LEAST-COST PLANNING FOR 21ST CENTURY ELECTRICITY SUPPLY

MEETING THE CHALLENGES OF COMPLEXITY AND AMBIGUITY IN DECISION MAKING

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EXECUTIVE SUMMARY

THE INCREASINGLY COMPLEX CHALLENGE OF RESOURCE ACQUISITION

Energy policy and regulatory decision making in the American electricity sector have always been a challenge because the U. S. is among the most electricity intensive of all nations and it has an extremely wide set of resources with which to meet its electricity needs. Moreover, in the past quarter of a century a fierce debate about the existence and response to climate change, a roller coaster ride in fossil fuel prices and a fizzled "nuclear renaissance" have made things much more difficult by casting doubt on the three primary fuels on which the U.S. relies for almost 90 percent of its electricity. In spite of this uncertainty, because electricity is an essential building block of modern life decision makers are under constant real-time pressures to ensure electricity supply at affordable prices.

This paper argues that the insights and recommendations from the study of financial portfolio and real option analysis, technology risk assessment, reliability and risk mitigation management, and Black Swan Theory all indicate that the 20th century approach to resource acquisition in the electric utility industry is ill-suited to the 21st century economic environment. Indeed, it can be argued that the approaches taken in a wide range of regulatory proceedings such as integrated resource planning, purchase power agreement reviews and general rate cases may have been rendered obsolete by a dramatic change in the terrain of decision making.

Traditionally, in resource acquisition proceedings utilities are required to do what a prudent person would. Using the best decision making tools applied to the best available data with the full range of options and possibilities considered, they should choose the least cost resources to provide reliable electricity. In the current environment these core principles should be reaffirmed, but a prudent, integrated, least cost resource plan must

- be hedged against **risk**,
- maximize options to reduce **uncertainty**,
- be flexible with respect to outcomes that are, at best, **vague** and
- be insulated against **ignorance** of the unknown.

RECOMMENDATIONS AND CONCLUSIONS

This paper uses contemporary theories of knowledge and decision making applied widely in other fields to build a comprehensive approach to analyzing the increasingly complex conditions under which regulators and policymakers must make decisions about resource acquisition. Applying this framework to familiar data sets on electricity resources, the paper makes an economic/analytic case for a richer and more nuanced view of prudence and offers practical advice for regulators.

- Identify the trade-offs between cost and risk and lower risk through hedging.
- Reduce exposure to uncertainty by buying time.
- Keep options open by acquiring small assets that can be added quickly.
- Minimize surprises by avoiding assets that have unknown or uncontrollable effects.
- Create systems that monitor conditions and can adapt to change in order to maintain system performance.
- Buy insurance where possible.
- Recognize that diversity is the best insurance.
- Build resilience with diversified assets by increasing the variety, balance and disparity of the resource mix.

This analysis calls into question many of the long standing tendencies in utility resource acquisition and capital allocation.

- Acquisition of central station facilities, particularly nuclear, makes long-term commitments in exactly the wrong way for the current decision making environment. It commits to assets that have high risk (e.g. fossil fuel and nuclear facilities) or create large exposure to uncertainty (large size, high capital costs, or long lead times) with technologies that have vague long-term prospects (unstable resource availability and poorly understood environmental impacts).
- The dash to gas that is developing is being significantly overdone because it unnecessarily exposes ratepayers to risk, uncertainty and vagueness.
- A balanced approach that begins with a great deal more efficiency and locally abundant renewables that can be acquired more quickly and in much smaller increments, combined with natural gas, yields lower expected costs.
- Long-term contracts for smaller increments of the more attractive resources, like wind, diversify the resource base, while reducing ratepayer risk and lowering the cost of the resources. They are a form of insurance that public utility commissions should require utilities to acquire.

As long as the conditions in the electricity sector did not deviate from the assumed stability and relative certainty, commissions did not have to incorporate tools of risk, option and diversity analysis. Now that it is obvious that the dramatic change in the underlying conditions have called entrenched approaches into question, public utility commissions simply cannot continue to claim that they are properly evaluating prudency without utilizing the tools that prudent decision makers throughout society are using.

ANALYTIC FRAMEWORK FOR EXPLORING THE TERRAIN OF DECISION MAKING

Over the past half century a number of analytic tools and investment strategies have been developed to deal with the ambiguity that affects decision making, as shown in Exhibit ES-1. These efforts start from the premise that there are two primary sources of ambiguity – lack of knowledge about the nature of outcomes and/or lack of knowledge about the

EXHIBIT ES-1: TOPOGRAPHY AND NAVIGATION TOOLS FOR THE REGIONS OF KNOWLEDGE

	REGIONS			
	IGNORANCE	**VAGUENESS**	**UNCERTAINTY**	**RISK**
TOPOGRAPHY				
Technology Risk Assessment				
Challenges	Unanticipated effects	Contested framing	Nonlinear systems	Familiar systems
Outcomes	Unclear	Unclear	Clear	Clear
Probabilities	Unpredictable	Predictable	Unpredictable	Predictable
Black Swan Theory				
Challenges	Black Swans Wild randomness	Sort of Safe	Safe	Extremely safe Mild randomness
Conditions	Extremely fragile	Quite robust	Quite robust	Extremely robust
Distributions	Fat tailed	Thin tailed	Fat tailed	Thin tailed
Payoffs	Complex	Complex	Simple	Simple
Reliability & Risk Mitigation Management				
Challenges	Chaos	Unforeseen uncertainty	Foreseen uncertainty	Variation
Conditions	Unknown/ unknowns	Unknown/ knowns	Known/ unknowns	Known/knowns
Characterizations				
Religious	Hell	Limbo	Purgatory	Land of the living
Greek Mythology	Pandora, Pythia	Damocles, Cassandra	Cyclops	Medusa
NAVIGATION				
Analysis				
Approach	Multi-criteria analysis	Fuzzy logic	Decision heuristics	Statistics
Tools	Diversity assessment	Sensitivity analysis	Scenario analysis	Portfolio evaluation
Focus	Internal resources/ structure	Internal resources/ structure	External challenges	External challenges
Data	<u>Swan Search</u> Consistency Unintended consequences Externalities <u>Diversity</u> Structural Variety, balance, disparity Alternative Instrument <u>Sufficiency</u> Adequacy Sequence	<u>Vagueness</u> Supply security Resource base Market scope Environmental impact Pollutants (air. Land water, waste) Greenhouse gasses	<u>Uncertainty</u> Capacity Construction period Sunk cost (Total capital = MW * $/MW)	<u>Cost</u> -<u>Risk</u> Levelized cost of energy Cost variability Fuel O&M Carbon ½ nuclear capital
Policy Tools				
Processes	Learning	Learning	Planning	Planning
Instruments	Insurance/diversity	Monitor & Adjust	Optionality	Hedging
Rules	<u>TECHNOLOGY RISK ASSESSMENT</u> Precaution Buy insurance for system survival Accept non-optimization Diversity Variety Balance Disparity <u>BLACK SWAN THEORY</u> Truncate Exposure Buy insurance for system survival Accept non-optimization Redundancy Numerical Functional Adaptive	<u>TECHNOLOGY RISK ASSESSMENT</u> Resilience Adaptability <u>BLACK SWAN THEORY</u> Multi- functionality What Works	<u>TECHNOLOGY RISK ASSESSMENT</u> Flexibility Across Time Across Space <u>BLACK SWAN THEORY</u> Optionality	<u>TECHNOLOGY RISK ASSESSMENT</u> Resilience Robustness Hedge <u>BLACK SWAN THEORY</u> Robust to Error Small, Confined, Early Mistakes Incentive & disincentives Avoid Moral Hazard Hedge

Sources: Black Swan: Nassim Nicholas Taleb, *The Black Swan* (New York: Random House, 2010), Postscript; Technology risk Assessment: Andrew Stirling, *On Science and Precaution in the Management of Technological Risk* (European Science and Technology Observatory, May 1999), p. 17, *On the Economics and Analysis of Diversity* (Science Policy Research Unit, University of Sussex, 2000), Chapter 2; "Risk, Precaution and Science; Toward a More Constructive Policy Debate," *EMBO Reports,* 8:4, 2007;Reliability and Risk Mitigation David A. Maluf, Yuri O. Gawdisk and David G. Bell, *On Space Exploration and Human Error: A Paper on Reliability and Safety,* N.D.; Gele B. Alleman, *Five Easy Pieces of Risk Management,* May 8, 2008; see also, Arnoud De Meyer, ChristophER H. Lock and Michel T. Pich, "Managing Project Uncertainty: From Variation to Chaos," *MIT Sloan Management Review*, Winter 2002.

probabilities of outcomes. Four regions of knowledge result from this basic analytic scheme – risk, uncertainty, vagueness and ignorance – each presenting a distinct challenge to the decision maker. The purpose of the framework is to identify the characteristics of each region, the analytic tools that are best suited to exploring it and the policy tools that are best able to navigate it, given with the state of knowledge. The integrated approach allows the decision maker to array the options under consideration in a multi-attribute space.

Risk: In some circumstances the decision maker can clearly describe the outcomes and attach probabilities to them. Risk analysis allows the decision maker to hedge by creating a portfolio that balances more and less risky assets. This risk analysis has it origin in the financial sector and was first articulated over half a century ago.

Uncertainty: In some circumstances the decision maker can clearly describe the outcomes but cannot attach probabilities to them. Here the decision maker would like to keep options open – to delay decisions if possible – until more information reduces the uncertainty. If the decision maker cannot wait, then the path chosen should be flexible, so that it affords the opportunity to deal with whatever outcomes occur. Real option analysis also emerged from the financial sector – a little over a quarter of a century ago.

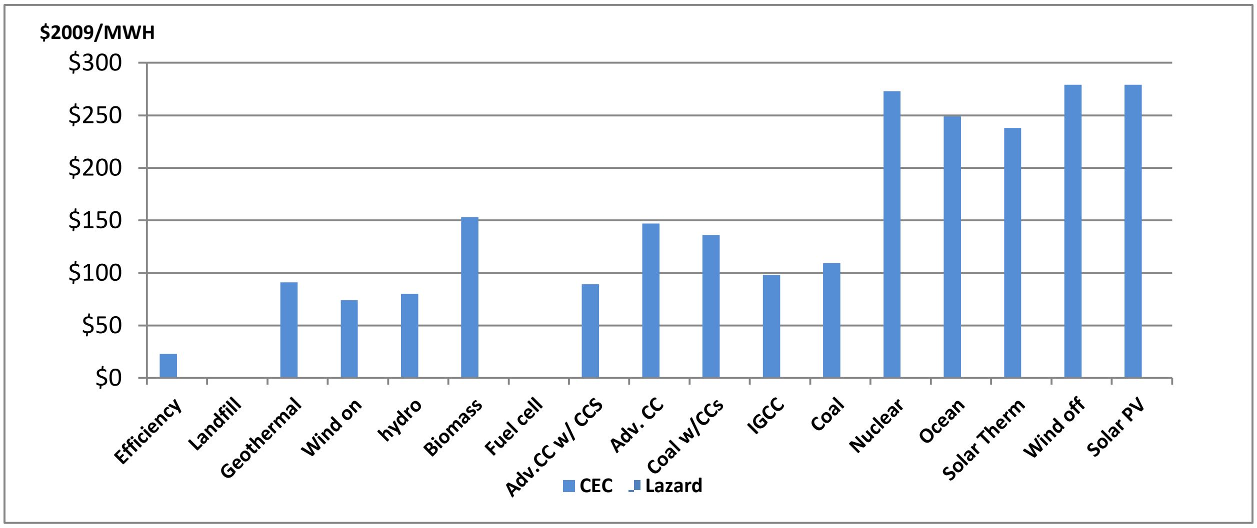
Vagueness: In yet another circumstance, decision makers may not be able to clearly identify the outcomes, but they know that the system will fluctuate. Here the decision maker wants to take an approach that can monitor the condition of the system and adapt as it changes. An approach to this situation of vagueness called “fuzzy logic” emerged from the computer science and engineering fields at about the same time as real option analysis.

Ignorance: In the most challenging situation, knowledge of the nature of the outcomes and probabilities is limited. Even in this state of ignorance, decision makers have strategies to cope and policies that can insulate the system. Here the analyst looks more inward, to the characteristics of the system to identify those that are most important, and seeks to build systems that ensure critical system functions are performed adequately to maintain system viability under the most trying of circumstances. Multi-criteria evaluations of outcomes point to strategies that buy insurance and diversify assets – summarized in the expression, “put lots of eggs in lots of baskets.” This framework has been developing for about two decades in technology risk assessment and the energy sector.

EMPIRICAL DEMONSTRATION OF THE APPROACH

Cost and Other Data: To demonstrate the usefulness of the proposed framework, I focus on a carbon-constrained future and apply the framework to the levelized cost of two well-known data sets, sourced in Exhibit ES-2. These two studies are also the source for the data used in the risk analysis and the uncertainty analysis. Exhibit ES-2 shows the average levelized cost for Lazard and the CEC (supplemented by several EIA estimates). There are half a dozen low-cost, low-carbon resources and half a dozen moderate cost, potentially low carbon resources.

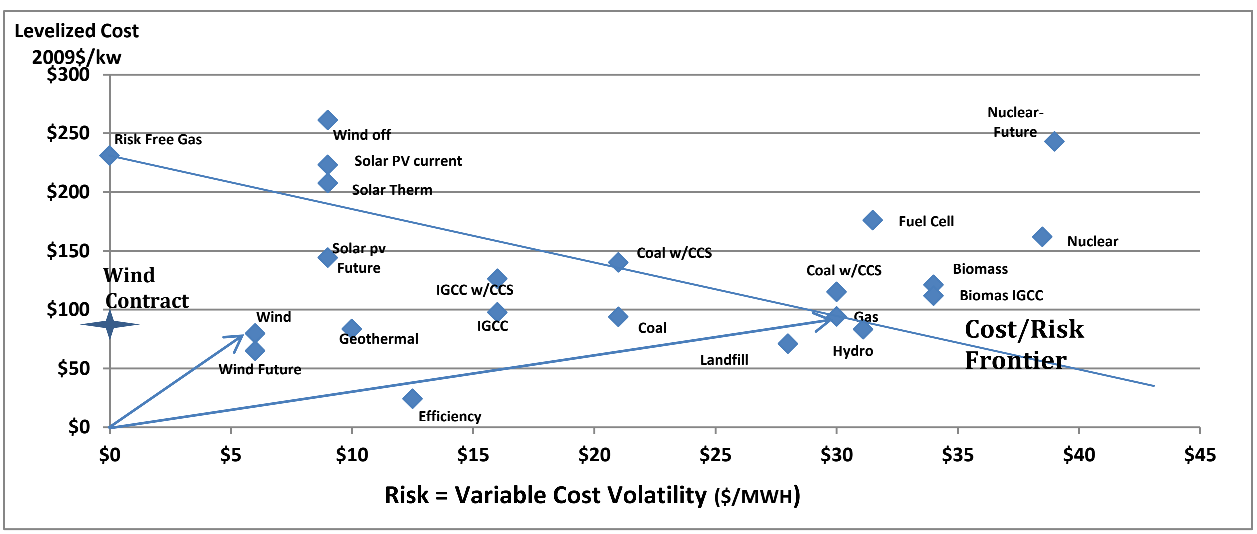
EXHIBIT ES-2: LEVELIZED COST OF ENERGY



Source: Lazard, *Levelized Cost of Energy Analysis – Version 4.0, June 2010:* California Energy Commission, *Comparative Cost of Central Station Electricity Generation,* January 2010; *EIA, Annual Energy Outlook: 2011, Levelized Cost of New Electricity Generating Technologies,* is used to provide the second estimate in the case of Lazard hydro and wind-off and CEC, coal w/CCS and coal.

Risk: Exhibit ES-3 builds the risk analysis from the cost data. The levelized cost is on the y-axis. The variability of cost is on the x-axis, which includes fuel cost, O&M, and carbon costs. The framework identifies two key measures by which alternatives are evaluated. It identifies a cost-risk frontier, defined by natural gas, which is the fuel of choice at present. The frontier is defined by the base case cost of gas and the "risk free" price of gas, which is the highest price that would occur if all the causes of variability in gas prices are at their highest level. Any option below the cost-risk frontier should be strongly considered since it embodies lower cost and/or risk. Options above the frontier are not attractive. The arrows in the Exhibit represent one method for calculating scales or scores for each resource. The farther from the origin (the greater the Euclidean distance), the less attractive the resource.

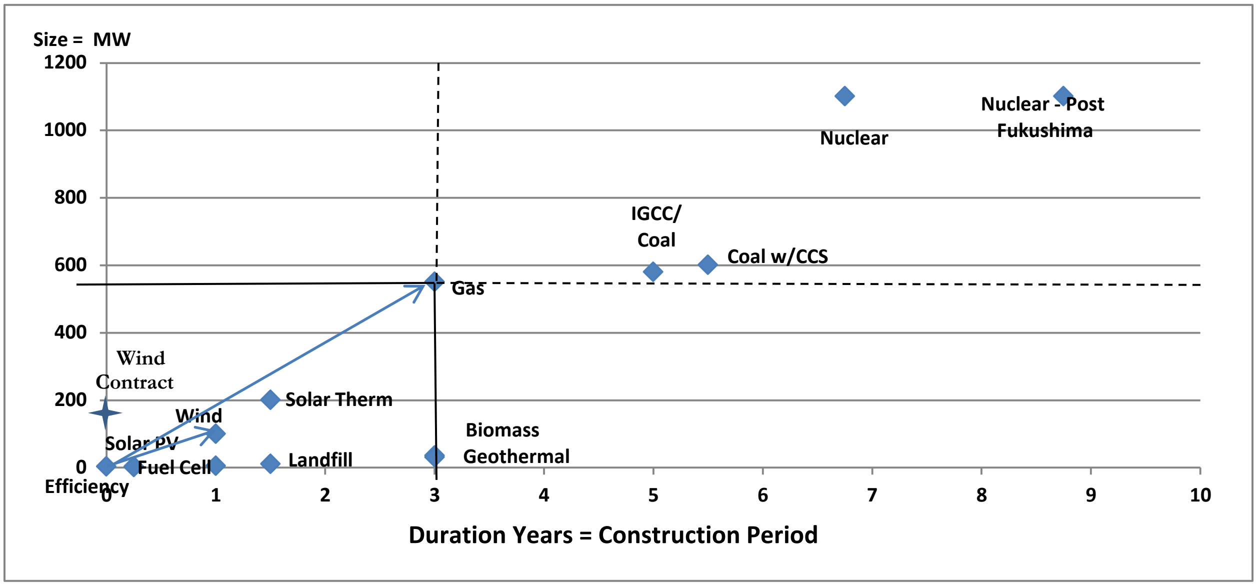
EXHIBIT ES-3: RISK AVERAGE LEVELIZED COST V. VARIABLE COST



Source: see ES-2

Uncertainty: The key to dealing with uncertainty is to keep options open. Several characteristics of technology options affect the ability to wait – the construction period, the size of the facility and the capital costs that must be sunk into the project. Exhibit ES-4 shows the size and lead time and identifies the "efficient" frontier as a rectangular area with gas as the referent. Anything inside the rectangle is preferable on both the size and duration of exposure to risk. The resources that fall outside the rectangle are less attractive.

EXHIBIT ES-4: EXPOSURE TO UNCERTAINTY



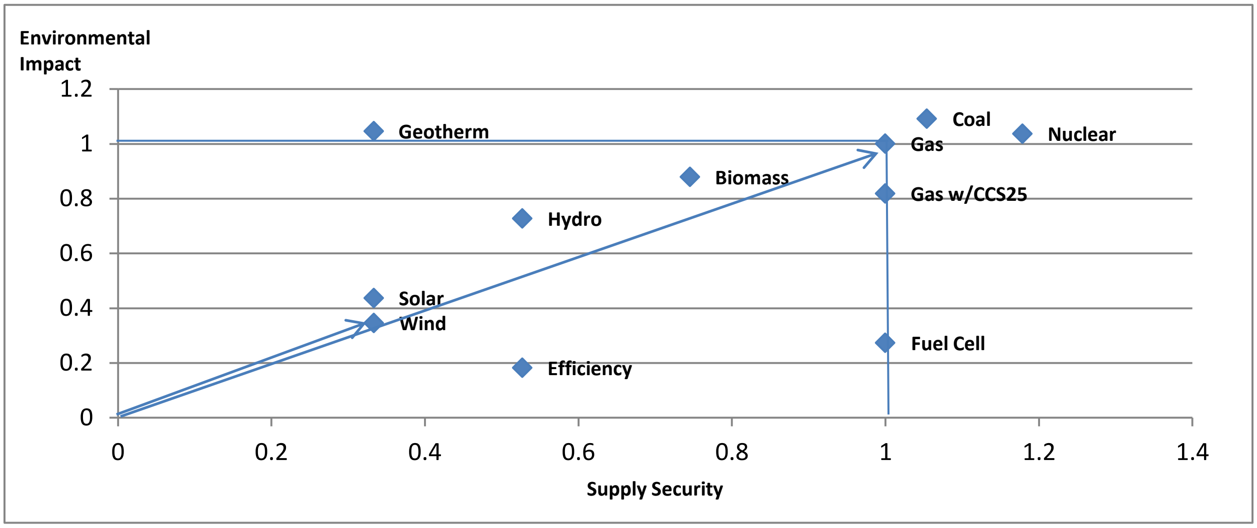
Source: Lazard, *Levelized Cost of Energy Analysis – Version 4.0, June 2010,*

Vagueness: The analysis of vagueness is a much more qualitative area than risk and uncertainty, as should be expected given that the underlying problem in this space is a lack of knowledge about the outcomes. In this region, the strategy is to avoid areas of vagueness. Several outcomes that fall in the area of vagueness in the utility sector are readily identifiable in the literature – security of supply and environmental impacts. Exhibit ES-5 ranks the resources compared to gas. These considerations reinforce the conclusions reached on the basis of the analysis of risk and uncertainty.

