NUCLEAR SAFETY AND NUCLEAR ECONOMICS, FUKUSHIMA REIGNITES THE NEVER-ENDING DEBATE:

NUCLEAR SAFETY AT AN AFFORDABLE COST, CAN WE HAVE BOTH?
IS NUCLEAR POWER NOT WORTH THE RISK AT ANY PRICE?

SUMMARY

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In the wake of a severe nuclear accident like Fukushima, the attention of policymakers, regulators, and the public is riveted on the issue of nuclear safety. The scrutiny is so intense that it seems like the only thing that matters about nuclear reactors is their safety. This paper shows that in fact, and for good reason, the central tension throughout the 50-year history of commercial nuclear power in the United States has been the relationship between the safety and economics of nuclear reactors, tension that is far from resolved.

The paper presents an analysis of two aspects of the "infrastructure of safety regulation" (as the Vice Chairman of the Japanese Atomic Energy Commission called it. It examines the organizational structure of safety regulation and the continuing operational challenges that confront the safety of nuclear reactors. This analysis relies on a qualitative review of safety concerns and a quantitative review of performance in the 1970s (including the reaction to the accident at Three Mile Island), as well as the post-Fukushima reviews of nuclear safety.

The economic analysis is based on a comprehensive data set on virtually all U.S.nuclear reactors (251) planned or docketed at the Nuclear Regulatory Commission. Two dozen variables believed to influence three key junctures in the development of nuclear reactors are examined, the build/cancel decision, construction costs and repair/retire decisions. The variables include characteristics of the reactors (e.g. size, technology, builder), the nature of safety regulation (e.g. rules in place, fines imposed), the status of the industry (e.g. experience and activity), the conditions in the economy (e.g. inflation), and the status of the state utility industry (e.g. demand growth rate, numbers of reactors under construction, fuel types).

THE REAL WORLD ROOTS OF THE SAFETY DEBATE

Sections II & III: In the late 1950s the vendors of nuclear reactors knew that their technology was untested and that nuclear safety issues had not been resolved, so they made it clear to policymakers in Washington that they would not build reactors if the Federal government did not shield them from the full liability of accidents. Having secured legislation in the late 1950s, electric utilities proposed a massive expansion of nuclear power over the course of a couple of decades that would have taken the industry from a handful of small reactors with a total generating capacity of about one Giga watt to over 250 reactors with a total capacity of almost 200 Giga watts (see Figure ES-1).

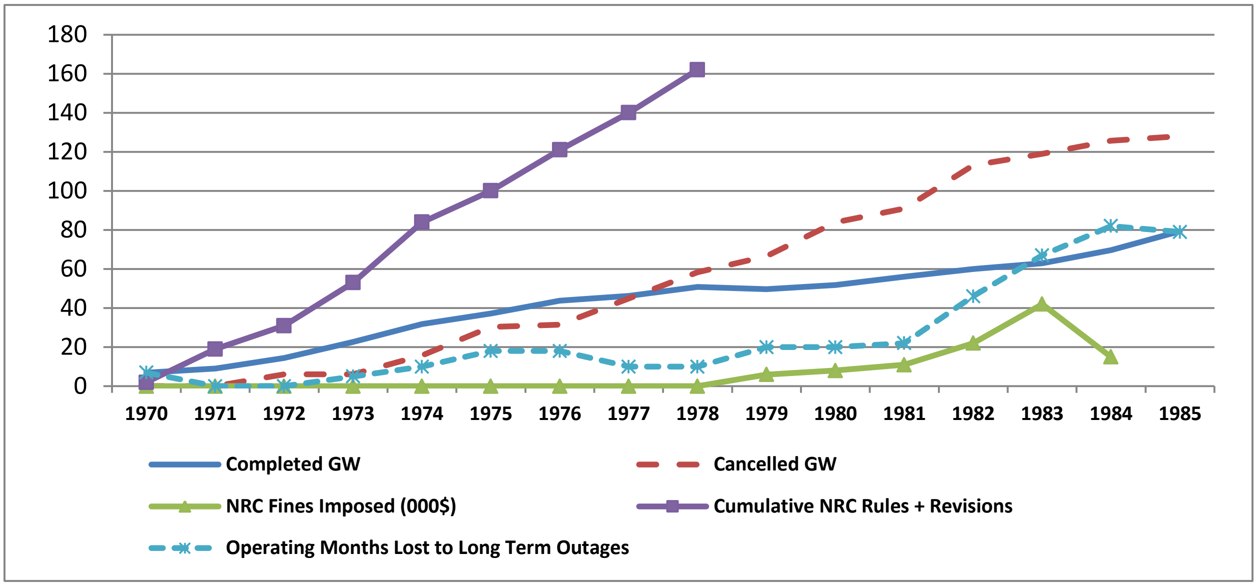
The expansion in size would have put large metropolitan areas with hundreds of millions of people in close proximity to nuclear reactors whose design and operation had never been fully tested. As more experience was gained with the operation of these huge reactors, the Nuclear Regulatory Commission (originally named the Atomic Energy Commission) became deeply concerned about the safety of nuclear power. Hundreds of safety regulations were written and revised over the course of the 1970s.

