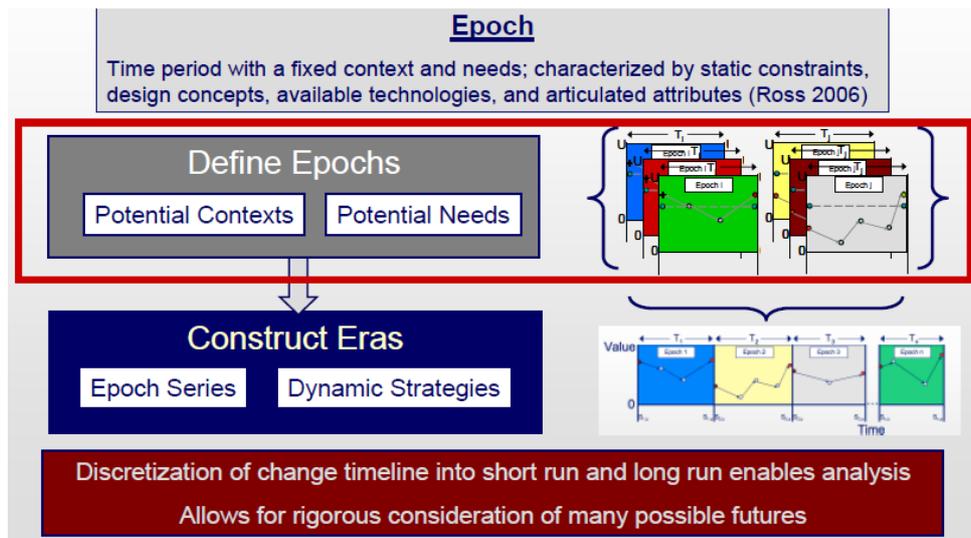
The MIT SEARI community describes Epoch-Era Analysis as considering the world to be similar to a movie composed of a series of static frames running in quick succession. This snapshot depiction allows for a simple extension of typical static tradespace exploration to a dynamic analysis. The below pictorial, Figure 17, shows a series of tradespace plots in a “movie real” format. Tradespace plot in the first epoch exists in a predefined external context and the portfolio designs are evaluated within that context, the tradespace plot in the second epoch exists in a different external context which may or may not change the value able to be delivered by the

different portfolio designs.



**Figure 17. Illustrative Example of Epoch-Era Analysis - Movie Reel Depiction**  
(Ross, Rhodes, 2008)

Below is an alternative visualization of Epoch-Era Analysis created by MIT SEARI.



**Figure 18. MIT SEARI's Visual Representation of Epoch-Era Analysis**  
(Ross, 2006)

## 6.7. Augmenting the Tradespace Evaluation Model for Epoch-Era Analysis

When extending the Tradespace Evaluation Model for use within an Epoch-Era Analysis

framework, several adaptations need to be made. Epoch-Era Analysis requires the evaluation of shorter timeframes, epochs, than MARKAL currently provides. MARKAL optimizes over a single forty to fifty year period. Therefore it is necessary to adjust MARKAL to run over shorter timeframes. An added benefit of running MARKAL over shorter timespans is the generation of a more accurate depiction of reality. Currently MARKAL assumes that the market has perfect foresight. If the cost of carbon capture and sequestration (CCS), for example, is modeled to drastically drop at a thirty year point – MARKAL will continue to rely on coal for generation rather than begin a switch toward renewables because it knows that its emissions reductions goals can be obtained at the thirty year point. This type of decision making is counter to reality where investors and policy makers do not have perfect foresight. Running MARKAL so that it optimizes over shorter time periods and only considers the information available within that context more closely resembles the actions which will be taken by various players and simultaneously enables the use of Epoch-Era Analysis.

The use of Epoch-Era Analysis will require the generation of an increased number of MARKAL runs with a richer context specification. The running of MARKAL, as has been stated previously, is time and resource intensive. A greater time demand would be placed on analysts and experts to develop and define probable epochs and eras. Fortunately, the vast knowledge of industry and technology experts located within the Department's Program Offices can be utilized. Additionally, many Program Offices currently run their own versions of MARKAL or other integrated assessment models. Monetary resources spent on these runs throughout the Department could be pooled or coordinated so that major assumptions and inputs are synchronized. In this way, a much greater number of MARKAL or other integrated assessment

model runs could be available for study within the Tradespace model. Thus, involving representatives from the Program Offices in the process and improving the accuracy of scenario, or era, development.

Alternatively, PA&E could disburse the Tradespace Evaluation model to the Program Offices along with required standards for its use: requirements for sending information and results back to PA&E, standard MARKAL assumptions, standard benefits weighting scheme, and standard utility curves. Thus, allowing a larger number of analysts to perform in-house trades between investments and investigate strategic options. Budgetary changes recommended by the Program Offices would be based on assumptions, reasoning, and analysis common to the entire Department. Providing Program Office experts' ownership over the results and an understanding of the process may alleviate residual conflict over final funding trades.