The Region of Ignorance: The analysis of risk, uncertainty and vagueness produces a very clear ranking of the resources, as shown in Exhibit ES-6. Efficiency and renewables are clearly preferable, with gas as the complementary and transitional resource. Central station facilities are the least attractive options. However, there are additional analyses that should round out the map of the terrain of decision making.

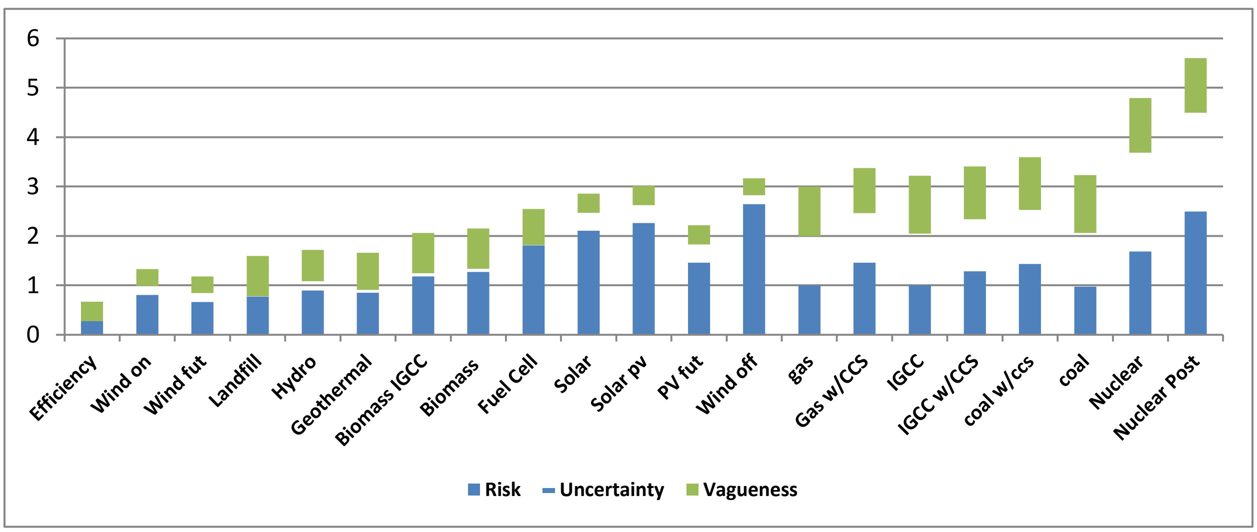
Search for Swans: Decision makers must be on guard against additional surprises. They should look for black or white swans that could be lurking beyond the area were the analysis has shed light. While surprises are not predictable, there are places to look. **Consistency:** One obvious step is to explore areas where the analysis in the other three regions has resulted in contradictory conclusions. These would indicate an important area for analysis in the ignorance region. We have not observed contradictory results.

EXHIBIT ES-5: VAGUENESS: SUPPLY SECURITY AND ENVIRONMENTAL IMPACT



Source: Author, see text

EXHIBIT ES-6: THE SEQUENCE OF RESOURCE ACQUISITION IN AN AMBIGUOUS ENVIRONMENT



Source: Author, see text

Unintended Consequences: Similar to inconsistencies, but broader, are unintended consequences. For example, increasing the reliance on variable renewables can create grid management challenges. At current relatively low levels of reliance on variable renewables, this is not a major problem, but as their use rises it becomes more serious and requires management responses. **Additional Externalities:** Identify potential costs and benefits that have not been factored into the risk, uncertainty or vagueness analyses – e.g. gas: fracking and other environmental concerns; wind: managing capacity factor, reduced natural gas consumption compared to a "dash to gas scenario; efficiency – execution sufficiency, rebound effect, consumption externalities of conservation.

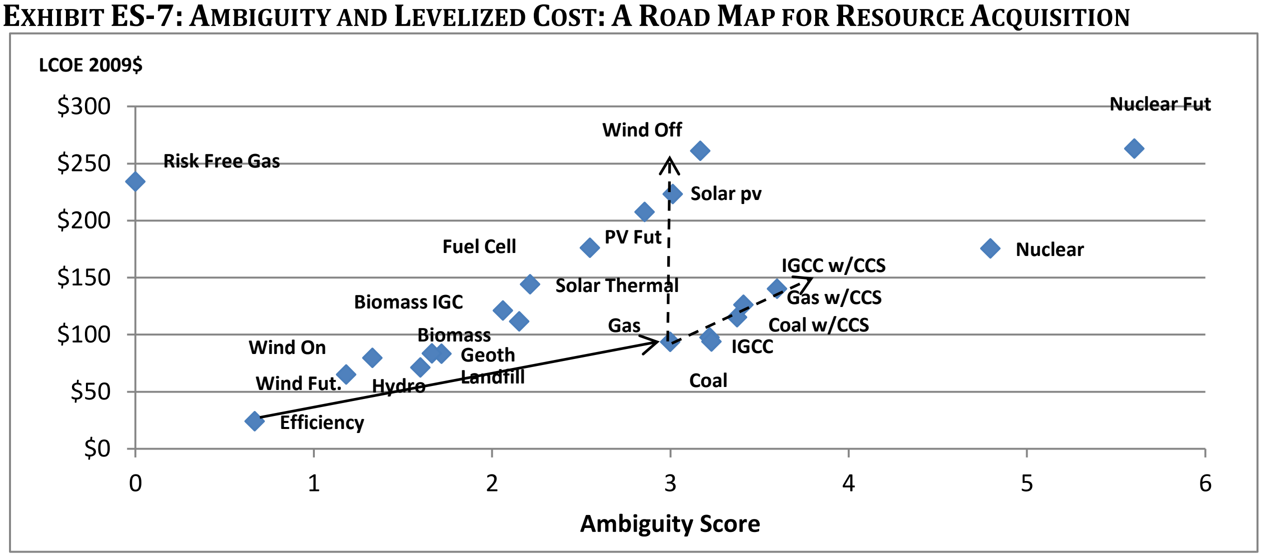
Diversity: Diversity is the key to building a robust resources acquisition strategy. Diversity has several aspects. **Structural:** In order to achieve the resiliency benefits of diversity, the portfolio requires resources that are varied, balanced and disparate. **Alternative Instruments:** Within the broad pursuit of diversity as a form of insurance, the examination of the opportunity to pursue diversity through alternative acquisition instruments is an important are of analysis. One approach to stretching the resources is to buy insurance in the form of long term contracts that acquire resources identified as preferable by the analysis of the other three regions.

Sufficiency: Given the primary purpose of ensuring an adequate supply, the sufficiency of the resources that are identified as preferable to meet the need for electricity should be considered as an independent question. **Adequacy:** The potential for the resources that are identified as attractive is substantial. Given the fact that five of the six resources that are attractive play a relatively small role in the current resource portfolio, adding these resources in significant quantities over the next decade is not likely to raise serious issues in this region. **Sequence:** These resources have short lead times, ensuring sufficient supply and allowing decision makers to wait to decide about less attractive options.

CONCLUSION

The analytic tools and policy instruments identified in the study of decision making in the face of ambiguity can help decision makers to become 'comfortable with' dramatically increased uncertainty and to be better able 'to manage what they have become much less able to master.' Exhibit ES-7 combines the 'new" ambiguity scale with the traditional core of utility regulation – levelized cost to identify the best path to the future. The route is clear. It begins with efficiency, wind and a mix of other renewables, with gas as a complement. It can then proceed on one of two paths, a renewable route that goes through solar and offshore wind, or a fossil fuel path that includes carbon capture and storage. Nuclear is the most unattractive of the resources.

EXHIBIT ES-7: AMBIGUITY AND LEVELIZED COST: A ROAD MAP FOR RESOURCE ACQUISITION



Source: author, see text

I. INTRODUCTION

A. MEETING THE CHALLENGE OF A COMPLEX DECISION MAKING ENVIRONMENT

Energy policy and regulatory decision making in the American electricity sector have always been a challenge because the U. S. is among the most electricity intensive of all nations in the world[1] and because it has an extremely wide set of resources with which to meet its electricity needs.[2] In the past quarter of a century fierce debate about the existence and response to climate change, a roller coaster ride in fossil fuel prices and a fizzled "nuclear renaissance," punctuated by the worst major accident outside of Russia in the history of the industry,[3] have made things much more difficult by casting doubt on the three primary fuels on which the U.S. relies for 90 percent of its electricity. [4]

Notwithstanding the ambiguity, decision makers are under constant pressures to ensure adequate electricity supply at affordable prices because electricity is a critically important building block of modern life.[5] Traditionally, this responsibility has been discharged with an approach that combined integrated resource planning with the principle of prudence. Utilities are asked to do what a prudent person would. Using the best decision making tools applied to the best available data with the full range of options and possibilities considered, they are supposed to choose the least cost resources that provide reliable electricity.

This paper argues that the insights and recommendations from the study of financial portfolio and real options analysis, technology risk assessment, reliability/risk mitigation management and Black Swan Theory all indicate that the 20th century approach to resource acquisition in the electric utility industry is ill-suited to the 21st century economic environment. Indeed, it can be argued that the dramatic change in the terrain of decision making may have rendered obsolete the approach taken in a wide range of regulatory proceedings, including integrated resource planning, general rate cases and review of purchased power agreements. These proceedings must analyze and project key factors over long periods like fuel price scenarios, environmental costs and capital costs. They frequently consider projections of construction periods and environmental impacts under different assumptions. Terms and conditions of purchased power agreement are evaluated against this set of uncertain factors.

In the current environment the core principles of prudency and least cost planning should be reaffirmed, but a prudent, integrated, least-cost resource plan must

- be hedged against **risk**,
- maximize options to reduce **uncertainty**,
- be flexible with respect to outcomes that are, at best, **<u>vague</u>** and
- be insulated against **<u>ignorance</u>** of the unknown. [6]

B. ANALYTIC APPROACH

The lengthy period of turmoil in the electricity sector has stimulated a search for new analytic tools to evaluate options. The academic literature and trade press are thick with examples,[7] borrowed primarily from the financial literature on risk evaluation and hedging, but these have not penetrated deeply into the utility resource planning process.[8] Three factors may account for the lack of uptake of these models. First, they are extremely complex.[9] Second, at root, they are still subjective, involving expert opinion-based assumptions, which, combined with their complexity, renders them far from transparent. Third, there have been several spectacular failures of these models.[10]

However, this paper shows that the drawbacks of the formal models do not mean that the concepts or principles on which they are based are invalid. Rather, the application of the principles needs to be simplified, made transparent and focused on conclusions that are directly relevant to regulatory decision making in the electricity sector.

Building on earlier, empirical analysis of alternative ways to meet electricity needs in the current environment,[11] the goal of this paper is to propose a comprehensive analytic framework that allows the principles for the analysis of risk, uncertainty, vagueness and ignorance that is being developed and used across society to better inform regulatory decision making without recourse to extremely complex statistical models or suggesting that regulators abandon their responsibility to the "quants."[12]

The paper provides a map of knowledge for policy makers and regulators to use in navigating the increasingly perilous terrain of resource acquisition to meet the need for electricity in the 21st century. The map of knowledge incorporates, refines and extends the foundations of electricity resources decision making. Noting that least cost has always involved reliability, safety and environmental concerns, in addition to cost, this analysis shows that in the current environment, least cost, prudent resource acquisition requires regulators to make choices that must recognize a great deal of ambiguity in the current environment.[13]

Neither the data sets used nor the recommendations are news to regulators; they have certainly heard them before. It is the goal of this paper to make these recommendations more compelling by grounding them in an analytic framework that shows that they are the prudent thing to do under the current decision making conditions.

C. OUTLINE

The paper is divided into two parts. Part I presents the analytic framework. Section II presents the theoretical background by reviewing several major schools of thought that have addressed the issue of decision making under uncertainty. Section III presents policy recommendations and describes the tools that can be used to analyze risk, uncertainty, vagueness and ignorance in the electricity sector is located and the analytic and policy tools to improve decision making.

Part II presents an empirical application of the framework to the contemporary terrain of resource acquisition in the electricity sector. Section IV lays the empirical foundation for the analysis by discussing the cost factors that have traditionally been the basis for resource decisions and reviews two recent estimates of the cost of a large number of alternative resources. These are the basis for the empirical analysis in the paper. The map of knowledge is applied to Lazard's *Levelized Cost of Energy Analysis*[14] and the California Energy Commission's *Comparative Cost of Central Station Electricity Generation*[15] to demonstrate its usefulness. These cover seventeen resources (including efficiency) and provide detailed ranges of estimates for fixed (capital, cost of capital) and variable costs (O&M, fuel, carbon), as well as qualitative assessments of key resource characteristics and trends.

Section V begins with an examination of the terrain of decision making where outcomes are known. This is the area of risk and uncertainty. Here the analysis is quantitative. It then examines the terrain of decision making where outcomes are not known. This is the area of vagueness and ignorance. Here the analysis is more qualitative, although metrics are suggested.

The paper highlights the relationship between wind and natural gas for both pedagogical and policy reasons.

- The carbon constraint that looms in the future of the electricity sector plays a key role in determining the terrain of decision making and gas an wind are seen as important low-carbon options.
- Among the low-cost, low-carbon options available in the U.S., they are close in cost, so they highlight the importance of other considerations.
- Among the low-cost, low-carbon alternatives, they have the potential to play the largest role in the short and mid-term in meeting need for electricity in a low carbon environment.
- Gas and wind can have a complementary relationship.
- There has also been a recent shift in the position of natural gas. New technologies have increased the recoverable resource base, driving down the cost, but those technologies raise significant environmental issues that potentially increase the societal impacts and raise the risk of gas.
- As a result of all of the above, important decision about which alternatives to pursue between gas and wind are being made in the present, decisions that should be informed by a rigorous analytic approach.

PART I:

MAPPING THE TERRAIN OF DECISION MAKING

II. IDENTIFYING THE REGIONS OF KNOWLEDGE

A. THE DIMENSIONS OF KNOWLEDGE

Over the past half century a number of analytic tools and investment strategies have been developed to deal with the ambiguity that affects decision making, including broad frameworks that map the terrain of knowledge into four regions, as shown in Exhibit II-1. As shown in Exhibit II-1, the efforts to map the terrain of knowledge start from the premise that there are two primary sources of ambiguity. Decision makers may lack knowledge about the nature of outcomes and/or they may lack knowledge about the probabilities of those outcomes. Four regions of knowledge result from this basic analytic scheme, risk, uncertainty, vagueness and ignorance. Each region of knowledge presents a distinct challenge to the decision maker.

These two dimensions have long been recognized in analytic models of decision making under uncertainty. They have been given different names, but the underlying concepts are the same. For example, the older engineering/project management literature defined them as follows.

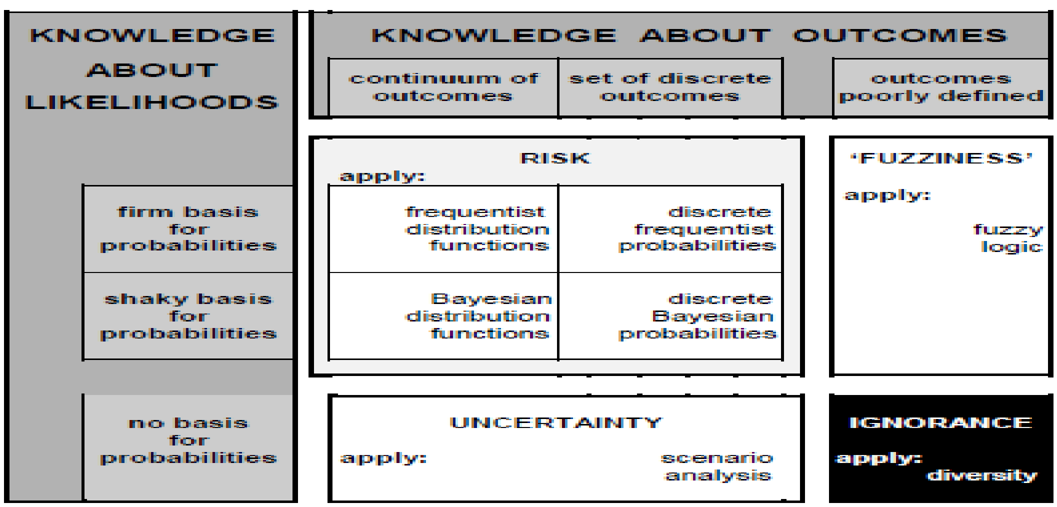
> Two dimensions of the environment are identified. The simple-complex dimension is defined as the number of factors taken into consideration in decision making. The static-dynamic dimension is viewed as the degree to which these factors in the decision unit's environment remain basically the same over time or are in a continual process of change. Results indicate that individuals in decision units with dynamic-complex environments experience the greatest amount of uncertainty in decision making. The data also indicate that the static-dynamic dimension of the environment is a more important contributor to uncertainty than the simple-complex dimension. [16]
>
> Uncertainty: Characteristic of a situation in which the problem solver considers the structure of the problem (including the set of relevant variables) as given, but is dissatisfied with his or her knowledge of the value of these variables.
>
> Ambiguity level 1: Characteristic of a situation in which the problem solver considers the set of potential relevant variables as given. The relationships between the variables and the problem solving algorithm are perceived as in need of determination.
>
> Ambiguity level 2: Characteristic of a situation in which the set of relevant variables as well as their functional relationship and the problem solving algorithm are seen in need of determination.
>
> In the case of uncertainty reduction the key tasks are information gathering and integration. In the case of ambiguity reduction, the tasks are model building, negotiation, problem framing evaluating and reframing, and model testing.[17]

Exhibit II-1: Framing the Terrain of Knowledge

Risk Management: Uncertainty-Ambiguity Matrix

	Uncertainty Low	Uncertainty High
Ambiguity Low	Model Using Variables known Values known Relationships known	Model Using Variables known Values unknown Relationships known
Ambiguity High Ambiguity Level 1	Model Building Variables known Values known Relationships unknown	Model Building Variables known Values unknown Relationships unknown
Ambiguity High Ambiguity Level 2		Variables unknown Relationships unknown

Technology Risk Analysis



Black Swan Theory

APPLICATION / DOMAIN	Simple payoffs	Complex payoffs
Distribution 1 ("thin tailed")	Extremely robust to Black Swans	Quite robust to Black Swans
Distribution 2 ("heavy" and/or unknown tails, no or unknown characteristic scale)	Quite robust to Black Swans	**LIMITS of Statistics – extreme fragility to Black Swans**

Sources: Andrew Stirling, *On Science and Precaution in the Management of Technological Risk* (European Science and Technology Observatory, May 1999), p. 17; Nassim Nicholas Taleb, *The Black Swan* (New York: Random House, 2010), p.365. Schrader, Stephen Schrader, William M. Riggs and Robert P. Smith, 1993, *Choice over Uncertainty and Ambiguity in Technical Problem Solving,* Alfred Sloan School of Management, Working Paper #3533-93-BPS, February 1993.

The literature on Reliability and Risk Mitigation Analysis summarizes the challenges as follows:

> NASA space exploration should largely address a problem class in reliability and risk management stemming primarily from human error, system risk and multi-objective trade-off analysis by conducting research into system complexity, risk characterization and modeling, and system reasoning. In general, in every mission we can distinguish risk in three possible ways: a) known-known, b) known-unknown, and c) unknown-unknown….
> Human reliability in systems cannot be verified with full coverage and components will fail or degrade, operators will make mistakes, and operating environments are uncertain. In addition the state of the system and its environment may dynamically increase control complexity or decrease reaction times such that traditional control means are inadequate.[18]

The project management literature describes the regions of knowledge as follows.