The U.S. and global experience with nuclear reactor development and operation provided a constant drum beat of incidents, near misses, and catastrophic accidents that demonstrated to regulators and the public that the concern about the safety of nuclear power was grounded in reality. The cost of the most severe accidents (e.g. Chernobyl and Fukushima) run into the hundreds of billions of dollars. The worst case scenarios (e.g. New York or Los Angeles) would exceed a trillion dollars.

THE CURRENT SAFETY DEBATE

Section IV: Confronted with catastrophic possibilities, safety regulators and others responsible for nuclear power seek to learn from major accidents. The pre-TMI debates about nuclear safety, the review of the TMI accident, and the post-Fukushima reviews exhibit strong similarities in finding flaws in nuclear safety regulation (see Table ES-2). These involve vitally important organizational characteristics of safety regulation as well as continuing operational challenges that confront the safety of nuclear reactors.

FIGURE ES-1: SAFETY REGULATION AND THE DISPOSITION OF NUCLEAR REACTORS



Sources: Fines: Tomain, *Nuclear Power Transformation* (Bloomington: Indiana University Press, 1987; Rules: Komanoff, Charles, *Power Plant Escalation: Nuclear and Coal Capital Costs, Regulation, and Economics,* (New York: Van Nostrand, 1981); Total reactors Fred A. Heddleson, *Summary Data for U.S. Commercial Nuclear Power Plants in the United States*, Nuclear Safety Information Center, April 1978; U.S. Energy Information Administration, *Nuclear Generating Units, 1955-2009;* Cancelled reactors *Jonathan Koomey, Was the Three Mile Island accident in 1979 the main cause of US nuclear power's woes?*, June 24, 2011.

In the United States more than 80 percent of US reactors face one or more of the issues that have been highlighted by the Fukushima accident – seismic risk, fire hazard, and elevated spent fuel. (see Figure ES-2) of this kind. Moreover, half of those that do not exhibit one of these issues had a "near miss" in 2011. Clearly, safety remains a challenge in the United States, one that has been magnified by Fukushima.

If, as Tomain (1987: ix) argued, "TMI made the United States aware of unforeseen costs, just as Chernobyl made the world aware of unforeseen risks," then Fukushima has made the perception of those risks real and expanded their scope dramatically. Fukushima reminds us that nuclear accident happen, but are impossible to predict because of the complex and dynamic interplay of technological, human and natural factors. severe impacts can be imposed on such large, unprepared populations, but the magnitude of the impact is hard to grasp and communicate. The understanding of the sequence of events in accidents is highly imperfect, which means that the immediate reaction called for is very uncertain. The uncertainty and involuntary nature of the harm and the inability of responsible authorities to deal with it creates an augmented sense of risk. Thus the heightened sense of concern that is attached to nuclear power and the psychological distress suffered by the public is grounded in the nature of the risk of the technology, which is made quite evident by severe accidents, like Fukushima.