## **Chapter 7: Conclusion and Future Work**

The Department of Energy (DOE) faces the daunting task of making critical decisions under extreme uncertainty with respect to the optimal size and shape of the nation's public energy portfolio. Recently, with passage of the Obama Administration's Recovery Act, the DOE's budget increased substantially. Beyond ensuring that taxpayer investments were employed efficiently and effectively, the spending increases required a more analytical, comprehensive and structured approach to evaluating the DOE's portfolio of programs and initiatives. Leaders in academia and industry similarly called for a systematic and holistic assessment of the nation's portfolio of energy investments (PCAST, 2010), (American Energy Innovation Council, 2011).

Despite numerous complexities inherent in evaluating individual funding impacts and their macro implications, the Department of Energy's PA&E group stepped forward to tackle this cognitively overwhelming yet vital challenge. A proposal was made to develop a first-of-a-kind decision tool aimed at providing rigorous analysis of cost and benefit trade-offs associated with the DOE's various potential investments. The decision tool was designed to couple a state-of-the-art climate and energy model with sophisticated multi-attribute-based decision methods.

Given that the DOE was committed to building a multi-attribute-based decision tool, the objective of this thesis was to investigate the most appropriate, tailored multi-attribute-based approach for the DOE's needs. First, the initial MADA model was reviewed in-depth. Six key shortcomings, three relating to the model's structure and three relating to its conceptual design, were identified as hindering the accuracy and transparency of results to decision makers. These

six shortcomings were investigated in Chapter 3 as well as approaches for improvement. The associated successes and failures of the initial MADA modeling effort led to a rich learning process. Those learnings formed the basis for the design of a second generation decision tool. In this way, the initial MADA modeling effort, though not fully successful, moved the DOE in a critical and positive direction.

Next, research was conducted into the design and build of an improved second generation model, based on 1) the use of lessons learned from the initial MADA modeling effort, and 2) an investigation into the literature identifying multi-attribute-based approaches more suitable to the DOE's needs. It was recognized that the core concepts of Multi-Attribute Tradespace Evaluation (MATE) provided a particularly good fit within the context of the DOE's portfolio assessment process. Specifically, the metric - Multi-Attribute Utility Theory - was valuable when assessing not easily quantifiable benefits whose perceived value varies widely amongst stakeholders within the DOE's highly politicized budgeting environment. Additionally, Tradespace Exploration was identified as advantageous by enabling the real-time visualization of investment trade-offs that the DOE's decision makers required. This modification, the generation of stakeholder tradespaces, allowed for the elimination of a complex optimization algorithm. This enabled designers to swap-out the cumbersome ABC Software with simple Excel spreadsheets - creating a decision tool which was more flexible to PA&E's quickly changing analytical needs. The combination of these theoretical and structural advancements resulted in a second generation, Tradespace Evaluation model, which applied methodologies more suited for assessing problems relevant to the energy sector. Despite remaining limitations within the Tradespace Evaluation model, discussed in Section 4.6, the model received positive reviews from PA&E leadership and

is currently being incorporated into their portfolio assessment process. Further efforts will validate the model's usefulness and extend its current capability.

Multi-Attribute Tradespace Evaluation (MATE), the core concepts of which are applied within the DOE's Tradespace Evaluation model, is typically used for exploring design options within a single system. The DOE's application of MATE to analyze the multifaceted energy sector introduces layers of interaction beyond that of a single system MATE application. A body of academic research was investigated which explores the application of MATE methods to System of Systems (SoSs). The use of multi-attribute analysis at the Department of Energy is more of an application onto an enterprise, rather than a SoS in the strict sense of the definition. However, many interesting parallels between the DOE's organizational structure and the structure of a SoS can be made. Thus, recommendations for improvement to the Tradespace Evaluation modeling process were gleaned from the body of SoS research and are described in Chapter 5.

The final research step was to explore further evolution of the Tradespace Evaluation model by applying recent methodological advancements. The complex dynamics of the global energy market make it impossible to clearly map contours of the future and select investments accordingly. Therefore, there is a strong need at the DOE for long-range scenario planning.

Given the broad spectrum of the DOE's current investments, from basic R&D to demonstration, across every major energy technology, evaluating possible futures is extremely complex.

Evolving the DOE's use of the Tradespace Evaluation model to conduct Epoch-Era Analysis is proposed to reduce the cumbersome nature of scenario planning. Epoch-Era Analysis allows for

the abstraction of multiple complexities, thus simplifying the analysis and allowing the decision-maker to see and evaluate trade-offs between investments and their impact on the future.

The DOE faces a highly dynamic and politicized funding environment. They must frequently rely on multiple, ad hoc decision making methods due to complexities inherent in their operating landscape. PA&E's recent decision tool development efforts moved the DOE in a critical and positive direction. The research described in this thesis illuminated shortcomings within the initial MADA model structure and played a significant role in researching, designing, and developing a second generation approach, tailored to the DOE's operational context.

No one model can do it all. The proposed function of the Tradespace Evaluation decision tool is not as a sole model through which to conduct a comprehensive energy portfolio assessment, as the original MADA model sought to accomplish, but is to play a significant and informative role as a component *within* a comprehensive portfolio review through enabling the enumeration of budgetary trade-offs which address high-level, strategy questions facing the DOE.

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