> Managing "in the presence" of risk, variance and uncertainty is the key to success. …Although each uncertainty type is distinct, a single project may encounter some combination of four types:
>
> *1. Variation* – comes from many small influences and yields a range of values on a particular activity.
> *2. Foreseen Uncertainty* – are uncertainties identifiable and understood influences that the team cannot be sure will occur. There needs to be a mitigation plan for these foreseen uncertainties.
> *3. Unforeseen Uncertainty* – is uncertainty that can't be identified during project planning. When these occur, a new plan is needed.
> *4. Chaos* – appears in the presence of "unknown unknowns."[19]

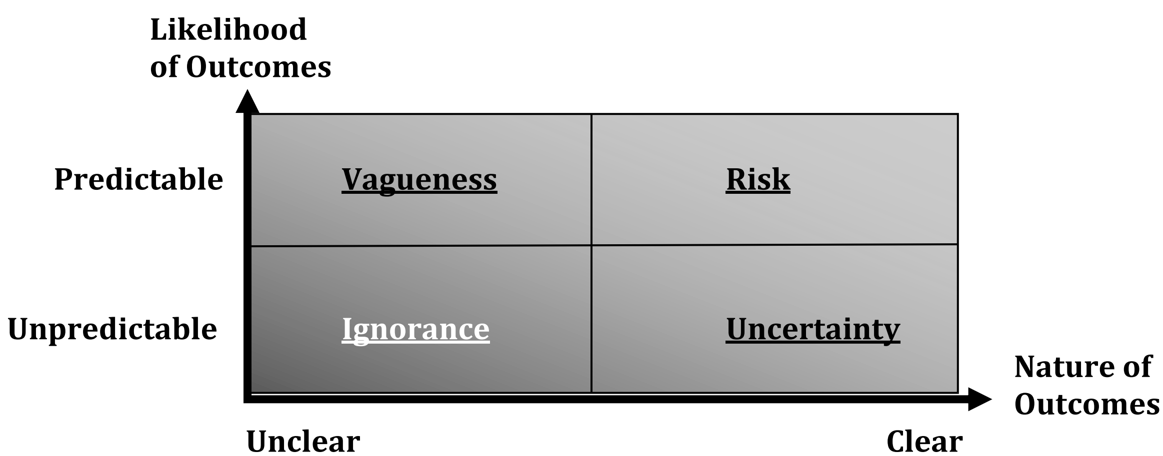
The regions of knowledge are defined simply in the Technology Risk Assessment literature are follows

- Risk is conventionally regarded to comprise the two basic elements of probabilities and magnitudes… Risk is a condition under which it is possible both to define a comprehensive set of all possible outcomes *and* to resolve a discrete set of probabilities (or a density function) across this array of outcome.
- The strict sense of the term *uncertainty,* by contrast, applies to a condition under which there is confidence in the completeness of the set of outcomes, but where there is acknowledged to exist no valid theoretical or empirical basis for the assigning of probabilities to these outcomes…

- The condition of 'fuzziness,' under which the various possible outcomes do not admit of discrete definition.
- Finally, there is the condition of *ignorance.* This applies in circumstances where there not only exists no basis for the assigning of probabilities (as under uncertainty), but where the definition of a complete set of outcome is also problematic. [20]

In Exhibit II-2 I have reversed the polarities from that in which the original arguments were presented. That is, I depict knowledge as increasing along two dimensions, knowledge about outcomes and knowledge about the likelihood of outcomes. The decision making space is darkest near the origin where knowledge is lacking. Exhibit II-2 inverts the colors to underscore this point. I think a good way to characterize the endeavor of policy, regulatory and financial analysts is to shed a little more light on the decision making environment so that we can see the swans a little better and make better choices.

EXHIBIT II-2: AMBIGUITY AND THE REGIONS OF KNOWLEDGE



Source: Author, see text

These frameworks arrive at the similar mapping of the terrain of knowledge and policy rules for coping with ignorance because they share a fundamental critique of the statistical models used in much predictive analysis.

- Statistical models are not very useful (are essentially useless) to predict rare events because the assumptions about frequencies or distributions necessary to build the models do not fit the reality of rare events.
- The application of inappropriate statistical models to predict improperly defined outcomes increases the exposure to rare events (surprise) because model builders "don't know what they don't know" and therefore they do not take the proper precautions against rare events.
- More broadly, the narrow optimization approach that flows from the statistical models that dominate economics increases the risk of harm from negative black

> swans because it produces social structures (organizations, institutions) that are overly specialized and unable to adapt to perturbation in their environment.

The contemporary critique focuses heavily on the over reliance on probabilities, which are suited to only one of the four regions. Technology Risk Assessment frames this issue as follows:

> Unfortunately, exclusively 'realist' or 'frequentist' probabilistic understandings of incertitude are open to serious doubts concerning the comparability of past and future circumstances and outcomes. The concept of a hypothetical series of trials is singularly inappropriate in cases where the decisions in question are large in scale or essentially unique, take place in a complex and rapidly changing environment or involve effectively irreversible impacts. Where the different aspects of performance are many in number and incommensurable in form, attempts to reduce this to a single metric further compound the difficulties. In disciplines such as financial investment appraisal , the existence of short time horizons and a dominating monetary 'bottom line' are often held to supersede such difficulties and justify the imposition of a single numeraire. Yet in fields such as industrial strategy, policy analysis and technology assessment, these issues of sale, novelty, uniqueness, complexity, change, irreversibility an incommensurability are manifestly the norm and cannot be readily set aside. In a strict 'frequentist' sense, then, techniques based on probability theory are quite simply inapplicable to many of the most important decision that take place within the economy. In these contexts at least… probability does not exist.[21]

Simplification of complex outcomes "can have explosive consequences since it rules out some sources of uncertainty; it drives us to misunderstanding the fabric of the world."[22]

The fundamental difference between Black Swan Theory and the other approaches is that it launches from and is preoccupied with a negative framing of the issue – a critique of the approaches analysts grounded in statistical models take. Black Swan Theory sees the primary task as insulation against the harmful effects of negative black swans. In fact, Black Swan theory suggests that "while in the first three quadrants you can use the best model you can find, this is dangerous in the fourth quadrant: no model should be better than just any model."[23] However, it does not examine those models, in part because they have been highly developed in the fields that the theory is critiquing.

Technology Risk Assessment takes a positive approach, seeking to examine the methods used in the other quadrants and extract useful insights, without losing sight of the limitations of the methods in the face of ignorance. The idea is to use the methods to explore each region to narrow the size of the region of ignorance. It may well be that ignorance is not the simple sum of risk, uncertainty and vagueness, but it is also reasonable to use what we can learn from the analysis of risk, uncertainty and fuzziness to narrow the scope of ignorance, as long as we do not make the mistake of assuming that that is all there is to ignorance. Technology Risk Assessment launches from a positive assessment of the value of diversity. The performance of a diverse system is superior because it fosters innovation and creativity, mobility, flexibility (anti-lock in), pluralism and a more rigorous selection process. Thus diverse systems diminish the impact of black swans and are better equipped to exploit the opportunity of white swans.

B. Describing the Terrain of Decision Making

As shown in Exhibit II-3, this paper presents an effort to integrate these various schools of thought into a comprehensive framework. The purpose of the framework is to identify the characteristics of each region, the analytic tools that are best suited to exploring it and the policy tools that are best able to deal with the state of knowledge in the region. The integrated approach allows the decision maker to array the options under consideration in a multi-attribute space. Decision makers may lack knowledge about the nature of outcomes and/or they may lack knowledge about the probabilities of those outcomes. Four regions of knowledge result from this basic analytic scheme, risk, uncertainty, vagueness and ignorance. Each region of knowledge presents a distinct challenge to the decision maker. I refer to the overall problem as one of ambiguity and then define four contributors to ambiguity.[24]

The topographic features show the primary challenge created by the conditions in the region. Two different ways of characterizing the regions are offered, which suggest that the problem of drawing a knowledge map has a long history. These are elaborated in Exhibit II-4. Under the navigational tools I include the analytic approaches and tools, as well as the data that are used in the below analysis. The policy tools and rules are grouped according to the regions for which they are best suited, but they should be viewed as a mutually reinforcing global set of principles.

Black Swan Theory argues that rare events have a huge impact on the development of daily life. The importance of rare events has been growing, but rare events are inherently unpredictable and humans have difficulty dealing with them.[25]

> "*The inability to predict implies the inability to predict the course of history…* But we act as though we are able to predict historical events, or, even worse, as if we are able to change the course of history… Black Swans being unpredictable, we need to adjust to their existence (rather than naively try to predict them). There are so many things we can do if we focus on antiknowledge, or what we do not know."[26]

Instead of focusing on gaining more precise knowledge about what is predictable, we need to gain a better understanding of what is unpredictable. Using the wrong models to try to predict the unpredictable causes us to expose ourselves to even greater risk and to be less prepared for events we failed to predict. The goal is not to predict, the future, but to offer observations about the possible rare events – "it is not easy to compute their probability, but it is easy to get a general idea about the possibility of their occurrence. We can turn these Black Swans into Gray Swans, reducing their surprise effect."[27]

EXHIBIT II-3: TOPOGRAPHY AND NAVIGATION TOOLS FOR THE REGIONS OF KNOWLEDGE

	REGIONS			
	IGNORANCE	VAGUENESS	UNCERTAINTY	RISK
TOPOGRAPHY				
Technology Risk Assessment				
Challenges	Unanticipated effects	Contested framing	Nonlinear systems	Familiar systems
Outcomes	Unclear	Unclear	Clear	Clear
Probabilities	Unpredictable	Predictable	Unpredictable	Predictable
Black Swan Theory				
Challenges	Black Swans Wild randomness	Sort of Safe	Safe	Extremely safe Mild randomness
Conditions	Extremely fragile	Quite robust	Quite robust	Extremely robust
Distributions	Fat tailed	Thin tailed	Fat tailed	Thin tailed
Payoffs	Complex	Complex	Simple	Simple
Reliability & Risk Mitigation Management				
Challenges	Chaos	Unforeseen uncertainty	Foreseen uncertainty	Variation
Conditions	Unknown/ unknowns	Unknown/ knowns	Known/ unknowns	Known/knowns
Characterizations				
Religious	Hell	Limbo	Purgatory	Land of the living
Greek Mythology	Pandora, Pythia	Damocles, Cassandra	Cyclops	Medusa
NAVIGATION				
Analysis				
Approach	Multi-criteria analysis	Fuzzy logic	Decision heuristics	Statistics
Tools	Diversity assessment	Sensitivity analysis	Scenario analysis	Portfolio evaluation
Focus	Internal resources/ structure	Internal resources/ structure	External challenges	External challenges
Data	Swan Search Consistency Unintended consequences Externalities Diversity Structural Variety, balance, disparity Alternative Instrument Sufficiency Adequacy Sequence	Vagueness Supply security Resource base Market scope Environmental impact Pollutants (air. Land water, waste) Greenhouse gasses	Uncertainty Capacity Construction period Sunk cost (Total capital = MW * $/MW)	Cost -Risk Levelized cost of energy Cost variability Fuel O&M Carbon ½ nuclear capital
Policy Tools				
Processes	Learning	Learning	Planning	Planning
Instruments	Insurance/diversity	Monitor & Adjust	Optionality	Hedging
Rules	TECHNOLOGY RISK ASSESSMENT Precaution Buy insurance for system survival Accept non-optimization Diversity Variety Balance Disparity BLACK SWAN THEORY Truncate Exposure Buy insurance for system survival Accept non-optimization Redundancy Numerical Functional Adaptive	TECHNOLOGY RISK ASSESSMENT Resilience Adaptability BLACK SWAN THEORY Multi- functionality What Works	TECHNOLOGY RISK ASSESSMENT Flexibility Across Time Across Space BLACK SWAN THEORY Optionality	TECHNOLOGY RISK ASSESSMENT Resilience Robustness Hedge BLACK SWAN THEORY Robust to Error Small, Confined, Early Mistakes Incentive & disincentives Avoid Moral Hazard Hedge

Sources: Black Swan: Nassim Nicholas Taleb, *The Black Swan* (New York: Random House, 2010), Postscript; Technology risk Assessment: Andrew Stirling, *On Science and Precaution in the Management of Technological Risk* (European Science and Technology Observatory, May 1999), p. 17, *On the Economics and Analysis of Diversity* (Science Policy Research Unit, University of Sussex, 2000), Chapter 2; "Risk, Precaution and Science; Toward a More Constructive Policy Debate," *EMBO Reports,* 8:4, 2007;Reliability and Risk Mitigation David A. Maluf, Yuri O. Gawdisk and David G. Bell, *On Space Exploration and Human Error: A Paper on Reliability and Safety,* N.D.; Gele B. Alleman, *Five Easy Pieces of Risk Management,* May 8, 2008; see also, Arnoud De Meyer, ChristophER H. Lock and Michel T. Pich, "Managing Project Uncertainty: From Variation to Chaos," *MIT Sloan Management Review,* Winter 2002.

EXHIBIT II-4: CHARACTERIZATIONS OF THE KNOWLEDGE DILEMMA

Religious

Ignorance is not bliss; it is hell for decision makers. Black Swan Theory focused on what it called the Fourth Quadrant (the region of ignorance), which, in my restatement, is closest to the origin. Decision makers are better off in Limbo than hell because in this space, characterized by vagueness, they can analyze contingencies and build in monitoring devices that adjust system performance. They are better off in purgatory than hell because, in this space characterized by uncertainty, they can analyze scenarios and buy real options delaying important decisions until the uncertainty is, hopefully, reduced. Unfortunately, there is no heaven on earth for decision makers dealing with electricity resource decisions; the best decision makers can hope for is to face risk, against which they can hedge.

In many religions, **Heaven** is a realm, either physical or transcendental in which people who have died continue to exist in an afterlife. Heaven is often described as the holiest place, accessible by people according to various standards of divinity, goodness, piety, faith or other virtues….

Many religions state that those who do not go to **heaven** will go to another place, hell, which is eternal in religions such as Christianity. Some religions believe that other afterlives exist in addition to heaven and hell, such as purgatory, though many hells, such as Naraka, serve as purgatories themselves. Some belief systems contain universalism, the belief that everyone will go to heaven eventually, no matter what they have done or believed on earth. Some forms of Christianity, and other religions believe hell to be the termination of the soul. http://en.wikipedia.org/wiki/Heaven

In many religious traditions, **Hell** is a place of suffering and punishment in the afterlife. Religions with a linear divine history often depict Hell as endless. Typically these traditions locate Hell under the Earth's external surface and often include entrances to Hell from the land of the living. Other afterlife destinations include Heaven, Purgatory, Paradise, Naraka, and Limbo. http://en.wikipedia.org/wiki/Hell

In the theology of the Catholic Church, **Limbo** (Latin *limbus*, edge or boundary, referring to the "edge" of Hell) is a speculative idea about the afterlife condition of those who die in original sin without being assigned to the Hell of the damned. Limbo is not an official doctrine of the Roman Catholic Church or any other. Medieval theologians described the underworld ("hell", "hades", "infernum") as divided into four distinct parts: hell of the damned (which some call Gehenna), Purgatory, limbo of the fathers, and limbo of infants. "Limbo of the Patriarchs" or "Limbo of the Fathers" (Latin *limbus patrum*) is seen as the temporary state of those who, in spite of the personal sins they may have committed, died in the friendship of God, but could not enter Heaven until redemption by Jesus Christ made it possible. http://en.wikipedia.org/wiki/Limbo.

Purgatory is the condition or process of purification or temporary punishment[1] in which, it is believed, the souls of those who die in a state of grace are made ready for Heaven. http://en.wikipedia.org/wiki/Purgatory.

Mythological risk classification

These risk types, named after metaphors from Greek mythology, are comprised by the following characterization of risks:

Damocles: high catastrophic potential, probabilities (widely) known

Cyclops: no reliable estimate for probabilities, high catastrophic potential

Pythia: causal connection confirmed, damage potential and probabilities unknown.

Pandora: causal connection unclear, high persistency and ubiquity

Cassandra: intolerable risk of high probability and great damage, but long delay between causal stimulus and negative effect

Medusa: large potential for social mobilization without clear scientific evidence for serious harm.

Damocles and Cyclops: risk-based. These risks can be handled and managed adequately by strategies and regulations based on the two main risk characteristics: extent of damage and probability of occurrence. That is particularly so with the Damocles class, since here the probabilities are well known. With the Cyclops class, precautionary measures are more appropriate, since here the probabilities are not well defined.

Pythia and Pandora: precautionary. These risks are characterized by a high degree of uncertainty as to probability of occurrence and extent of damage, hence a "just in case" approach may be justified.

Cassandra and Medusa: discursive. These risks are characterized by either a delay effect, where the dangers initially may not be known or perhaps are even ignored, or risks where presumably harmless effects are perceived as threats by certain portions of the public or pressure groups. These risks require knowledge-building strategies to raise awareness and confidence.

Klinke Andreas, Renn Ortwin, research blogging, risk analysis, risk management, risk society

http://www.husdal.com/2010/10/11/a-new-way-of-classifying-and-managing-risks/Renn, A. Klinke, O. (2001). Precautionary principle and discursive strategies: classifying and managing risks *Journal of Risk Research, 4* (2), 159-173 DOI: 10.1080/136698701750128105

Technology risk assessment frames the challenge as follows: "Knowing your ignorance is the best part of knowledge."[28]

> A 'scientific' approach to the regulatory appraisal of risk is conventionally taken to imply the use of quantitative aggregating techniques…. The basic aspiration underlying the use of 'risk-based' techniques is that in and of themselves, they offer a robust means to prescribe and justify commercial and regulatory decision-making in the governance of technological risk. The authority of this 'risk-base' approach lies in an appeal to monolithic notions of methodological rigour and on the unitary nature of the analytical results thereby obtained.
>
> For its part, a '*precautionary'* approach reflects a rather different perspective, introducing a wide range of emerging concerns in the risk governance debate. In the most general of terms, it contrasts with a reductive 'risk-based' approach in extending attention to theme such as complexity, variability and nonlinear vulnerabilities in natural systems. A precautionary approach highlights the consequent potential for 'surprise.' It places greater emphasis on active and dynamic choices between technology and policy alternatives than do 'risk-based' approaches.[29]

The precautionary approach to decision making argues that it requires a more active and dynamic approach to process, more than structure, but it is reliability and risk mitigation management that emphasizes these processes, particularly with regard to information flow and human error.

> In general, when work is distributed across space and time among multiple people, certain latent conditions necessarily exist that may lead to future mishaps. These include information sharing, coordination, communication, procedures, training, and knowledge capture and reuse. Information sharing may be absent, incomplete, incorrect, or not done in a timely manner. Coordination activities may be disorganized, untimely, missing, or unnecessarily difficult for a particular organizational structure. Poor communications practices, inappropriate initial framing of the interaction, poor training and poor procedure design may lead to poor information sharing and coordination, which may directly lead to mishaps… Distributed work also requires distributed knowledge; therefore, poor knowledge capture and lack of reuse are issues as well.
>
> The challenge in managing uncertainty, to whatever degree, is to find the balance between planning and learning. Planning provides discipline… Projects in which variation and foreseen uncertainty dominate allow more planning, whereas projects with high levels of unforeseen uncertainty and chaos require greater emphasis on learning.[30]

III. ADVICE AND TOOLS FOR DECISION MAKERS

A. Relevance of Knowledge Analysis to the Electricity Sector

Black Swan theory argues that the increasing importance of rare evens stems from the nature of the modern world.

> Our modern, complex, and increasingly recursive world… means that the world in which we live has an increasing number of feedback loops, causing events to be the cause of more events, thus generating snowballs and arbitrary unpredictable planet-wide winner-take all effects. We live in an environment where information flows too rapidly, accelerating epidemics. Likewise event can happen *because* they are not supposed to happen.[31]

A related second characteristic of the modern world that increases the importance of rare events is their viral nature which results in scalability – the tendency for impacts to spread widely. "Those who start, for some reason getting some attention can quickly reach more minds than others and displace the competitors,[32] fads will be more acute, so will runs on banks… a very strange virus spreading throughout the planet."[33]

This is particularly important for policy and regulatory decision makers who deal with electricity resource acquisition. They are in an extremely difficult situation because they have the real time challenge of keeping the lights on, preferably at reasonable and affordable prices. The challenge flows from the physics of electrons, which are very demanding, and the importance of electricity in daily life. The characteristics of the contemporary world that cause the increasing importance of Black Swan, rare events are characteristics that the electricity grid has always possessed. It is a recursive, scalable network through which black swans can spread virally.

As a description of the challenges of a hostile environment in which the terrain and presence of swans is difficult to see, the expression "fog of war" interpreted to mean that "[w]ar is inherently volatile, uncertain, complex and ambiguous" [34] can be aptly applied to these efforts to map the terrain of knowledge.[35] The advice offered to the military commanders when contemplating "cyberwar" is similar to the advice derived from the schools of thought cited in this section.

> We need to practice with the "radios turned off" and officers must become comfortable with uncertainty rather than keep grasping for more certainty. While we have the most robust communications, we also want to make sure we can operate with none of it… Advantage on any battlefield – albeit episodic and ephemeral – will favor the commanders who best manage what they cannot master.[36]

Resource acquisition in today's electricity sector may not be as daunting as war or space exploration, but it faces the "fog of the future," which, at the start of the 21st century, has certainly become much more "volatile, uncertain, complex and ambiguous." I suggest that the analytic tools and policy instruments identified by these efforts to describe the regions of knowledge can help decision makers to become comfortable with dramatically increased uncertainty and to be better able to manage what they have become much less able to master.

B. POLICY PRINCIPLES

Knowledge and action go hand in hand in these schools of thought.