Traditionally, the focal point of analysis of the "harms" of nuclear power has been on the public health risks of exposure to radiation that may be released from a reactor, but Fukushima makes it clear that the social and economic impacts of a severe accident close to population centers are very serious and also deserve a great deal of attention. We are now having a debate about nuclear evacuation zones of 50 miles.. The disruption of daily life in a large area around a nuclear accident has become a focal point of concern. Large numbers of people may be temporarily or permanently uprooted. The fact that the Japanese government was considering evacuating Tokyo, 150 miles away and there are large dead exclusion zones a year later underscores this concern.

TABLE ES-2: THE INADEQUATE INFRASTRUCTURE OF NUCLEAR SAFETY REGULATION

ORGANIZATIONAL FLAWS

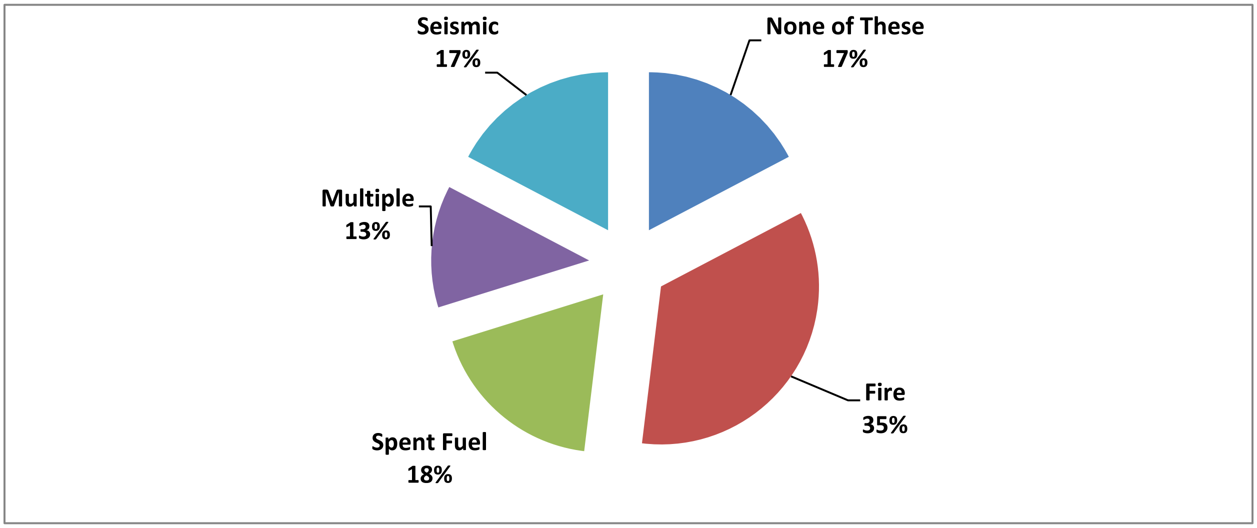
Lack of a Comprehensive, Consistent, Safety Regulation Framework
Denial of the Reality of Risk
Complexity, Confusion, and Chaos in the Response to a Severe Accident
Failure of Voluntary, Self-Regulation
Perverse Incentives in Commercial Attitudes toward Safety:
Deficient management process including planning, standard setting, inspection, communications
Failure to Resolve Important Safety Issues:
Failure to Retrofit Safety on Existing Reactors
The Challenge of Continuous Change and the Future of Safety

THE IMMEDIATE OPERATIONAL CHALLENGES

Design (event tolerance, cooling, venting, backup system resilience and redundancy),
Siting (reactor crowding, seismic and flooding vulnerabilities)
Waste storage,
Evacuation plans and
Cost increases

Source: Komanoff, C, 1981 *Power Plant Escalation: Nuclear and Coal Capital Costs, Regulation, and Economics*, Van Nostrand, 1981. John G Kemeny *Report of The President's Commission on the Accident at Three Mile Island,* October 30, 1979; Nuclear Regulatory Commission, *TMI-2 Lessons Learned Task Force Final Report,* October 1979;Tatsujiro Suzuki, "Deconstructing the Zero-Risk Mindset: The Lessons and Future Responsibilities for a Post-Fukushima Nuclear Japan, " *Bulletin of the Atomic Scientists, September 20, 2011;* Nuclear Regulatory Commission, *Recommendations for Enhancing Reactor Safety in the 21st Century: The Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident,* U.S. NRC, July 12, 2011; Yoshiro Nakagome, *JNES's Response to TEPCO Fukushima NPS Accident,* November 2011; Eurosafe Forum, Experience Feedback on the Fukushima Accident, November 8, 2011; D. Degueldre, T. Funshashi, O. Isnard, E. Scott de Martinville, M. Sognalia, "Harmonization in Emergency Preparedness and Response;" P. De Gelder, M. Vincke, M. Maque, E. Scott de Martinville, S. Rimkevicius, K. Yonebayashi, S. Sholmonitsky, *"The Evolution of the TSO Programme of Work after the Fukushima Daiichi NPS Accident*.

FIGURE ES-2: SIGNIFICANT ONGOING SAFETY ISSUES



Source: Union of Concerned Scientists, *Nuclear Power Information Tracker,* March 2012, http://www.ucsusa.org/nuclear_power/reactor-map/embedded-flash-map.html

Fukushima is a real economic disaster. The costs are estimated as high as a quarter of a trillion dollars. Tokyo Electric Power Company, the fourth largest utility in the world, was instantly pulled into virtual bankruptcy, when its stock plunge 90 percent, notwithstanding liability limits and governmental commitments to shoulder much of the cost. The Japanese grid is under severe stress. The economy has been damaged. Safety regulators have known about these potential impacts, but they were hypothetical. Fukushima makes them real.

REAL WORLD ECONOMIC PROBLEMS OF NUCLEAR REACTORS

Section V: Reactor cost overruns were endemic from the very beginning of the commercial industry because nuclear vendors and enthusiasts had underestimated the costs and overestimated the ability of economies of scale and "learning by doing" to lower the cost. The increasing demand for safety compounded the problem. The final reactors built cost ten times the initial estimates and by1978, the year before the worst nuclear accident in U.S. history, more reactor capacity had been cancelled than completed. After the TMI accident, the Nuclear Regulatory Commission stepped up its enforcement of safety rules, which extended the construction period and further increased the cost of reactors. No order for a new nuclear reactor was placed in the United States for over a quarter of a century.

TABLE ES-1: STATISTICALLY SIGNIFICANT VARIABLES IN THE ECONOMETRIC ANALYSIS

Factors/variables	**Probability of building**	**Construction period**	**Overnight cost ($/kw)**
Stricter safety regulation	Less likely	Longer	More costly
Technology			PWR less costly
Larger capacity		Longer	Less Costly
Multiple Units at a site			Less Costly
Longer construction			More costly
More industry activity		Longer	More costly
More builder experience		Shorter	
Higher demand growth	More likely		
Higher interest rates			More costly
Post-TMI	Less likely		
Explained variance (R^2)	.91	.76	.82