> A map is a useful thing because you know where you are safe and where your knowledge is questionable. So I drew… a tableau showing the boundaries where statistics work well and where it is questionable. Now once you identify where the danger zone is, where your knowledge is no longer valid, you can easily make some policy rules.[37]

The policy principles that can be extracted from this list fall into half a dozen broad categories including the following:

Precaution	**Diversity**	***Redundancy***	**Resilience/*Durability***
Truncate Exposure	Variety,	*Numerical*	Adaptability
Buy insurance for system survival	Balance,	*Functional*	*Multi-functionality*
Accept Non- optimization	Disparity	*Adaptive*	*What Works*

Flexibility/*Optionality*	***Robustness to Error***
Across Time	*Small, Confined, Early Mistakes*
Across Space	*Incentive & disincentives*
	Avoid Moral Hazard
	Hedge

Exhibit III-1 provides detail which shows that Technology Risk Assessment and Black Swan Theory both draw heavily on biological and ecological sciences for their recommendations. Both analogize and emphasize the importance of insurance and look to natural forms, such as redundancy, flexibility and adaptability.

The practical advice for decision makers that can be extracted from the framework is quite relevant to the electricity sector as well. While decision makers must start from their traditional data, they should challenge the underlying assumptions and recognizing that in this space we generally know less than we would like. The framework offers broad principles policy makers should apply:

- Identify the trade-offs between cost and risk and hedge to lower risk.
- Reduce exposure to uncertainty by buying time.
- Keep options open by acquiring small assets that can be added quickly.
- Minimize surprises by avoiding assets that have unknown or uncontrollable effects.

EXHIBIT III-1: DEFINING POLICY RULES FOR THE REGIONS OF KNOWLEDGE

Technology Risk Analysis

Knowing your ignorance is the best part of knowledge. Precaution: Specific methods, techniques, instruments or measures which implement an approach which directly addresses the problems of multidimensionality, incommensurability and ignorance. (a: 40)

Diversity: diversity remains effective (at least in part) *even if the source or modalities of the prospective disruptions are effectively unknown* By maintaining an evenly balanced variety of mutually disparate options, we may hope to resist impacts on any subset of these, even if we do not know in advance what these impacts might be. parallel series of different strategies Diversity => the inclusion
of options which appear to perform less well as an insurance against changes in performance in other options (a: 27)
Variety: e.g. the number of functionally redundant – but morphologically or operationally distinct – options sustained in parallel (b: 39)
Balance: the pattern in the apportionment across the relevant categories of the options. (b: 39)
Disparity: the nature and degree to which the categories themselves are different from each other (b: 40)

Flexibility
Capacity to retain as many options for as long as possible in advance of commitment, and
Ability to withdraw (when commitment is made) without great penalty if prohibitive conditions arise (a: 27)

Resilience: capacity to sustain performance under external perturbation (b: 27)
Robustness: The capacity to sustain performance under extreme perturbation maintaining an established internal structure
Adaptability: The capacity to sustain performance under external perturbation by changing internal structures (a: 27)

Black Swan Theory

The Black Swan attempts to provide a map of where we get hurt by what we don't know, to set systematic limits to the fragility of -- knowledge. and to provide exact locations where these maps no longer work (347) The most obvious way to exit the Fourth Quadrant is by "truncating," cutting certain exposures by purchasing insurance, when available (370); One can buy insurance, or construct it to "robustify" a portfolio (371)

Redundancy equals insurance and the apparent inefficiencies are with the cost of maintaining these spare parts and the energy needed associated – to keep them around in spite of their idleness exact opposite of redundancy is naïve optimization (312)

Numerical, functional, adaptive: The availability of spare parts, where the same function can be performed by identical elements, very often the same function can be performed by two different structures. When an organ can be employed to perform a certain function that is not its current central one (316- 317). Species density: Based on the nonlinearity in damage, spread the damage … larger environment are more scalable allowing the biggest to get even bigger, at the expense of the smallest… the successful killer will spread vastly more effectively (317)
Avoid over-specialization, promote optionality The organism with the largest number of secondary uses is the one that will gain the most from environmental randomness and epistemic opacity (318) Optionality – since you have the option of taking the freebie from randomness(319) Compensate complexity with simplicity (375)

Robust to error: Nothing should ever become too big to fail. What is fragile should break early, while it is small (374). Big is ugly & fragile: Mother Nature does not limit the interactions between entities; it just limits the size of the units (314)

Confine mistakes The idea is simply to let human mistakes and miscalculations remain confined and to prevent their spreading through the system (322)
Durability: Things that have worked for a long time are preferable (371) No Socialization of losses and privatization of gains (374).
No incentives without disincentives (375)

Reliability & Risk Mitigation

Development of critical technologies that **provide system resiliency will enable future systems to adapt and recover from these unanticipated problems. …**

Current technologies are not optimal for carrying out effective risk mitigation as they lack significant capability to assess system condition or to validate system performance. **System robustness, redundancy and capability for rapid recovery are currently inadequate….**

NASA space exploration should largely address a problem class in reliability and risk management stemming primarily from human errors, system risk and multi-objective trade-off analysis, by conducting research into system complexity, risk characterization and modeling, and system reasoning... Development activity will have to support **risk analysis, design robustness, failure modeling, and system trade-offs** through the entire lifecycle of the enterprise, with **particular emphasis on early-phase capabilities.**

Development of *tools for identifying, assessing and trading risks* before and during formulation…

Development *of safety and risk related systems analysis tools* combines two thrusts, **addressing a) how risk profiles can be maintained and utilized through the fully lifecycle**, and b) **how system evolution affects designs.**

Development of methods and tools that constitute a human learning 'feedback' loop. Their goal is to improve *our understanding of the factors that contribute to aerospace accidents* and to develop ways to use that experience to improve designs.

Sources: Nassim Nicholas Taleb, *The Black Swan* (New York: Random House, 2010), p.365; Andrew Stirling, *On Science and Precaution in the Management of Technological Risk* (European Science and Technology Observatory, May 1999), p. 17, *On the Economics and Analysis of Diversity* (Science Policy Research Unit, University of Sussex, 2000), Chapter 2; "Risk, Precaution and Science; Toward a More Constructive Policy Debate," *EMBO Reports,* 8:4, 2007; David A. Maluf, Yuri O. Gawdisk and David G. Bell, *On Space Exploration and Human Error: A Paper on Reliability and Safety,* N.D.

- Create systems that monitor conditions and can adapt to change to maintain system performance.
- Buy insurance where possible.
- Recognize that diversity is the best insurance against ignorance.
- Build resilience with diversified assets by increasing variety, balance and disparity in the resource mix.

To apply this advice, we need more precise tools to analyze the terrain of the regions of knowledge.

C. RISK

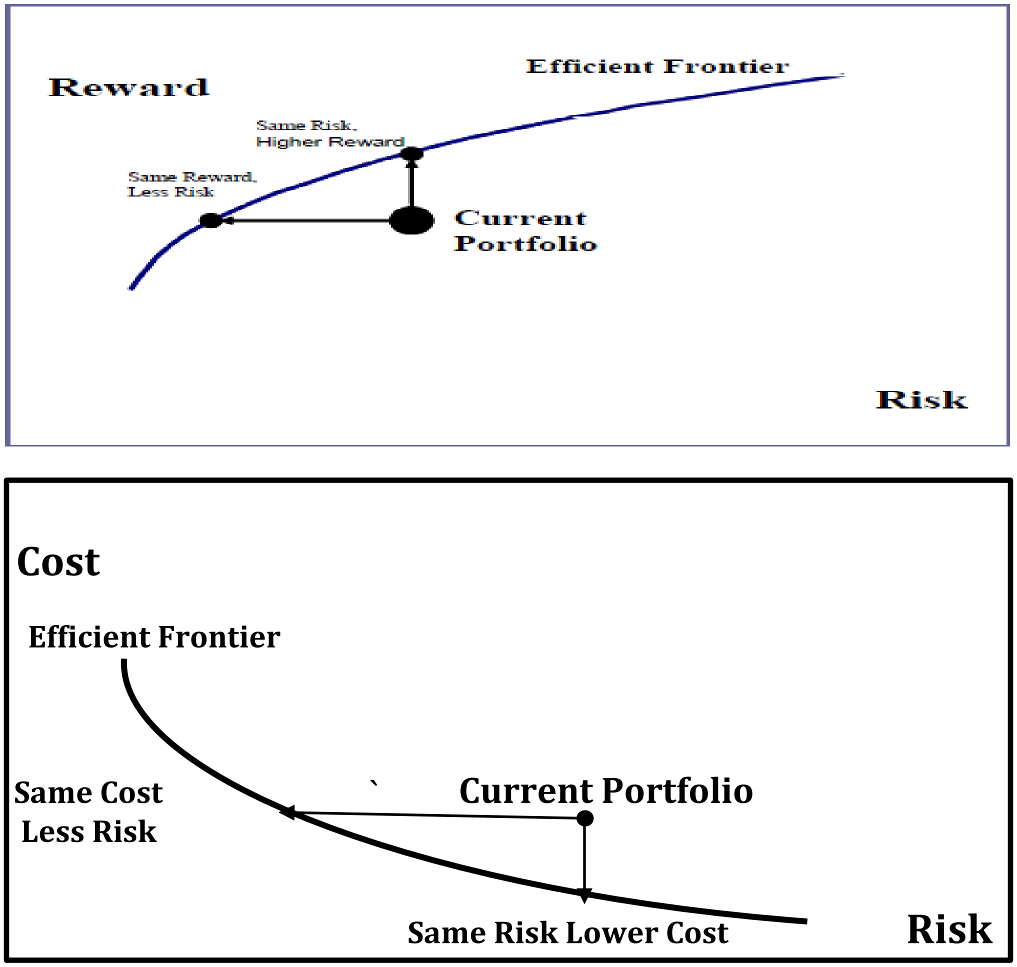
In some circumstances the decision maker can clearly describe the outcomes and attach probabilities to them. Risk analysis allows the decision maker to hedge by creating a portfolio that balances more and less risky assets. This risk analysis has it origin in financial analysis and was first articulated over half a century ago.

Financial market theory provides a framework for evaluating the trade-off between performance and risk. The top graph in Exhibit III-2 presents the basic approach, as a publication from the National Regulatory Research Institute attempted to introduce it to regulators.[38] Investors want to be on the efficient frontier, where risk and reward are balanced. They can improve their expected returns if they can increase their reward without increasing their risk, or they can lower their risk without reducing their reward. In the financial literature, risk is measured by the standard deviation of the reward.[39]

In applying this framework to the evaluation of generation options, analysts frequently measure reward as kilowatts per dollar (a measure of economic efficiency). This is the inverse of cost. Indeed, they use the two – efficiency and cost – interchangeably.[40] The lower graph in Exhibit II-3 shows the cost/risk frontier. Options that would move the portfolio toward the efficiency frontier should be adopted since they embody lower cost and/or risk.[41]

Much of the literature on portfolio and real option management as applied to the electricity sector focuses on identifying the optimal long- term mix of resources. This creates problems from the point of view of the current analysis. Since the longer term conditions of the system are unknown, the analysis must make assumptions about constraints and run numerous scenarios, using statistics to present patterns of results. The results are complex and they decide little. The patterns are instructive but the cost in terms of complexity and transparency is significant.

EXHIBIT III-2: RISK/COST REWARD, COST/RISK ANALYSIS



Source: Ken Costello, *Making the Most of Alternative Generation Technologies: A Perspective on Fuel Diversity,* (NRRI, March 32005), p. 12, upper graph.

An alternative approach that can be found in the literature is to use these tools to deal with more incremental decisions (see Exhibit III-3). The map of the terrain of decision making indicates which alternatives are preferable today, on an individual basis. In other words, rather than worry about exactly where the efficient frontier lies, we focus on the relative position of the individual technologies in the decision space that are moving in the right direction. This approach was offered in direct response to a desire for more incremental and transparent applications of the theory. As shown in the top graph in Exhibit III-3, movement toward the origin is considered positive.

In the empirical analysis below, I use the array of resources to map two key features of the terrain of decision making. First, I identify a cost-risk frontier defined by gas. Natural gas is the fuel of choice at present but, based on recent history and contemporary debates, it may expose ratepayers to a great deal of risk. The cost-risk tradeoff may be substantial. Resources that involve much less risk are more attractive, particularly if they

EXHIBIT III-3: APPROACHES TO EVALUATING COST RISK TRADE-OFFS

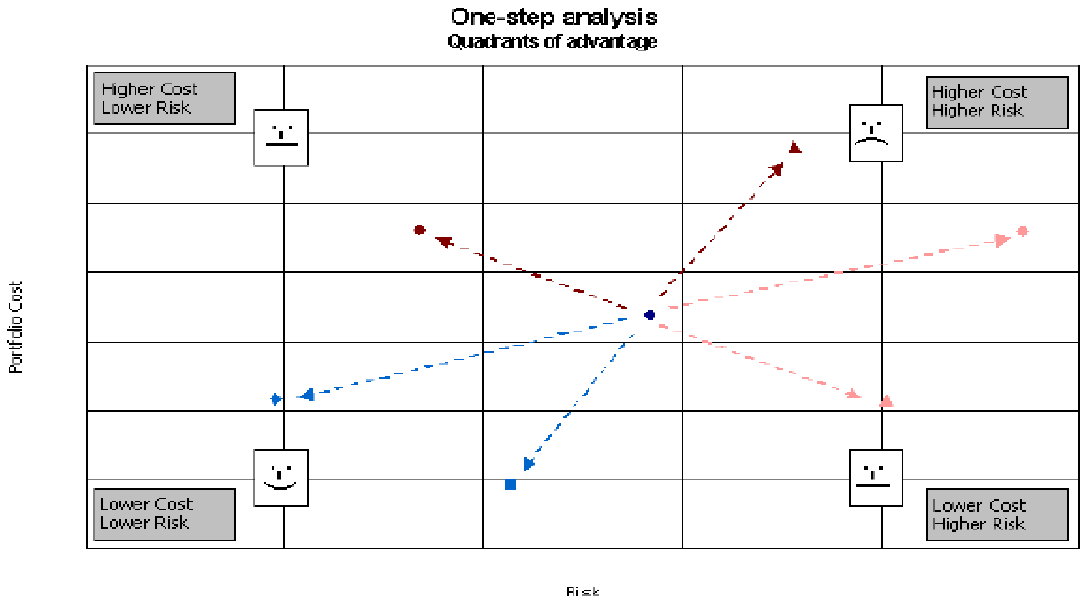
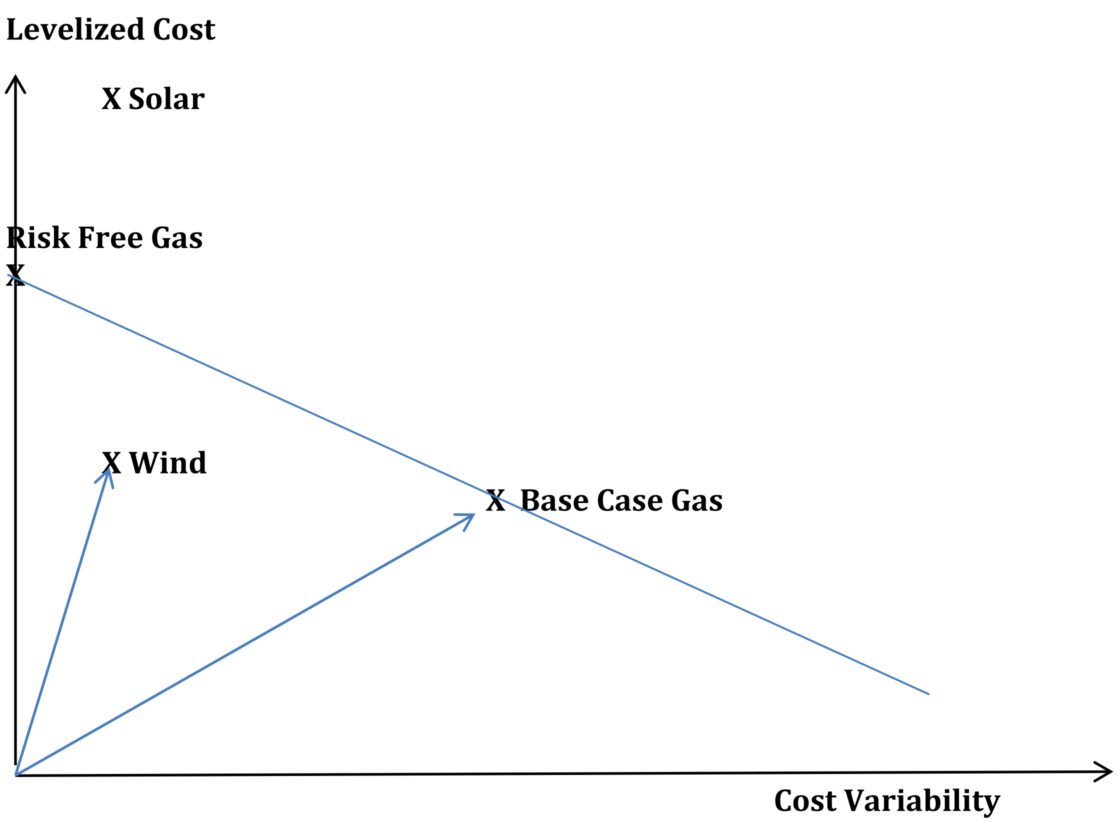


Figure D.1 *Possible risk-cost impacts*

Source: Jansen, J.C., L.W. M. Beurskens, and X, van Tilburg, 2006, *Application o Portfolio analysis to the Dutch Generating Mix,* ECN, February,



Source: author see text

do not involve higher costs. I calculate the risk free price of gas as the highest cost for power generated with natural gas, assuming all of the variable costs are at their highest levels.

Second, I use the array of resources to calculate a relative attractiveness scale. The distance of a resource from the origin measures the risk-cost characteristics of the resource (giving risk and cost equal weight). Resources that are farther from the origin (measured as the Euclidean distance with each factor weighted equally) are less attractive.

While the quantification of costs and benefits and risk should include the full life of the project, 'inferior' resources should not be chosen if the supply is adequate and the decision maker can wait and still have time to select the rejected alternative. This focus on the near and mid-term incremental decisions is consistent with regulatory practice, which tends to rely on ten year plans. Moreover, since all of the resources that are generally considered could be brought online within ten years, that is the practical limit for having to make a decision about which resources to acquire.

As long as supply will be sufficient when incremental decisions are taken and there is adequate time to acquire resources that will ensure sufficiency in the future, incremental choices that are headed in the right direction are prudent and preferable. In this analysis, the key constraint is to distinguish between low carbon resources (including carbon capture and storage) and non-low carbon resources. That is the primary constraint on future resources in the current environment. As long as the incremental choices are low carbon and sufficient, the incremental resources are headed in the right direction and should be chosenn.

D. Uncertainty

In some circumstances the decision maker can clearly describe the outcomes but cannot attach probabilities to them. Here the decision maker would like to keep options open – to delay decisions if possible – until more information reduces the uncertainty. If the decision maker cannot wait, then the path chosen should be flexible, so that it affords the opportunity to deal with whatever outcomes occur. Real option analysis also emerged from the financial sector – a little over a quarter of a century ago.

Real option analysis asks whether the expected outcome can be improved by waiting for more information.

> Unlike traditional discounted cash-flow analysis, real option theory explicitly accounts for flexibility in the manner in which an asset is developed and operated, often leading to higher asset values, as well as different optimal capacity planning and operation decisions. For example, accounting for different plant construction lead times in the face of demand uncertainty can lead to significantly different optimal capacity planning strategies.[42]

A discussion of the real option approach to assessing the impact of the uncertainty surrounding climate change policy provides a more technical summary of this issue. It describes the value of waiting as follows, with respect to the Exhibit III-4:

EXHIBIT III-4: REAL OPTION ANALYSIS APPLIED TO CLIMATE POLICY

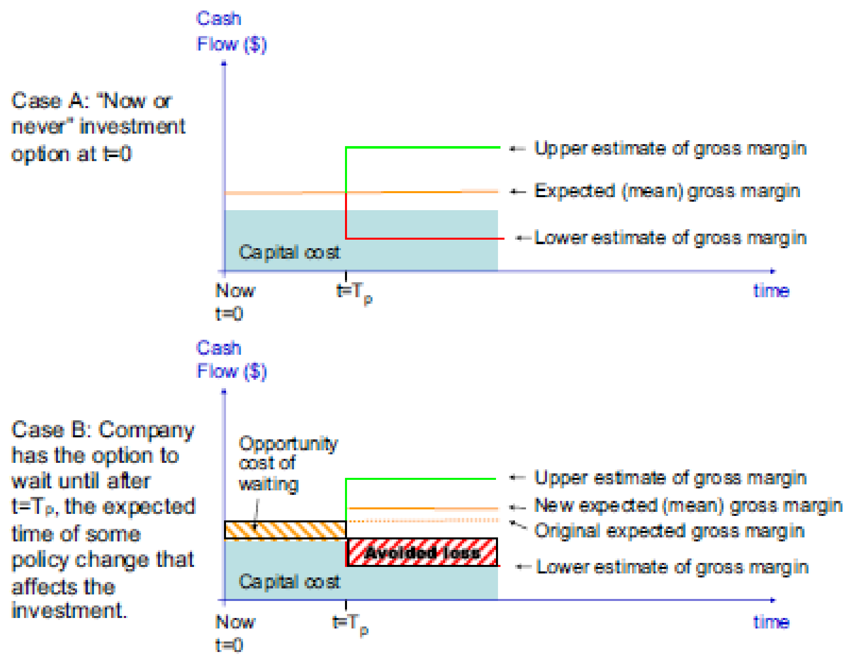


Fig. 1. A conceptual framework to show the value of waiting: (A) "Now or never" investment option at $t = 0$. (B) Company has the option to wait until after $t = T_p$, the expected time of some policy change that affects the investment.

> In [Case A] the company facing this uncertain cash flow has to choose whether or not to invest in the project—it does not have the option to wait. The expected 'best guess' is that the project will continue to be profitable, so that the project satisfies the normal investment rule (i.e. gross margin is greater than capital cost) justifying immediate investment. In [Case b], the company has the opportunity to wait until after time T_p before making the investment. This allows it to avoid the potential loss that might occur if conditions turn out worse than expected (shown as a zebra dashed area). Waiting could lead to a greater return on investment—the new expected gross margin from the project would be higher than the original expected gross margin without the option of waiting—but revenues from the project would only accrue after time T_p if the project does go ahead. It would be rational to invest prior to T_p only if this value of waiting is overcome by the opportunity cost of waiting (i.e. the income forgone due to delaying the investment). In order to trigger immediate investment, the expected gross margin of the project would need to exceed some threshold level which makes the opportunity cost of waiting greater than the value of waiting. This threshold depends on the length of time before T_p, the size of the anticipated price shock and the discount rate. These thresholds are calculated using a

cash-flow model in which climate change policy is represented using carbon price as a proxy.[43]

E. VAGUENESS

In yet another circumstance, decision makers may not be able to clearly identify the outcomes, but they know that the system will fluctuate. Here the decision maker wants to take an approach that can monitor the condition of the system and adapt as it changes. An approach to this situation of vagueness called fuzzy logic emerged from the computer science and engineering fields at about the same time as real option analysis.

The analysis of fuzzy logic has its origins in computer theory and its applications in various forms of artificial intelligence and system control. Rather than assume simply binary outcomes, fuzzy logic recognizes a much more complex condition, where outcomes occur in degrees and real time systems exhibit identifiable trends. Applications of the theory utilize monitors that recognize trends and adjust the system performance to stay within preset parameters.

> Advances in "fuzzy logic" … have been incorporated into a logical form that continues to produce successes in such fields as meteorology, politics, biology, engineering, art, and economics. The success of fuzzy logic… underscores the types of achievements and refinements made possible when scientists depart from a traditional two-valued system to a many valued system. A many-valued logic capable of handling vague or "fuzzy" concepts (e.g., slow/fast, cheap/expensive, liberal/conservative, hot/cold) allows machines to operate almost as flexibly and "intuitively" as we do… By using fuzzy logic, scientists can often arrive at a practical solution to intractable problems that have arisen out of systems that are too complex to analyze in any other manner. In short, Zadeh provided a basis for a subjective quantification of essentially qualitative abstraction. This approach has permitted better maps of varied, complex territories.[44]

The application of knowledge in this sector is more active than in the realm of risk or uncertainty. Hedging or optionality are structural characteristics, monitoring and adjustment deal more with flows. An iterative, pragmatic process of design, build, monitor, correct, redesign, rebuild, monitor, correct, etc., is the goal.[45]

F. IGNORANCE

In the most challenging situation knowledge of the nature of the outcomes and probabilities is limited.

> This is a state under which there exists neither ground for the assignment of probabilities, *nor* even a basis for the definition of a broad set of outcomes… [T]his broad concept of 'ignorance' is nevertheless of considerable practical importance. It arises from many familiar sources, including incomplete

> knowledge, contradictory information, data variability, conceptual imprecision, divergent frames of reference and the intrinsic indeterminacy of many natural and social processes. Put at its simplest, ignorance is a reflection of the degree to which we don't know what we don't know. It is an acknowledgment of the importance of the element of 'surprise' (whether positive or negative in nature) – emerging not just from the actuality of unexpected events, but from their very possibility.[46]

Even in this state of ignorance, decision makers have strategies to cope and policies that can insulate the system. Here the analyst looks more inward, to the characteristics of the system to identify those that are most important, rather than outward to the threats from the environment, and builds systems that ensure critical functions are performed under the most stressful of circumstances. Multi-criteria evaluations of possible outcomes are conducted and strategies that buy insurance and diversify assets are recommended – summarized in the expression, "put lots of eggs in lots of baskets." This framework has been developing for about two decades in technology risk assessment and the energy sector.

> Of all the many strategies developed to deal with incertitude, only one has been elevated to the status of a figure of speech... only fools put all their eggs in one basket. The potency of this cliché is evident in many fields, where diversification is felt to be a major strategic response to incertitude. In the energy policy literature, references to the need to diversify reliance on different options are ubiquitous.[47]
>
> Attention tends to focus on what are held to be relatively well-known sources of disruption, like fuel-price fluctuations, constraints on the availability of specific primary resources or a restricted number of clearly identified threats. However, to focus exclusively on these relatively readily characterized parameters in some ways circumscribes the real value of diversification. As distinct from a range of more specific and targeted preventive and mitigating strategies, diversity remains effective (at least in part) *even if the source or modalities of the prospective disruptions are effectively unknown.* By maintaining an evenly balanced variety of mutually disparate options, we may hope to resist impacts on any subset of these, even if we do not know in advance what these impacts might be.[48]

PART II:

EXPLORING THE TERRAIN OF 21ST CENTURY ELECTRICITY RESOURCE ACQUISITION

IV. Economic Cost and Other Considerations

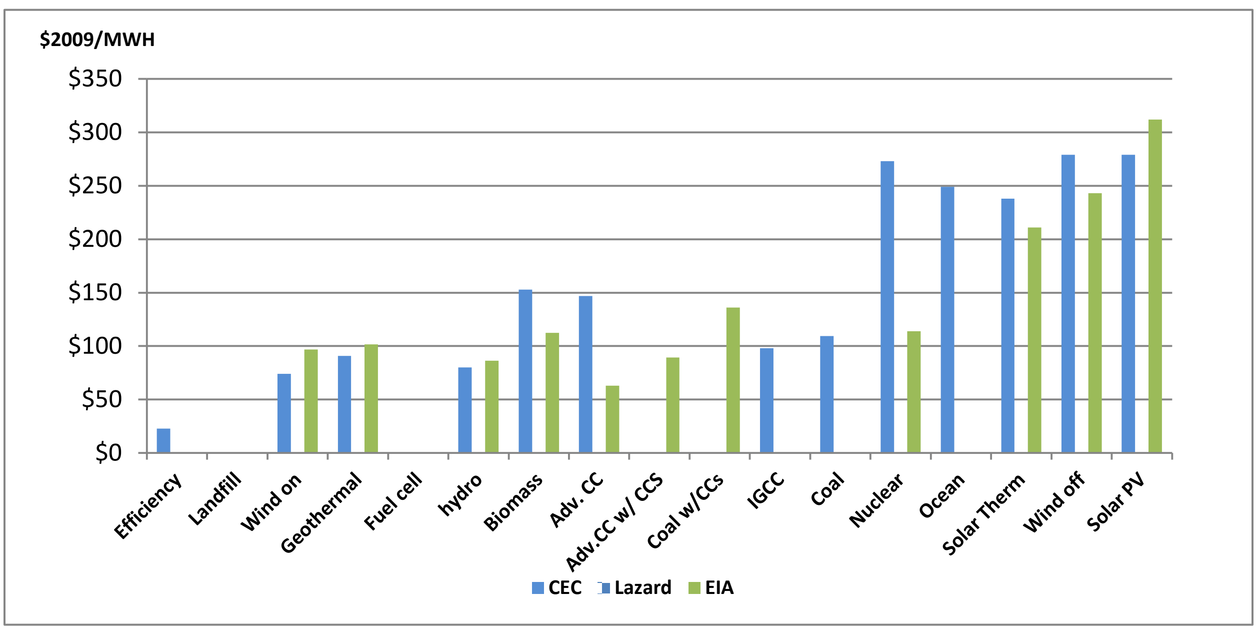
A. Current Projections of Levelized Cost

Economic cost receives the most attention in policy analysis and regulatory proceedings and it must be the starting point for resource acquisition decisions. Economic costs are frequently expressed as the real levelized cost per kilowatt hour or megawatt hour. Levelized cost is the real present value of the total cost of building and operating a generating plant over its economic life, converted to equal annual payments. The revenue requirement created by a resource is deflated and discounted back to the present. Because generation resources are long-lived assets, the choice of the discount rate has a major impact on the estimation of economic costs. In the context of risk analysis, the choice of the discount rate takes on conceptual significance as well.

The more detailed the cost and policy analyses break costs down into at least four broad categories – fixed investment, fixed operation and maintenance (O&M), Variable O&M, and fuel. The two economic analyses relied on in this paper provide that level of detail. As discussed below, the distinction between variable and fixed costs is critically important for analysis that confronts risk and uncertainty head on.

I have chosen to demonstrate the analytic framework by applying it to two recent sets of cost estimates, one done by the California Energy Commission (CEC) and one by Lazard (see Exhibit IV-1) These data sets are chosen because they are recent, consider the full range of alternative resources, include multiple scenarios, and provide detail that supports careful analysis of various types of risks. Of course, individual utilities and states will have

Exhibit IV-1: Levelized Cost of Alternatives



Source: Lazard, *Levelized Cost of Energy Analysis – Version 4.0, June 2010,* California Energy Commission, *Comparative Cost of Central Station Electricity Generation,* January 2010. *EIA, Annual Energy Outlook: 2011, Levelized Cost of New Electricity Generating Technologies,* used for Lazard hydro and wind-off, CEC coal and w/CCS, coal.

somewhat different resources available to them, which will modify the picture of costs somewhat. On the other hand, the costs of many of the resources are generally applicable, so the question is which resources are locally available.

I analyze the average of the Lazard and CEC estimates. Lazard is one of the few analysts to include efficiency in the broader resource analysis. The cost of efficiency is well documented, with the point estimate of $25/MWH, implicit in the Lazard estimate, well supported in the literature. I augment the CEC data with an independent estimate of the cost of efficiency.[49] I augment the Lazard data with several estimates from the EIA. I use EIA estimates to provide a second estimate for hydro, wind-offshore (which are absent in Lazard) and coal and coal with carbon capture and storage (which are absent in the CEC).

Exhibit IV-1 shows the base case cost estimates from the California Energy Commission and Lazard. They each include over a dozen alternatives. The base case for Lazard is the average of the high and low. For California, the base case is the reference case, which differs slightly from the average of the high and low. I rank fossil fuel options according to their costs with carbon capture and storage, although the costs are shown with and without capture.

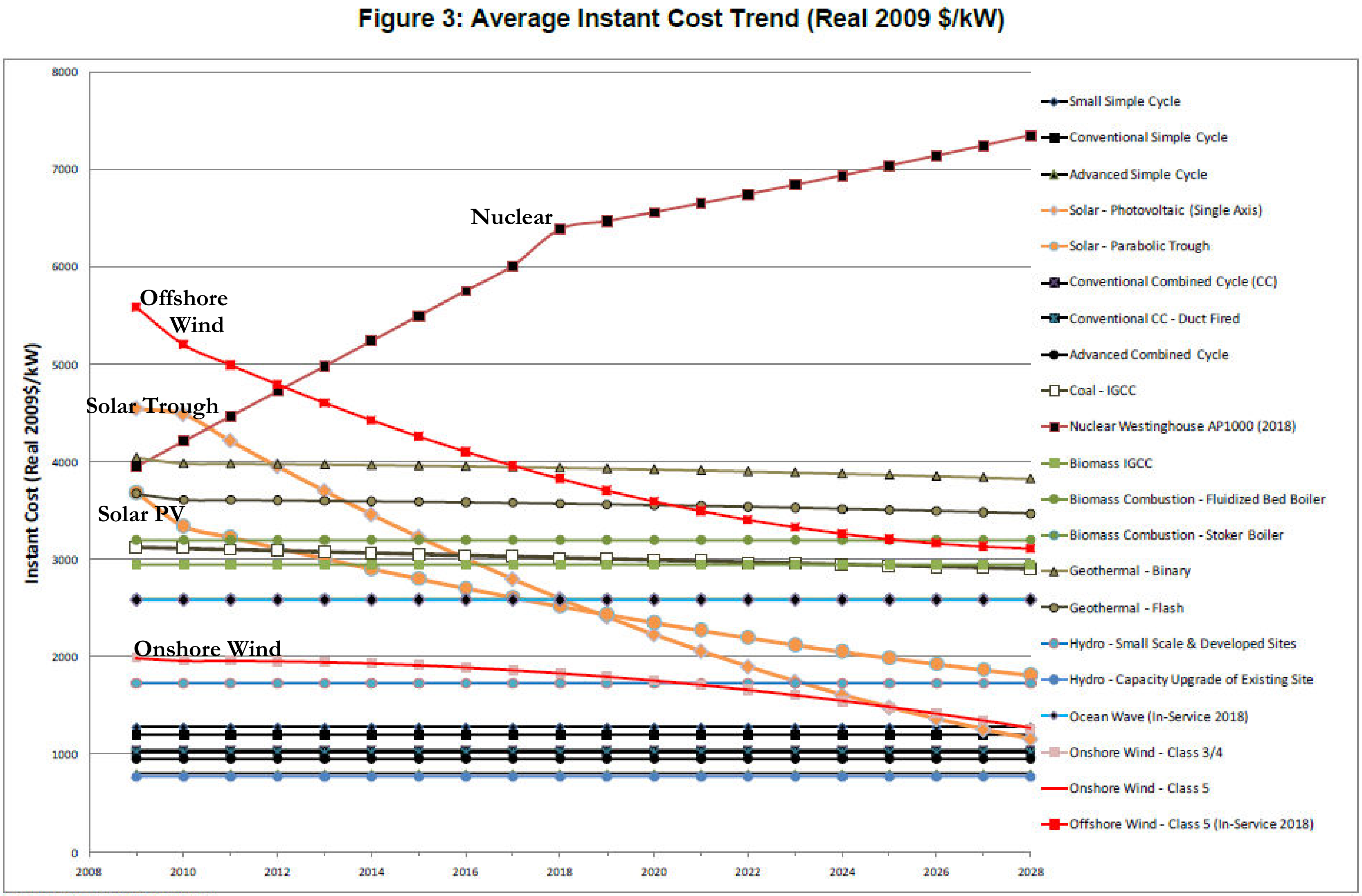
A subset of low-cost, low-carbon alternatives is readily identifiable in these graphs. Efficiency stands out as the lowest cost option by far. There are then a half dozen generation options with relatively low cost – landfill, geothermal, wind onshore, gas, biomass and hydro. Beyond this set, the estimates of costs rise and/or the range of the cost estimates expands. Nuclear, solar and wind offshore show great variability in estimated cost. Coal without carbon capture is low in cost, but with carbon capture is well above the low carbon options.

B. COST TRENDS

The range of estimates shown in Exhibit IV-1 covers several different time frames in the sense that not all of the technologies could be brought online at the same time, given differences in construction periods necessary to build facilities. This will be discussed below in the uncertainty analysis, but one important implication should be dealt with in the context of cost estimation. Cost trends may be important. For example, in the California analysis projected cost for 2018 are used, since that is the first year a nuclear reactor (under extremely optimistic assumptions) could be brought online.

California projects significant cost changes over that period, as shown in Exhibit IV-2. Since the technologies that are projected to decline in cost can be brought online in a much shorter period of time, the cost comparison between nuclear and the alternatives should be based on the future cost of bringing resources online in a specific year. Since the five resources that have strong trends in capital costs in the California analysis all have

EXHIBIT IV-2: CEC OVERNIGHT COST TRENDS



Source: Energy Commission

very low operating costs and capital costs make up a large part of their levelized cost, these trends are extremely important to take into account in decision making. These trends underscore the importance of the uncertainty analysis in the next section.

Lazard shows a similar trend for solar, with solar becoming cost competitive with natural gas within the time fame in which nuclear reactors can be brought online.[50] The Lazard analysis points out that while the costs per MWH converge for solar and gas, even taking capacity factors into account, solar power has a different pattern of availability. Therefore, gas and solar should be seen as complements, rather than substitutes, even when their prices converge. Much the same can be said of the wind-gas comparison. These five trends are included in the analysis below, where appropriate.

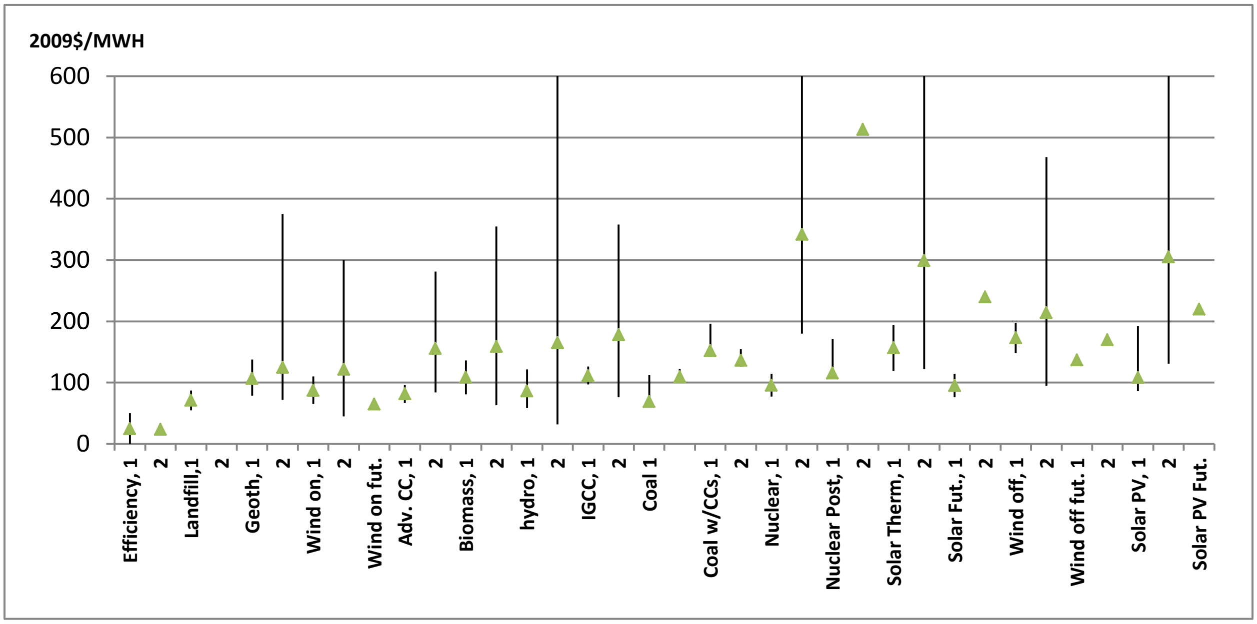
The sharp increase in nuclear costs in the CEC data is a projection about the future that is consistent with historical trends. In earlier analysis I have shown that cost escalation is an endemic problem that afflicts nuclear reactor construction for a variety of reasons.[51] That analysis need not be repeated here. There is one aspect of the current electricity decision making environment that does merit comment. The Fukushima accident has stimulated a great deal of concern about the safety of nuclear reactors. It is likely that policymakers, regulators and financial analysts will re-examine nuclear in light of the recent incident. This will raise the cost and risk of nuclear reactors considerably.[52]

After a nuclear accident, policymakers will likely re-examine energy policy, including a re-assessment of standards of care and safety and the regulatory processes that sets safety standards (regulatory risk), a re-valuation of the weighting of societal costs and benefits of all available options (policy risk), and consideration of the value of gathering more information before committing substantial resources that are locked in (policy risk). As a result, the perception of the environmental impact of nuclear power is likely to be seen as greater. New safety measures are likely to be deemed necessary, which will require more resources to be expended and the construction period, which is a key determinant of costs, will be lengthened (execution and marketplace risk). Financial analysts will re-examine the economics of nuclear reactors. Capital markets are likely to increase the cost of capital for nuclear reactor construction because reactors will be seen as more risky – more difficult to complete (execution risk), less attractive compared to alternative options (marketplace risk), less popular with policymakers (policy risk) and imposing more financial risk on utilities (financial risk). To assess how this re-evaluation of nuclear reactors will affect the cost of nuclear power, I use and econometric estimate of the historic impact of the Three Mile Island incident on U.S. nuclear construction. Post-TMI reactors took one-third longer to build and costs were 50% higher. This is consistent with the capital cost increase in the California study.

Exhibit IV-3 shows the high and low estimates for Lazard and CEC, augmented with EIA estimates. It includes projections for five technologies where there would appear to be strong trends that should be taken into account, as discussed above. The five projections are declining costs for wind onshore, wind offshore, solar PV and solar thermal, and rising costs for nuclear in light of the Fukushima accident. The high- low graph foreshadows the risk analysis in the next section. The analysis makes wind-onshore more attractive. Solar

PV could become a low cost, low carbon option if the cost trends projected by Lazard come to pass. Offshore wind would be competitive with the coal capture options. Carbon capture cost is critical for fossil fuels-fired generation.