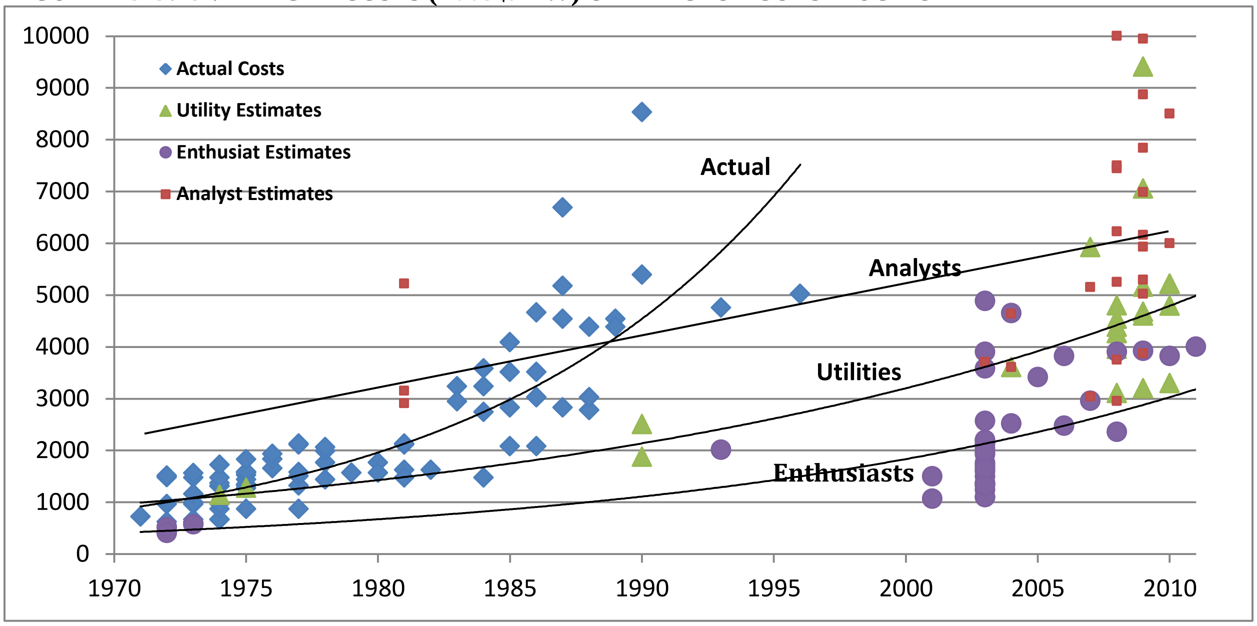
Table ES-1 summarizes the results of the statistical analysis. Safety is the most consistent explanatory variable, with stricter standards associated with less likelihood of building, longer construction period and higher cost. The findings on technology and industry characteristics reinforce the conclusion that the industry did not benefit from a "learning by doing" process. The belief that higher growth rates were associated with a higher probability of being completed and higher interest rates were associated with higher costs is confirmed in this statistical analysis. However, over the period of the 1970s-1980s, the amount of fossil fuel generation capacity added actually exceeded the amount of nuclear capacity cancelled. In other words, if the economics of nuclear reactors had not been so unfavorable, fewer would have been cancelled and more fossil fuel capacity would have been displaced.

Analysis of early retirements reinforces the above conclusions. A combination of factors causes retirement, but there tends to be a precipitating event like a major equipment failure, system deterioration, repeated accidents, increased safety requirements, etc. Economics is the most frequent proximate cause and safety is the most frequent factor that triggers the economic re-evaluation. Although popular opposition "caused" a couple of the retirements (a referendum in the case of Rancho Seco; state and local government in Shoreham), this was far from the primary factor and in some cases local opposition clearly failed (two referenda in eh cases of Trojan and Maine Yankee). External economic factors like declining demand or more cost competitive resources can render existing reactors uneconomic on a "stand alone" basis or (more often) in conjunction with one of the other factors.

THE CURRENT ECONOMIC CHALLENGES

Section VI: In the 1970s and 1980s the nuclear industry could not overcome the problem of escalating costs and lower cost alternatives. It continues to be afflicted by the same problems. The "nuclear renaissance," which was loudly heralded with extremely optimistic cost projections proved to a re-run of the collapse of the "Great Bandwagon Market" of the 1970s and 1980s (see Figure ES-3). The industry could not live up to the hype and cost projections escalated rapidly. The estimates now used by utilities are three times the initial “renaissance” estimates, while independent analysts on Wall Street, put the cost estimates at five times the original estimates.

FIGURE ES-3: OVERNIGHT COSTS (2009$/KW) OF REACTOR CONSTRUCTION



Source: Actual Costs from Jonathan Koomey, and Nathan E. Hultman, 2007, “A Reactor Level Analysis of Busbar Costs for US Nuclear Plants, 1970-2005,” *Energy Journal*, 2007; Projections updated from Mark Cooper, *The Economics of Nuclear Reactors: Renaissance or Relapse* (Institute for Energy and the Environment, Vermont Law School, June, June 2009).

The subsidy problem in nuclear reactor construction has actually become much more severe. The liability limitation is still in place and, given the magnitude of the impact of the Fukushima accident, the gap between private liability and public liability is likely to be much larger. In addition, the utilities proposing new nuclear reactors have demanded many more and larger direct subsidies. They have demanded much more direct ratepayer support in the form of advanced cost recovery. Since construction of nuclear reactors cannot be financed in normal capital markets, federal loan guarantees and partnership with public power that has independent bonding authority appear to be necessary ingredients to move projects forward.

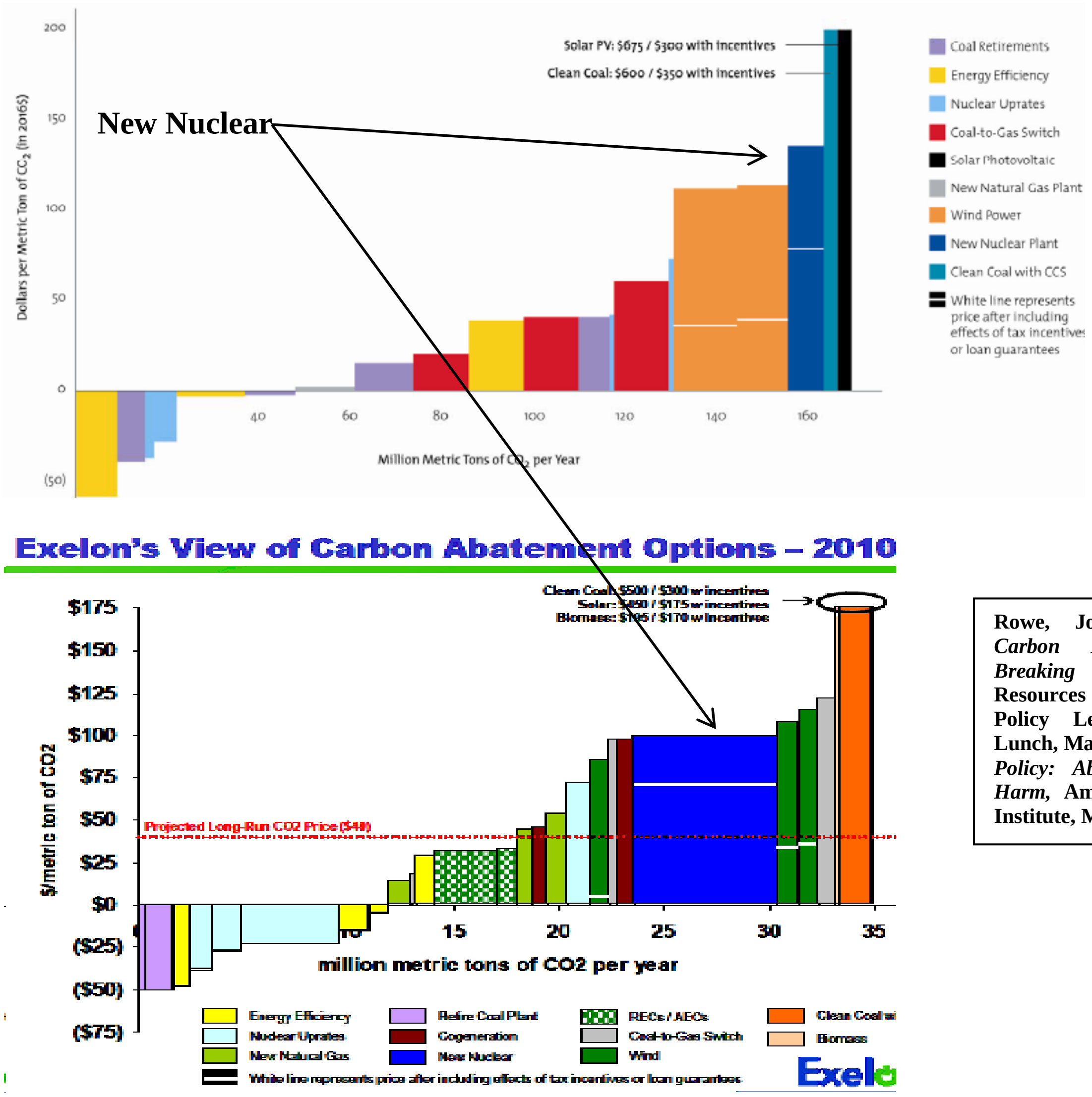
In addition to the challenge of cost escalation, nuclear power continues to be unable to meet the challenge of lower cost alternatives, even in a carbon-constrained future. Many analysts and utilities, including those that own operating nuclear reactors, have concluded that there are numerous lower cost alternatives available. As shown in Exhibit ES-4, even before Fukushima, nuclear was way up the supply curve of low carbon resources.