EXHIBIT IV-3: HIGH – LOW, BASE CASE LEVELIZED COST FOR FULL SET OF RESOURCE OPTIONS



Source: 1 = Lazard, *Levelized Cost of Energy Analysis – Version 4.0, June 2010*, 2 = California Energy Commission, *Comparative Cost of Central Station Electricity Generation*, January 2010. However, *EIA, Annual Energy Outlook: 2011, Levelized Cost of New Electricity Generating Technologies*, is used to provide the second estimate in the case of Lazard hydro and wind-off, CEC coal and w/CCS, coal.

C. OTHER CONSIDERATIONS

Economic cost has never been the sole criteria on which electricity resources have been selected (see Exhibit III-4). Reliability has been a second consideration that greatly influences decisions. Electricity systems are built to an extremely high level of reliability – a 1-in-10,000 standard. Building a system that is expected to deliver 99.99% of the time is both a rigorous standard and a costly one. To achieve this level of reliability, one must not only include individual components that are reliable but the parts of the system must complement and reinforce one another. A substantial amount of spare capacity is generally needed to meet the daily and seasonal fluctuations in demand. The list of performance criteria by which the electricity system is evaluated varies from study to study, as shown in Exhibit IV-4.

However, the list of performance criteria general includes the following:

Economic costs – including financial, capital and operating cost, price volatility

Reliability of supply – including operational characteristics, variety

Security – including availability and origin of fuel supply

Flexibility – including construction lead time

Environmental Impact – including greenhouse gasses, pollutants, waste, water
Social Wellbeing – health, consumption externalities.

EXHIBIT IV-4: ELECTRICITY SYSTEM PERFORMANCE, CHARACTERISTICS AND STRATEGIES

Multiple Performance Criteria → **Key System Characteristics** → **Coping Strategies** → **Strategy Effects**

Multiple Performance Criteria

Stirling, 2010
- Financial
- Operational
- Supply security
- Environmental
- Health
- Social Wellbeing

Hickey, et al
- Reliability
- Security
- Flexibility
- Environmental Impact
- Safety

Costello, 2005
- Economic
- Operational
- Supply security
- Environmental
- Social Wellbeing

Key System Characteristics

Stirling 2010
- Technology
  - Combustion
    - Fossil v. Other
  - Non-combustion
- Geographic Scale
  - Local, Regional, National, Global
- Resource
  - Depleting
  - Non-depletable
  - Renewable

Costello, 2005
- Technology
  - Type
  - Lead Time
  - Intermittency
- Geographic
  - Domestic
- Resource
  - Abundance
  - Supply security

Coping Strategies

Stirling 2010,
- Risk Management
  - Real Options
  - Portfolio
  - Hedging
  - Diversity

Costello 2005
- Hedge Against
  - Price
  - Supply
  - Reliability
  - Regulatory Risk
- Fuel Diversity

Strategy Effects

Stirling 2010
- Portfolio Benefits
  - Hedging ignorance
  - Mitigating lock-in
  - Fostering innovation
  - Accommodating pluralism
  - Positive Synergies
- Portfolio Challenges
  - Negative Feedback
  - Crowding out

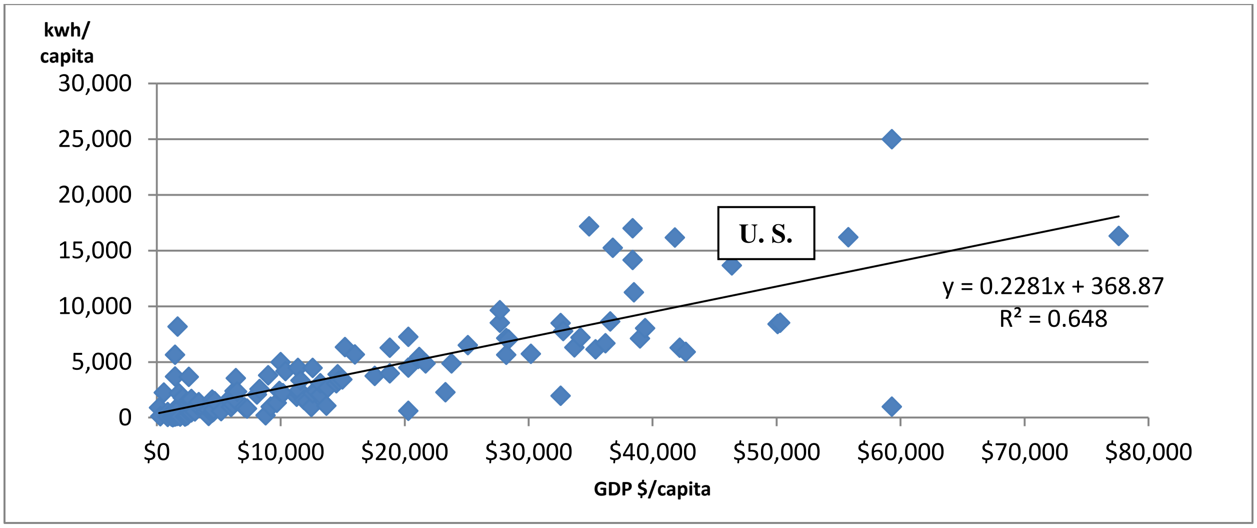
Costello 2005
- Portfolio theory
- Real Options theory

The risk, uncertainty and vagueness analyses in the next section will introduce many of these factors in a systematic framework. The data elements identified at the bottom of Exhibit II-2 cover the first six of these areas, arranged according to the region of knowledge for which they are most appropriate.

Understanding the reason that electricity systems are built to such a high level of reliability is critical to developing a multi-criteria framework for analysis. Electricity is considered too important – a basic necessity of daily life without close substitutes – to tolerate operation at lower levels of reliability. It is the importance of electricity as infrastructure[53] that affects the performance of the economy and the conduct of daily activity that dictates the performance criteria by which the electricity system is measured.[54] Indeed, electricity is deemed to be one of a few general purpose technologies that transform and therefore deeply affect the fundamental nature of social and economic life.[55]

Exhibit IV-5 shows both the strong correlation between electricity consumption and economic output and the relatively high consumption of the U.S. Controlling for climate reinforces the conclusion, as the nations with higher levels of consumption tend to have more severe climates.

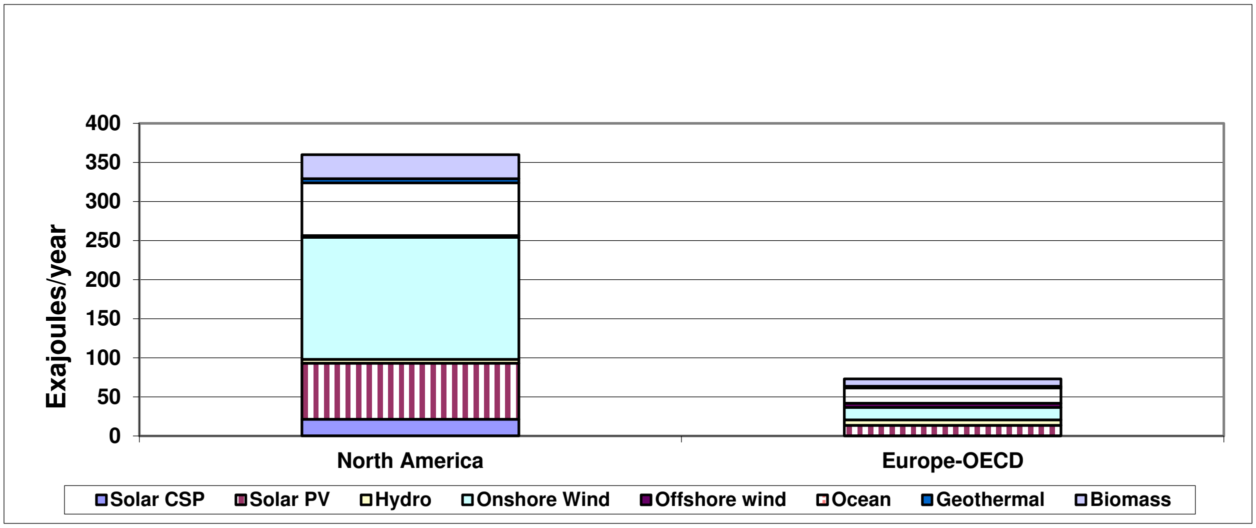
EXHIBIT IV- 5: ELECTRICITY CONSUMPTION V. GROSS DOMESTIC PRODUCT



Sources: Electricity is based on the World Fact Book, GDP from World Bank
http://en.wikipedia.org/wiki/List_of_countries_by_electric_energy_consumption,
http://en.wikipedia.org/wiki/List_of_countries_by_GDP_(nominal)

Exhibit IV-6 shows the supply-side of the equation. The U.S. has much more renewable potential than the European –OECD nations, which are close to the U.S. in consumption. At the same time, the U.S. is referred to as the Saudi Arabia of coal, gas and wind.[56]

EXHIBIT IV-6: POTENTIAL ELECTRICITY FROM RENEWABLE RESOURCES



SOURCE: Hoogwijk, Monique, 2008, *Global Potential of Renewable Energy Sources: A Literature Assessment,* Renewable Energy Policy Network for the 21st Century, March

V. THE REGIONS OF KNOWLEDGE IN THE ELECTRICITY SECTOR

A. RISK FOR ELECTRICITY RESOURCES

1. Variable Costs

The top panel of Exhibit V-1 presents a risk analysis based on the average of the Lazard and CEC levelized cost analysis (on the y-axis), with several additions based on other sources. Lazard is used to measure the risk (variable cost variability on the x-axis) because it has the detail necessary to identify all the variability in variable costs. I calculate the variability in cost directly based on fuel, O&M and other variable costs (e.g. carbon cost). I identify the widest possible range of variable costs in the sensitivity cases considered in the study. The bottom two panels show the individual results for the Lazard-only analysis and the CEC only analysis. In the CEC analysis I use the standard deviation of the cost estimate, which is another approach frequently used in the literature.[57]

The assumption underlying the analysis is that fixed costs are riskless, while fuel and other variable costs carry risk to ratepayers. In a world of merchant sellers that is certainly the case, since the merchant knows his or her cost of construction when the contract for electricity is negotiated with the utility. Fixed price contract are executed, which will frequently include a cost escalator to reflect variable costs that may be tied to some measure of inflation.

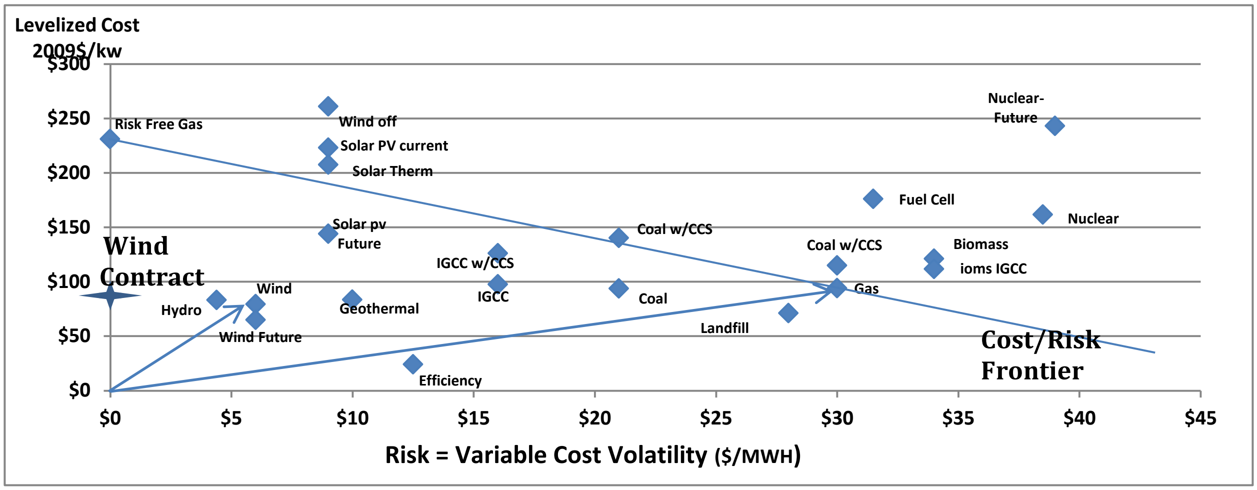
In theory, public utility commissions impose similar discipline on regulated utilities by only allowing prudently incurred costs to be included in the rate base. Utilities bear the risk of capital costs, for which they are compensated by the rate of return. Cost overruns can be a contentious issue and consumers bear the risk of fuel price fluctuation in fuel adjustment clauses.

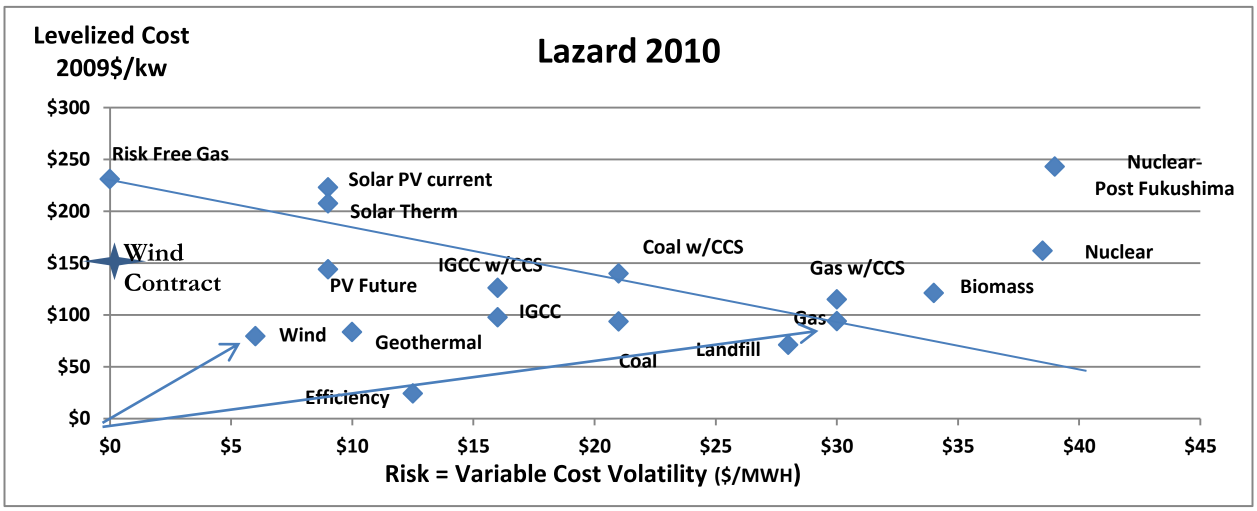
Moreover, in the contemporary environment, utilities have refused to build nuclear reactors without shifting a substantial part of the capital cost risk to ratepayers in the form of advanced cost recovery (construction work in progress) and they have steadfastly resisted any risk sharing mechanisms.[58] From the ratepayer point of view, part of the variability in nuclear construction costs is a variable cost. In Exhibit V-1, half of the variability in nuclear capital costs is included in the measure of variability.

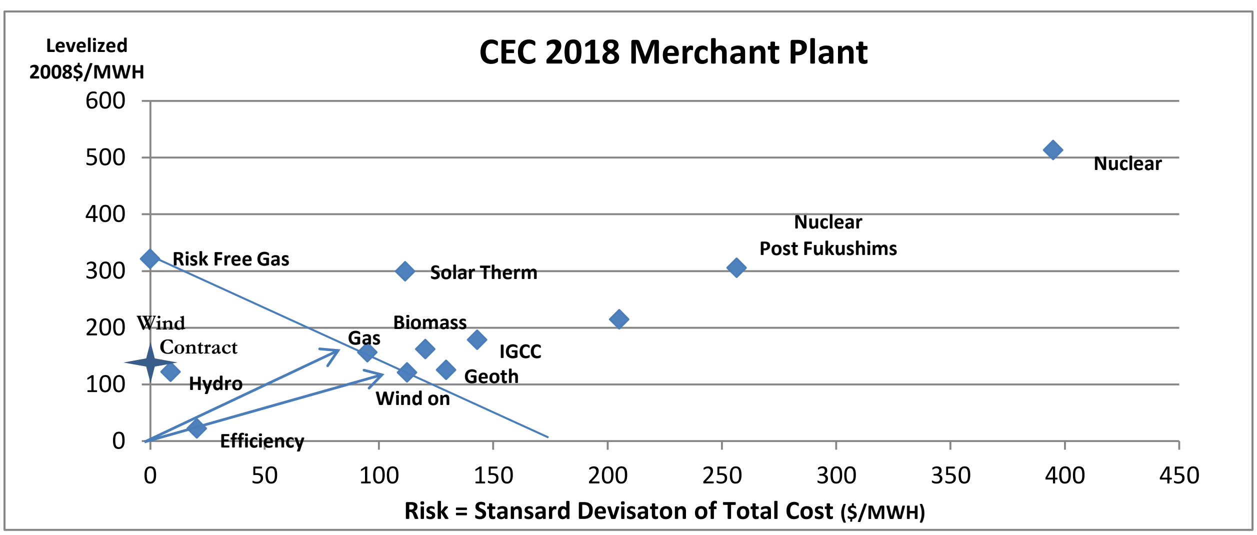
For hydro, variable cost variability is attributed to hydro based on the share of variable cost in total cost. In the CEC analysis one-eighth of the overall cost of hydro is attributed to variable costs. Since one-eighth of the total cost is attributable to variable cost, one-eighth of the variability of total costs is attributed to variable costs.

For wind and solar, it is important to distinguish between output that is predictable and costs that are variable. We incorporate the full range of variability in cost due to uncertainty about capacity factors and O & M costs into the measure of variability on the x-axis.

EXHIBIT V-1: RISK: AVERAGE LEVELIZED COST V. VARIABLE COST







Source: Lazard, *Levelized Cost of Energy Analysis – Version 4.0, June 2010,* California Energy Commission, *Comparative Cost of Central Station Electricity Generation,* January 2010. *EIA, Annual Energy Outlook: 2011, Levelized cost of New Electricity Generating Technologies, is used to provide the second estimate in the case of* Lazard hydro, Lazard wind-off, CEC, coal w/CCS, coal.

The concept of variable cost makes little sense for efficiency, although there could be variability in the cost of efficiency. Here I use the standard deviation of the cost of efficiency in the Lazard study. I do the same for the CEC data, adding an independent estimate of efficiency cost to the CEC analysis.[59]

The graphs use natural gas to identify the gas risk-cost frontier, since gas is the fuel of choice at present. The risk free gas cost is based on the assumption that all of the variable costs considered for gas are at their highest level. That would be the highest cost these studies would contemplate for gas-fired generation and there would be no risk of it being higher.

The arrows in the graph indicate the relative attractiveness of options can be measured as the distance from the origin. This approach values each of the dimensions equally. In order to be able to summarize and compare the views from the analysis of different regions, I normalized the distance from the origin compared to gas, which is the resource of choice at present.

Adding the risk dimension to the cost analysis does not change the rank ordering of the options. Efficiency, wind, hydro, geothermal and landfill are attractive relative to gas.

2. Long-Term Contracts

This discussion of merchant versus utility finance and "risk free gas" immediately raises another issue – the role of long term contracts. Merchants who offer long term fixed price contracts to utilities take the risk out of resources acquisition, depending on how the contracts are written. Long term contracts have been part of the industry and can be a tool for bringing assets into the resource base while allocating risk in a more consumer-friendly manner. The key is the reduced uncertainty associated with contracts.

- While long term contract "lock in" resources, the resources with which they are associated have attractive characteristics, particularly those tied to renewable resources. They tend to be small projects that can be brought on line in short periods of time and possess little variable cost variability.

- Producers take all of the construction cost risk and frequently absorb some or all of the variable cost risk.

- Long term contract also enable the developer to secure lower cost financing, since the contract can be taken to the bank. They help to "level" the financing playing field between utility-based options and merchant-based options and lower the cost of the project, cost savings that are passed through to consumers.

- Long term contracts are an ideal way of flexibly diversifying the resource base, the antithesis of utility-built base load facilities, which are commitments to large project, with long lead times and, particularly in the case of nuclear reactors, put ratepayers at risk of much of the construction costs.

The feasibility and attractiveness of long term contract for renewable resources has been well recognized, because they do "not have key internal contributors to uncertainty"[60]

> Laddering contracts and diversification of technologies, fuels and suppliers should be pursued. Careful analysis of load forecasts and price projections should be used to establish a reasonable amount and type of long-term forward contracts what should be included….
>
> In contrast to fossil fuels, renewable resources typically have a less-variable (or even free) fuel cost stream, resulting in less fuel price risk for either party to an electricity contract. Hence, it is more common to have fixed-price contract for renewable electricity than for natural gas-generated electricity. Since the use of renewable resources decreases fuel price risk for both parties to a contract, all else equal, a fixed-price renewable electricity contract is a more complete hedge against fuel price risk for the Buyer than a fixed-price contract for natural gas-generated electricity.[61]

Exhibit V-1 inserts a risk free wind contract with a zero risk value slightly above the levelized cost to reflect the likely escalation factor. Wind was already well inside the gas risk-cost frontier and long term contracts make it more attractive. Other resources could be offered in long term, fixed price contracts, but the variability of fuel costs for fossil fuels, and the uncertain construction costs for nuclear make them unlikely candidates. Solar and biomass are candidates, but only in the case of biomass would a fixed cost contract move it within the efficiency frontiers.

B. UNCERTAINTY

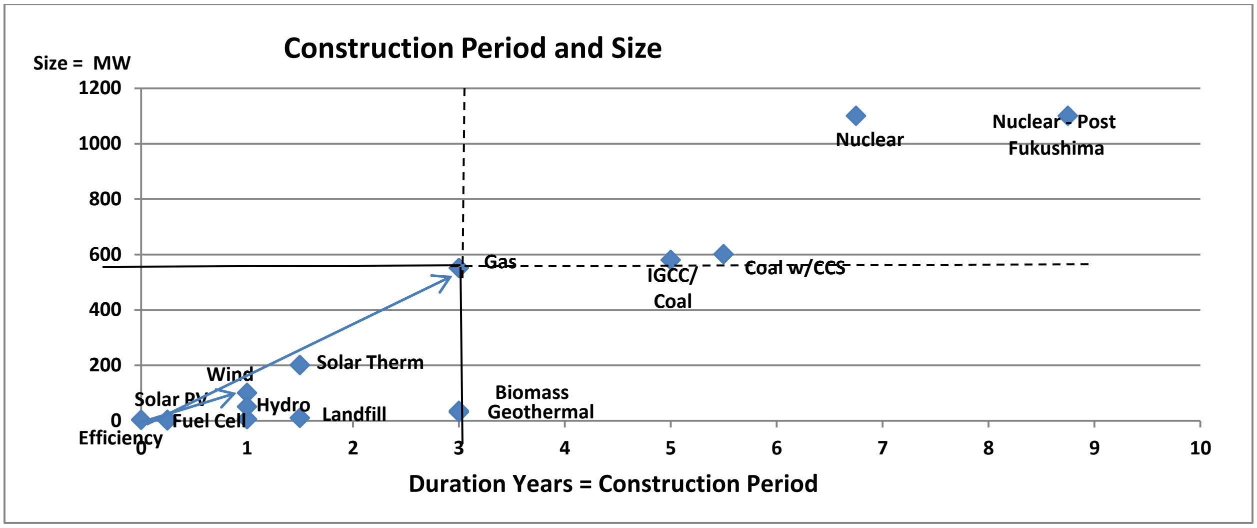
The analysis of uncertainty can be approached from the principles of real option analysis. Real option calculations would be specific to projects, but general insight into the issue of uncertainty can be gained by focusing on key factors that expose consumers and utilities to the ravages of uncertainty. In conditions of uncertainty, the greater the ability to wait or change, the better. Several key characteristics of technology options affect the ability to wait or change – the construction period, the size of the facility and the capital costs that must be sunk into the project.

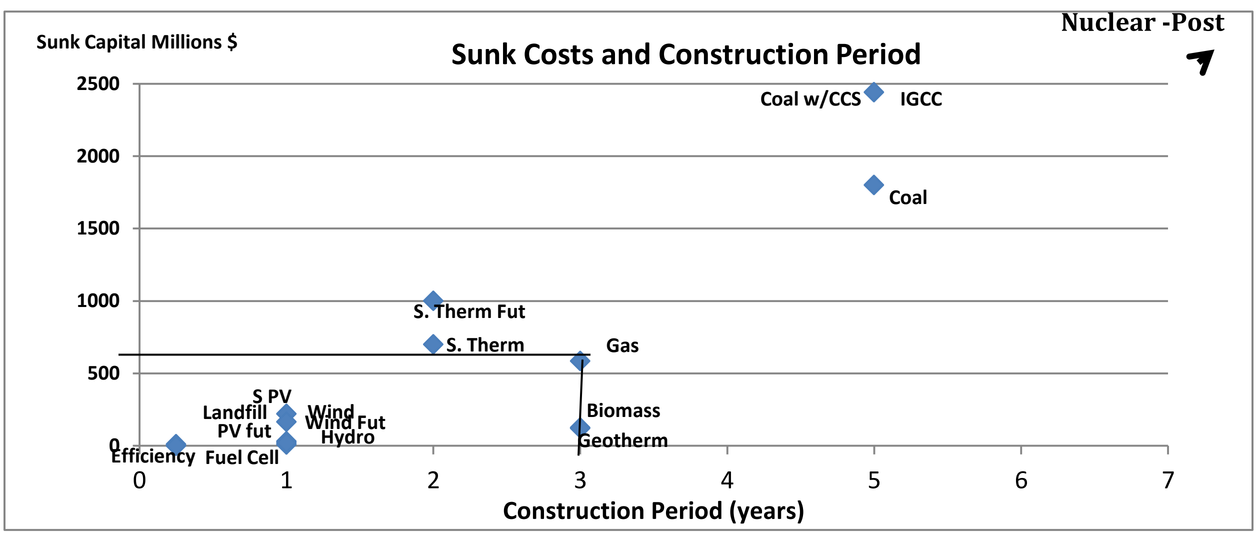
Exhibit V-2 shows two measures of exposure to uncertainty, which are taken from Lazard. The two data sets are quite close on these two aspects of uncertainty. The top graph in Exhibit V-2 plots the size of the project against the construction period. Large projects not only take longer, but I have shown that they tend to crowd out smaller projects, so they take away real options.[62]

The bottom graph plots sunk costs (calculated as the cost per MW times the number of MW) against the construction period. The bottom graph also shows the point estimates for future trends, assuming the same project size and construction period.

Exhibit V-2 identifies the gas "frontier" as a rectangular area with gas as the referent. Anything inside the rectangle is preferable on both the size and duration of exposure to risk. Anything on the border of the rectangle would represent an improvement

EXHIBIT V-2: EXPOSURE TO UNCERTAINTY: LAZARD DATA





Source: Lazard, *Levelized Cost of Energy Analysis – Version 4.0, June 2010,*

on one dimension. Options outside of the box, but to the left or below gas would represent a trade off against gas, reducing either the size or the duration of exposure to risk. Anything outside the rectangle and above or to the right of gas is less attractive. The rank ordering of the options is similar to the conclusion on cost and risk. Efficiency and landfill are the most attractive. Fuel cells, hydro, wind and solar are more attractive compared to gas because of their smaller size. The two coal based technologies appear substantially more attractive than nuclear.

C. VAGUENESS IN ENVIRONMENTAL IMPACTS AND SECURITY OF SUPPLY

Although the statistical assumptions underlying probability models have been the primary targets of criticism in Black Swan Theory and Technology Risk Analysis, it would appear that the complexity of outcomes deserves at least as much attention. The real world deviates from simple binary outcomes. In this analysis, a useful lesson is that one should avoid areas of vagueness. Several outcomes that fall in the area of vagueness in the utility sector are readily identifiable in the literature.

One area of vagueness involves environmental impacts. There are fierce debates over, and shifting policy to address, a range of environmental issues (climate change, hydraulic fracking, nuclear waste handling); major black swans like accidents (nuclear melt downs, coal waste releases, mine explosions) and surprise findings (biomass emissions, methane leaks from pipelines). Given the extreme vagueness of environmental impacts, there are many, varied and complex approaches to evaluating options. At root, they all embody judgments about the various aspects of the impact. We can appreciate the vagueness if we consider the complex issues associated with environmental and technology impacts, as depicted in Exhibit V-3, which is derived from the Technology Risk Assessment framework.

EXHIBIT V-3: EVALUATION OF TECHNOLOGY IMPACTS: ROUTINE IMPLEMENTATION OR RARE EVENTS

Occurrence	Nature	Distribution	Response
Probability	Severity	Benefits and Costs	Controllability
Certainty of assessment	Immediacy	Spatial	Reversibility
	Gravity	Intergroup	Trust in institutions
	Persistence	Intergenerational	Familiarity
		Vulnerable groups	
		Voluntary	

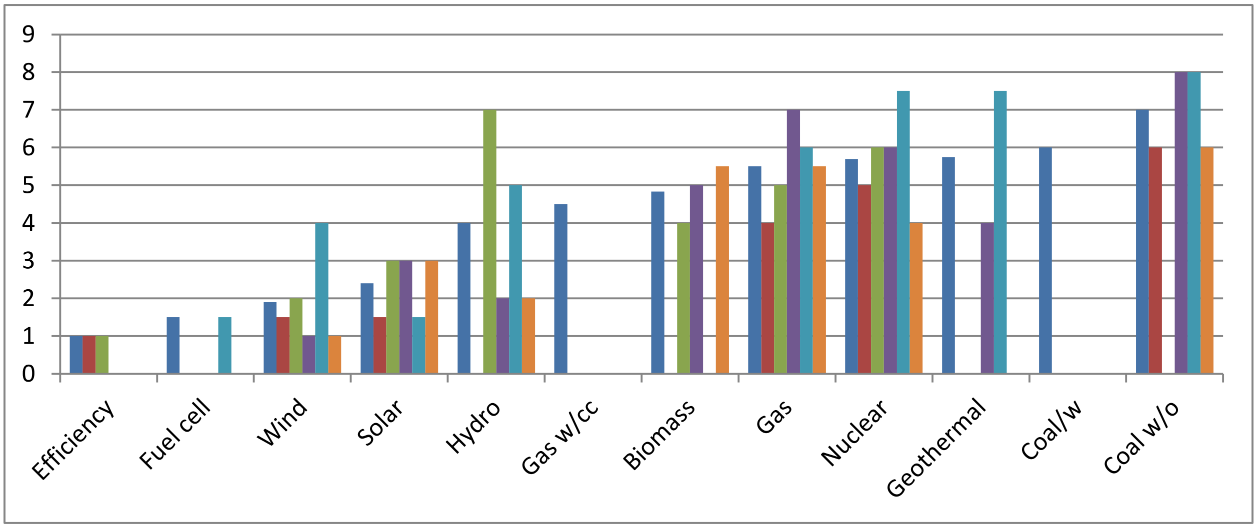
Source: Andrew Sterling, 1999, *On Science and Precaution in the Management of Technological Risk,* European Science and Technology Observatory, pp. 11, 13.

Exhibit V-4 shows the rank ordering of a dozen resources from five studies of the environmental impact of alternative resources. The first bar for each resource is the average ranking across all of the studies and the blanks represent studies that did not rank the resource. I use the average rank for each technology as its environmental impact score.

A second area of vagueness stems from the prospects of long term supply. The peak oil controversy, shifts in projections of the natural gas resource base and debates about the quality of uranium deposits, are examples of this area of vagueness. These concerns are often combined with concerns about the scope of the market in which fuels are acquired. Both concerns tap into the overall concern with security of supply. These issues turn on the reliability and inability to control long-term supply.

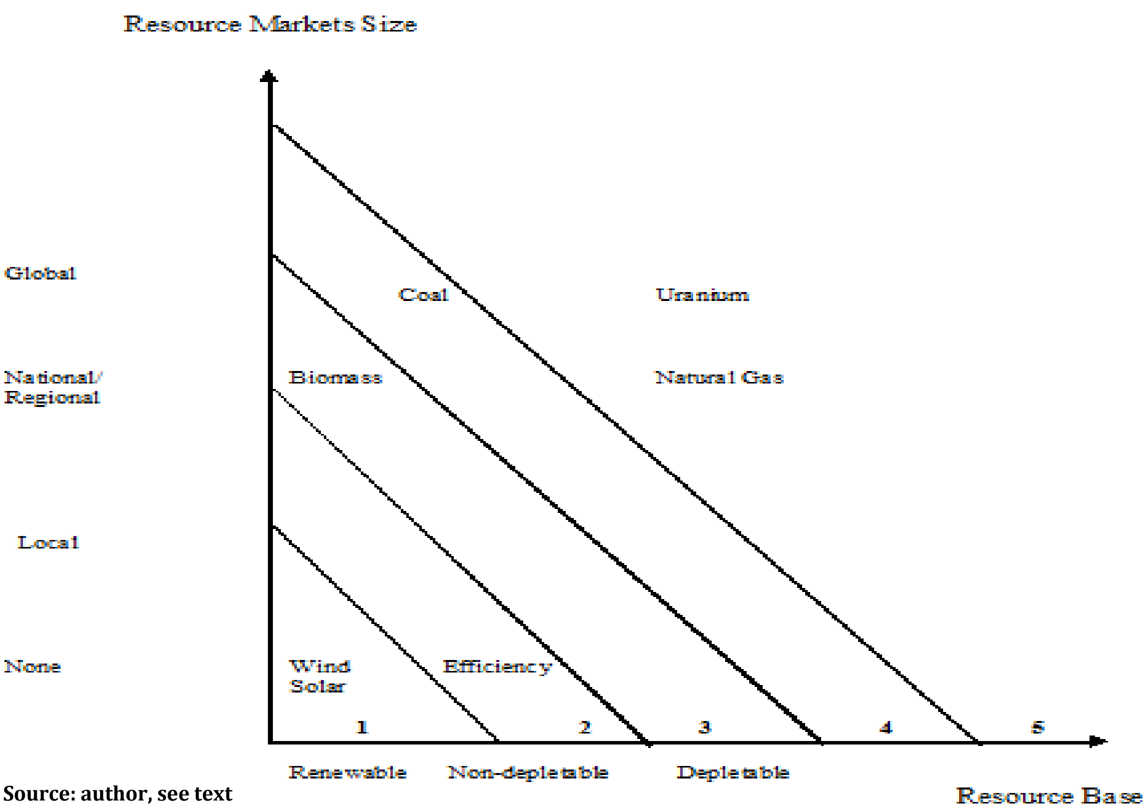
The evaluation of the problem involves judgments and approaches to measurement can be very complex. Exhibit IV-5 keeps it simple, rank ordering the resources on two dimensions and creating a five point scale. I use the five point scale as the supply security score.

EXHIBIT V-4: QUALITATIVE RANK ORDERING OF ENVIRONMENTAL IMPACTS



Sources: Wilson B. Goddard, *A Comparative Study of the Total Environmental Costs Associated with Electrical Generation Systems* (G&GE Applied Research, 1997); *U.S* Congressional Office of Technology Assessment, *Studies of the Environmental Costs of Electricity* (Washington, D.C. September 1994), evaluating Richard Ottinger, et. al., Pace University Center for Environmental Legal Studies, *Environmental Costs of Electricity* (New York,: Oceana, 1990), Paul Chernik and Emily Caverhill, "the Valuation of Externalities from Energy Production, Delivery and Use (Fall 1989); Olave Hohmeyer, *Social Costs of Energy Consumption: External Effects of Electricity Generation in the Federal Republic of Germany* (Berlin: Springer-Verlag, 1988);Michael Shuman and Ralph Cavanagh, *A Model of Conservation and Electric Power Plan for the Pacific Northwest: Appendix 2: Environmental Costs* (Seattle, WA: Northwest Conservation Act coalition, November 1982).

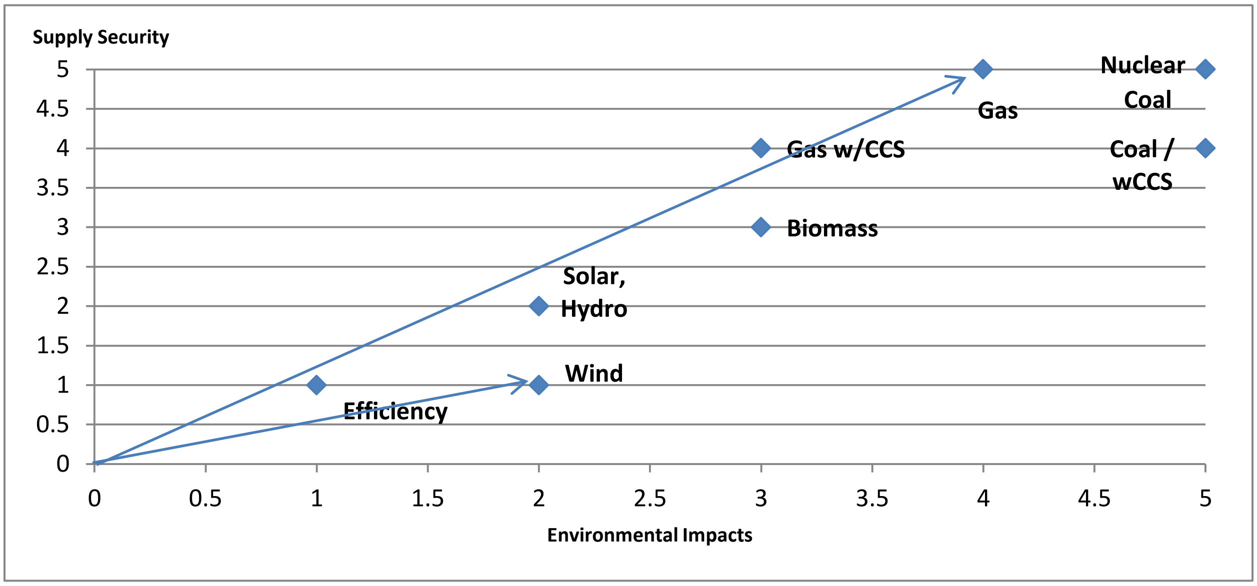
EXHIBIT V-5: A QUALITATIVE SCALE OF SUPPLY SECURITY



Source: author, see text

Exhibit V-6 combines the two analyses in this section into a map of the terrain of vagueness. The map is similar to the maps bases on risk and uncertainty.

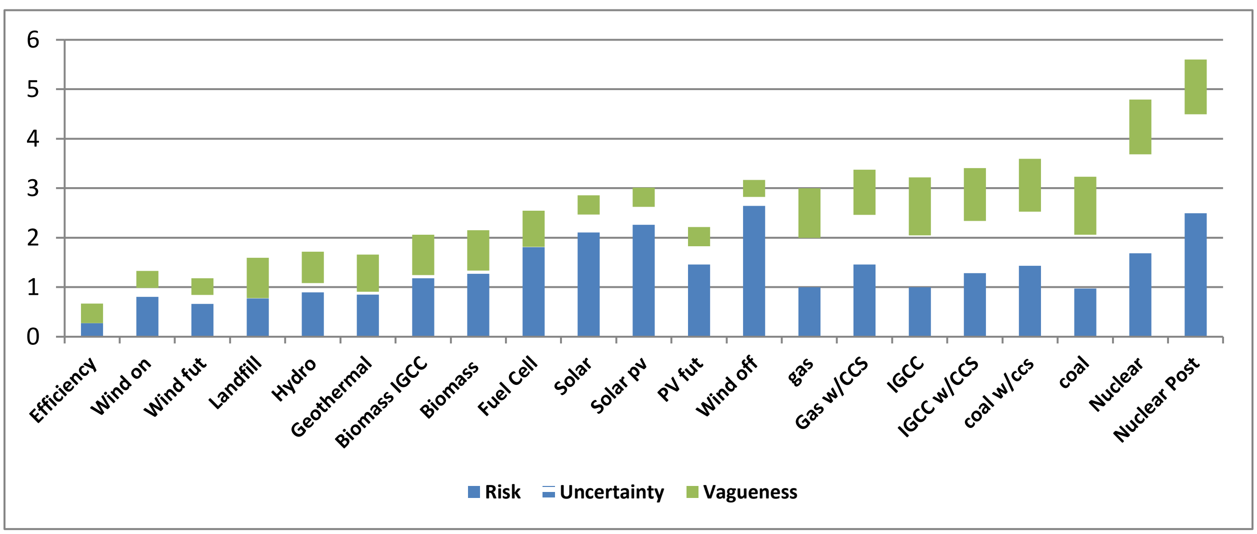
EXHIBIT V-6: A MAP OF THE VAGUENESS REGION



Source: author, see text

Adding the analysis of vagueness to risk and uncertainty as in Exhibit V-7 changes the rankings of several of the resources somewhat although the basic conclusion stands.

EXHIBIT V-7: THE SEQUENCE OF RESOURCE ACQUISITION IN AN AMBIGUOUS ENVIRONMENT



Source: author, see text

D. The Region of Ignorance

The strategy that I advocate is for decision makers to intensively explore the risk, uncertainty and vagueness regions, thereby, hopefully, shrinking the region of ignorance.

When the first three regions have been explored, the analyst should consider what else needs to be done. There are several additional analyses that should round out the map of the terrain of decision making.

1. Swan Search

Decision makers should examine the preferred alternatives for evidence that surprises, black or white swans, could be lurking beyond the area where the analysis has shed light. Identify additional potential costs and benefits that flow from sources of risk, uncertainty or vagueness that have not been included in the previous analysis. In the words of Black Swan theory, this 'robustifies" the confidence in the path chosen. While the primary concern is black swans, decision makers should not miss the opportunity to exploit the benefits of white swans. **Consistency:** One obvious type of black swan to look for is inconsistencies in recommendations from the other three regions. These would indicate an important area for analysis in the ignorance region. We have not observed contradictory results. **Unintended consequences:** Similar to inconsistencies, but broader, are unintended consequences. For example, increasing the reliance on variable renewables can create grid management challenges. At current relatively low levels of reliance on variable renewables, this is not a major problem, but as their use rises it becomes more serious and requires management responses. **Externalities:** Finally, other black swans are positive and negative externalities. For example, for gas fracking and other environmental concerns arise. Renewables and efficiency that displace gas have large, positive consumption externalities. Efficiency raises rebound effects, where consumers spend some of their savings on bills to purchase more electricity.

2. Diversity

Because the different regions of knowledge are responsive to different the causes of ambiguity, we would expect the risk, uncertainty and vagueness analyses to yield a diverse bundle of assets. Since five of the six resources identified as attractive in the other analyses do not play a very large role in the current resource portfolio, the recommendation that regulators seek to diversify the resource mix can be met by adding these resources first. However, since resources are constrained in the real world and the decision maker cannot just "do everything," decision makers need to squeeze the greatest benefit out of the available resources. **Measurement:** The focal point of the diversity in the electricity sector is its ability to enhance resiliency (by reinforcing durability, robustness and flexibility) but diversity is believed to have other beneficial effects. It also creates value (competition, rigorous selection, comparative advantage), enhances innovativeness (mobility, creativity, the avoidance of lock-in), and supports pluralism.[63] In order to achieve the benefits of diversity, the resources need to be varied, balanced an different. The literature contains numerous indices to capture these three dimensions of diversity. A few of the more popular examples are depicted in Exhibit V-8.

Exhibit V-9 depicts the data analyzed in this section in another way. It uses five dimensions to define the decision space. Cost and construction period are used, since they are at the center of traditional least cost planning. The indices of risk, uncertainty and

EXHIBIT V-8: CONCEPTS AND MEASURES TO BUILD A DIVERSITY INDEX

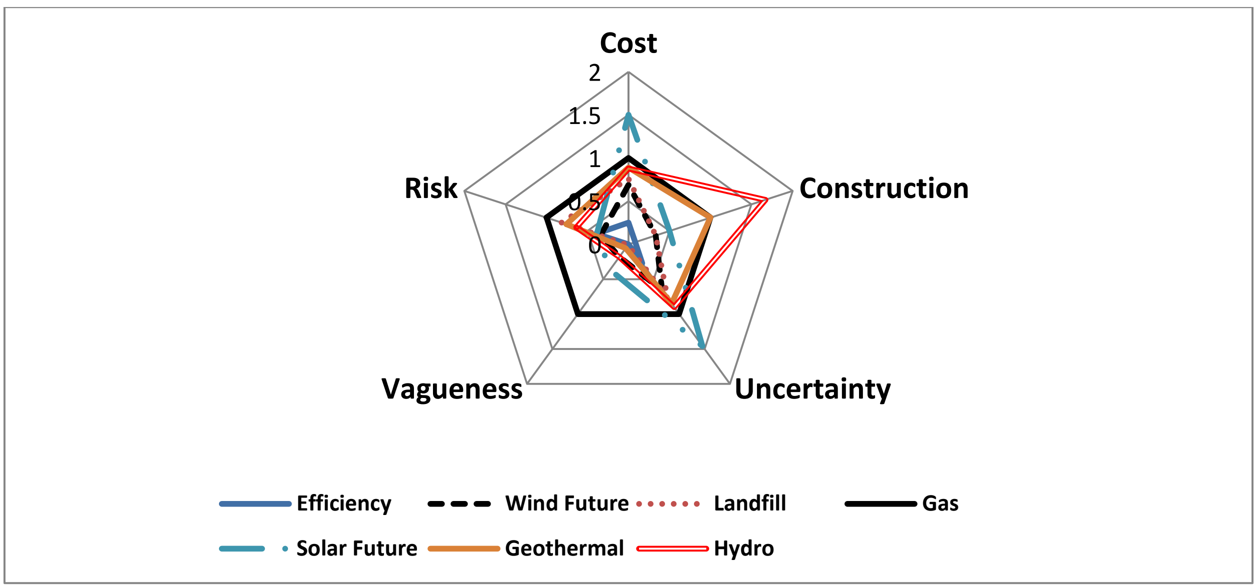
Concept	Name	Formula
Variety	Simple	N
	Scaled	$(N^2 – N)/2$
Balance	Gini/2	$\sum_{ij}^{n} (p_j * p_j)$
Variety and Balance	HHI	$\sum_{i}^{n} p_i * p_i$
	Shannon-Weiner	$-\sum_{i}^{n} p_i * \ln p_i$
Disparity		$\sum_{ij}^{n} d_{ij}$
Diversity	Stirling	$\sum_{ij}^{n} d_{ij}^{\alpha} * (p_j * p_j)^{\beta}$

Where:
n= number of resource
p= share of each resource
d= differences between resources
α, β = exponents reflect relative importance of disparity and balance

Source: Andrew Stirling, 2010, Multicriteria Diversity Analysis; A Novel Heuristic Framework for Appraising energy Portfolios, *Energy Policy*, 38

vagueness are used for the other three dimensions. Gas is the referent, which is reflected in the fact that its score is 1 on each dimension. The Exhibit shows all of the resources that are more attractive than gas on at least three of the five dimensions. To be more attractive, a resource would have a value less than gas. To achieve diversity, we select resources that overlap along the five dimensions. The analysis of these three regions of the knowledge terrain makes a strong case that these are the resources that a prudent utility will pursue in the current economic environment because the lower risk vagueness and uncertainty, while they contribute to diversity.

EXHIBIT V-9: ALTERNATIVE ELECTRICITY RESOURCE MID-TERM OPTION IN FIVE DIMENSIONS (Preferable Options Closest to the Origin, Normalized on Gas = 1)



Source: author, see text

Alternative Acquisition Instruments: Within the broad pursuit of diversity as a form of insurance, the examination of the opportunity to pursue diversity through alternative acquisition instruments is an important are of analysis. The previous analysis has focused on physical assets as resources.[64] For decision makers in the electricity sector, this is the right place to start. There are other instruments that can augment physical strategies. Price hedging with financial instruments is a short term approach that has proven to be perilous for utilities. It leaves doubts about how resources will be brought into the system. There are good reasons to believe that these types of markets will not provide an effective solution to risk reduction and resource acquisitions in the long term.[65] As we have noted earlier and shown throughout this analysis, long-term contracts, on the other hand, can be an attractive form of insurance.

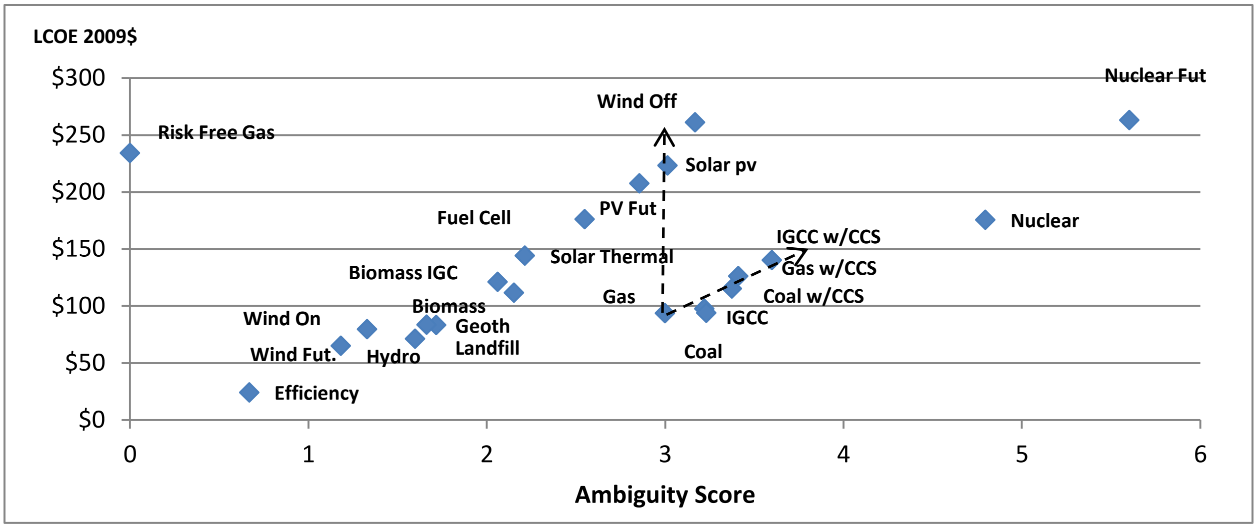
3. Sufficiency

Given the primary goal of ensuring an adequate supply, the sufficiency of the resources that are identified as preferable to meet the need for electricity should be considered as an independent question. The uncertainty/real option component of the overall approach is intended to address this issue, but it deserves special attention. **Adequacy:** The objective of achieving a robust resource mix points toward diversity of resources as a primary goal, but diversity should not come at the expense of sufficiency. Insufficiency is the most important black swan to consider. A properly defined concept of diversity takes this into account. Thus, sufficiency is a constraint on diversity. **Sequence:** When analyzing sufficiency, time is of the essence. Long term predictions are extremely ambiguous. Flexibility requires that options are kept open as long as possible. The decision making time frame should be only as long as the longest lead time of the options being considered. If there are preferable options with shorter lead times, then they should be chosen, since there will be adequate time to bring the inferior option online later, if or when the preferable options are exhausted. Sufficiency analysis also should recognize constraints on both the availability and management of resources. Sufficiency will be utility and region specific, but given the current level of utilization of the resources that have been found to be attractive in the risk, uncertainty and vagueness analyses and the potential for development of these resources; they should be the resources of choice over the next couple of decades.[66] These resources can meet the need for electricity – normal growth, replacement – over at least a ten to twenty year period. Relying on this mix of resources would be compliant with generally stated goals for reduction in greenhouse gas emissions in the sector over the period.

E. Conclusion

Exhibit V-10 combines the 'new" part of this analysis – the ambiguity scale – with the traditional core of utility regulation – levelized cost. The map is quite clear. Efficiency is especially attractive because it lowers cost and ambiguity, while renewables like hydro and wind, and biomass, as well as landfill and geothermal reduce ambiguity. The route to the future is also clear. It begins with efficiency, wind and a mix of other renewables, with gas as a complement. It then can proceed on one of two paths, a renewable route that goes through solar and offshore wind, which would continue to rely on gas as a complement, or a fossil fuel path that includes carbon capture and storage. Nuclear is the most unattractive of the resources.

EXHIBIT V-10: AMBIGUITY AND LEVELIZED COST



Source: author, see text

The big picture conclusion of this analysis is that the affinity for large base load facilities is a relic of a past that involved much less ambiguity. The prudence of that affinity has been contested for at least a quarter of a century, but this analysis shows the debate should be over. The very characteristics that made central station facilities attractive in an environment with much less ambiguity makes them singularly unattractive in the current environment.

Acquisition of central station facilities, particularly nuclear, makes long-term commitments in exactly the wrong way for the current decision making environment. It commits to assets that have high risk (e.g. fossil fuel facilities) or create large exposure to uncertainty (large size, high capital cost, or long lead times) with technologies that have vague long-term prospects (unstable resource availability and poorly understood environmental impacts). As a result, it is no longer acceptable for the bias in favor of large central station facilities to dominate resource planning.

In order to overcome this bias utilities and Commission should move toward long term contracts for the more attractive resources, which levels the playing field for the more attractive alternatives. Public utility commissions should require utilities to sign long-term purchased power agreements for resources that lower cost or risk. The failure to do so should be considered imprudent because contracts for resources, like wind, promote the development of a more diversified, stable long-term resource mix that provides flexibility and reduces uncertainty. They are a form of insurance that public utility commissions should require utilities to acquire.

The dash to gas that is developing is being significantly overdone because it unnecessarily exposes ratepayers to risk, uncertainty and vagueness. A balanced approach that begins with a great deal more efficiency and locally abundant renewables that can be acquired more quickly and in much smaller increments, combined with natural gas, yields lower expected costs.

The growth of alternatives that have more attractive characteristics – lower cost, lower risk and/or less exposure to uncertainty – allows decision makers to escape from risky and uncertain of central station options. The urgent strategy is to take every opportunity to diversify. The prudent thing to do is to choose the lower cost, low carbon, lower emission and less risky alternatives. Once the compelling economic case for these alternatives is appreciated, the issue of administering a more complex network can be addressed, but a heavy burden of proof should fall on those who want to pursue the "uneconomic" resources.

As long as the conditions in the sector did not deviate from the assumptions of stability, commissions did not have to incorporate the tools of risk, option and diversity analysis that were being widely used in other sectors. Now that it is obvious that the dramatic changes in the underlying conditions have called entrenched approaches into question, public utility commissions simply cannot continue to claim that they are properly evaluating prudency without utilizing the tools that prudent decision makers throughout society are using.

ENDNOTES

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[1] See Exhibit IV-5.
[2] See Exhibit IV-6.
[3] Cooper, 2011a.
[4] http://www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states
[5] Infrastructure, Kahn, 1988, p. 11; Whether or not electricity is a General Purpose Technology, it is certainly true that is it a big technology and "big technological changes are going to produce noticeable effects on growth and productivity trends (Ristuccia and Solomou, 2010), p. 18.
[6] Awerbuch, 2006, p. 695.
[7] Portfolio Analysis: Fabien, et al., 2009, Grub, Chapuis and Duong, 1995, Awerbuch and Berger, 2003, McLohglin and Bazilian, 2006, Moller, Christopher, et al., 2011, Valentina and Plourde, 2010, Roques, Fabien, A, et al., 2006, Shimon, 2006, Delarue, Erik, et al., 2011, Hickey, Carlson and Loomis, 2010, Jansen, J.C., L.W. M. Beurskens, and X, van Tilburg, 2006; Real Options: Chatterjee and Ramesh, 1999, Hiouska, Jaroslava et al. ,2002, Murto and Nese, 2002, Sicarli, 2004, Blyth, et. al, 2007, Abdelhamid, N.D.; Siddiqui and Fleten, 2010; Diversity: Stirling, Andrew, 1994, 2007, 2010, Yoshizawa, Stirling and Suzuki, 2009,
[8] Stirling, 2010, noting the failure to implement the diversity concept.
[9] Roques, Newberry, Nuttal; Cohen, 2008, p. 7.
[10] Taleb, 2010.
[11] Cooper, 2009a, 2009b.
[12] http://en.wikipedia.org/wiki/Quantitative_analyst: A **quantitative analyst** is a person who works in finance using numerical or quantitative techniques. Similar work is done in most other modern industries, but the work is not always called quantitative analysis. In the investment industry, people who perform quantitative analysis are frequently called **quants.**
[13] Roques, Newberry and Nuttal, 2006, p. 10.
[14] Lazard, 2010.
[15] California Energy Commission, 2010.
[16] Duncan, 1972, p. 313
[17] Schrader, Riggs and Smith, 1993.
[18] Maluf, Gawdisk and Bell, N.D. David A. Maluf, Yuri O. Gawdisk and David G. Bell, N.D.
[19] Alleman, 2002.
[20] Stirling 2000, pp. 15. 7…16.
[21] Stirling 2000, p. 15.
[22] Nassim Taleb, 2007, p. 213.
[23] Taleb, 2008, p. 16
[24] Technology Risk Management Analysis used the word incertitude to describe the overall challenge and ambiguity to describe what I call vagueness I use the term vagueness as opposed to ambiguity based on the following definitions. Stirling used fuzzy logic as the analytic tool in this sector, and the wikipedia uses fuzzy logics to elaborate on the definition of vagueness.
Ambiguity is a term used in writing and math, and under conditions where information can be understood or interpreted in more than one way and is distinct from vagueness, which is a statement about the lack of precision contained or available in the information. Context may play a role in resolving ambiguity. For example the same piece of information may be ambiguous in one context and unambiguous in another.
The term **vagueness** denotes a property of concepts (especially predicates). A concept is vague:[1]

if the concept's extension is unclear;

if there are objects which one cannot say with certainty whether they belong to a group of objects which are identified with this concept or which exhibit characteristics that have this predicate (so-called "border-line cases");

In everyday speech, vagueness is an inevitable, often even desired effect of language usage. However, in most specialized texts (e.g., legal documents) vagueness is distracting and should be avoided whenever possible.
Fuzzy logic
Main article: Fuzzy logic

One theoretical approach is that of fuzzy logic, developed by American mathematician Lotfi Zadeh. Fuzzy logic proposes a gradual transition between "perfect falsity", for example, the statement "Bill Clinton is bald", to "perfect truth", for, say, "Patrick Stewart is bald". In ordinary logics, there are only two truth-values: "true" and "false". The fuzzy perspective differs by introducing *an infinite number of truth-values* along a spectrum between perfect truth and perfect falsity. Perfect truth may be represented by "1", and perfect falsity by "0". Borderline cases are thought of as having a "truth-value" anywhere between 0 and 1 (for example, 0.6).

[25] Stirling 2000, p. 15,

[26] Taleb, 2007, p. xx-xxi

[27] Taleb, 2007.

[28] Stirling 1999, p. 16.

[29] Stirling, 2001, p. 56.

[30] Meyer, Loch and Pich, 2002, p. 67

[31] Taleb, p. xxii.

[32] Taleb, 2008, p. 30.

[33] Taleb, 2010, p. 317)

[34] Clauzwitz is credited with the metaphor based on quotes like "War is the realm of uncertainty; three quarters of the factors on which action is based are wrapped in a fog of greater or lesser uncertainty."
"The great uncertainty of all data in war is a peculiar difficulty, because all action must, to a certain extent, be planned in a mere twilight, which in addition not infrequently — like the effect of a fog or moonshine — gives to things exaggerated dimensions and unnatural appearance. (cited in Kiesling, 2001).

[35] It certainly fits the description of space exploration above. It did not work as an excuse for not finding weapons of mass destruction, as Secretary of Defense Rumsfeld found when he invoked the terminology of Reliability and Risk Mitigation management. He was roasted in the press for his statement that [T]here are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns – the ones we don't know we don't know." http://www.defense.gov/transcripts/transcript.aspx?transcriptid=2636; The producer of the Documentary on McNamara's musing on the fog of war weighed provides insights and identifies the affliction of not knowing what we don'tknow, "The Anosognosic's Dilemma: Something's Wrong but You'll Never Know What It Is (Part 1)," in a New York times blog, Morris, 2010.

[36] Campden, 2010. Efforts to statistically model attacks in modern warfare end up in the "precaution" mode: Bland, 2010, "This won't necessarily help a commander in the field deal with the day-to-day… However, if the model predicts that a large attach is likely to happen soon, governments or military commanders could take steps to prevent its occurrence by more closely monitoring communications of enemy combatants. Officials may also potentially lessen the impact of an attack by moving civilians and soldiers away from likely targets. "

[37] Nassim Nichols Taleb, "The fourth quadrant: A Map of the Limits of Statistics," *Edge: the third culture,* September, 15, 2009, p. 3.

[38] Costello, 2005.

[39] The **Standard deviation** is a widely used measurement of variability or diversity used in statistics and probability theory. It shows how much variation or "dispersion" there is from the "average" (mean, or expected/budgeted value). A low standard deviation indicates that the data points tend to be very close to the mean, whereas high standard deviation indicates that the data are spread out over a large range of values.

[40] Jansen Beurskens, and Tiburg, 2006, p. 13 argue for a risk-cost frontier.

[41] Jansen Beurskens, and Tiburg, 2006, Appendix, p. 59, ""the question of whether a tool could be develop for gauging the impact of incremental technology deployment… the use of a (sort of) Sharpe ratio, showing the tangent of the direction a certain portfolio at (or to the right of) the efficient frontier would move into by incremental use of a certain technology."

[42] Gardner and Zhuang, 2000, p. 9.

[43] Blyth, et al., 2007, 5268.

[44] Allen, 2003, p. 11.

[45] Kent and Tapiero, 2009

[46] Sirling,2 000, p. 17

[47] Stirling, 1994, 196.

[48] Stirling, 2010, pp. 1622-1623.

[49] American Council for an Energy Efficient Economy, 2009

[50] Lazard, 2010, p. 9.
[51] Cooper, 2010,
[52] Cooper, 2011.
[53] Kahn, 1988, p. 11.
[54] Roques, 2008
[55] Ristouci and Solomou, 2010, argue it is not a general purpose technology, just a major technology that has a large impact over time.
[56] According to the Energy Information Administration, *International Energy Statistics,* Saudi Arabia accounts for roughly one-fifth of global crude oil reserves. The U.S. accounts for over one-quarter of global coal reserves. Russia is the Saudi Arabia of natural gas, with over one-quarter of global reserves, while the US. Has about 5 percent.
[57] Roques, Newberry and Nuttal, 2006.
[58] Cooper CWIP,FLA
[59] American Council for an Energy Efficient Economy, 2010.
[60] Boonin, p. 7. advises decision makers to engage in "Uncertainty Assessment Analysis (UAA)" as follows, "it is necessary to perform the UAA applying internal uncertainties and probabilities for the alternative resource against the proposed resource's expected internal assumptions." This is a form of risk/uncertainty analysis that is similar to the one presented below. The author notes that contracts can be handled differently, since "the alternative resource does not have key internal contributors to uncertainty, such as a bonded guaranteed price and output purchase power contract."
[61] Biewald, et al., pp. 45-46,
[62] Cooper, 2010.
[63] Stirling, 2000.
[64] Awerbuch, 2006, p. 700.
[65] Roques, Newberry and Nuttall, pp. 6-9.
[66] Cooper, 2009.

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