A NEW INFRASTRUCTURE OF DECISION MAKING

Section VII: As pressing as the need for a new “infrastructure of safety regulation” is in the nuclear sector, the need for a new “infrastructure of decision-making” for resource acquisition in the electricity sector is even greater. Fukushima reminds us that nuclear accidents fall into a realm of knowledge that involves unknown unknowns. The NRC identifies the challenge of dealing with “low likelihood, high consequence events,” while the Office of Technology Assessment referred to “low probability, catastrophic accidents.” The nuclear unknowns are part of an increasingly ambiguous decision-making space afflicted by price volatility, supply insecurity and growing concerns about environmental externalities that confronts those responsible for resource acquisition to ensure an affordable, reliable, secure, and sustainable supply of electricity.

FIGURE ES-4: TWO UTILITY VIEWS OF RESOURCE COST

PJM



Rowe, John, *Fixing the Carbon Problem without Breaking the Economy*, Resources for the Future Policy Leadership Forum Lunch, May 12, 2010; *Energy Policy: Above All, Do No Harm*, American Enterprise Institute, March 8, 2011

How does one make effective decisions in a space where the impacts of significant events or use of important resources are unclear (outcomes unknown) and the occurrence of those events or the availability and price of those resources are unpredictable (the probabilities are unknown)? A number of frameworks for navigating in regions where knowledge is extremely limited have been developed over the past half century in military strategy, space exploration, technology assessment, engineering science, and financial analysis.

As suggested by Figure ES-5, the efforts to map the terrain of knowledge 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 probabilities of those outcomes. Four regions of knowledge result: risk, uncertainty, vagueness, and the unknown. The decision-making space is darkest where knowledge is lacking, but each region of knowledge presents a distinct challenge to the decision-maker. The crucial starting point for all these analyses is to admit that you don't know what you don't know and then develop tools for navigating with imperfect knowledge. Unfortunately, admitting what you do not know is not something that builders and operators of nuclear reactors are inclined to do. Their reaction is to insist their reactors are safe and commit to making them safer, but then complain bitterly about and resist additional safety measures that increase their costs.

In the current environment for resource acquisition must:

- identify the trade-offs between cost and risk to allow hedging to lower risk;
- maximize options to reduce exposure to uncertainty by buying time and keeping options open with small assets that can be added quickly;
- be flexible with respect to outcomes that are, at best, vague creating systems that monitor and can adapt to change in order to maintain system performance and minimize surprises by avoiding assets that have unknown or uncontrollable effects, and
- be insulated against ignorance of the unknown by buying insurance and building resilience with diversified asset portfolios that exhibit variety, balance and disparity resources.

Acquisition of nuclear facilities is particularly unattractive-- the antithesis of the type of asset a prudent investor wants to acquire, because of their long lead times and lives, large sunk costs, and high risk profile.

"Nuclear safety at an affordable cost, can we have both?" seems like a straightforward question to journalists and policy makers, but is actually a very complex question. Phrased as Tomain did shortly after Chernobyl the question is more pointed: "Is nuclear power not worth the risk at any cost?" If a simple answer is demanded, as it frequently is during post-accident review, then the answer must be no.

- If we use a market standard, nuclear power is neither affordable nor worth the risk.
- If the owners and operators of nuclear reactors had to face the full liability of a nuclear accident or meet alternatives in a competition unfettered by subsidies, no one would have built a nuclear reactor in the past, no one would build one today, and anyone who owns a reactor would exit the nuclear business as quickly as they could.
- The combination of a catastrophically dangerous resource, a complex technology, human frailties, and the uncertainties of natural events make it extremely difficult and unlikely that the negative answer can be changed to a positive.

The post-accident safety reviews have revealed that a "public myth of absolute safety" lulled the industry into a false sense of security and a "lack of preparedness." The post-Fukushima economic review must expose the myth of economic viability that has been created by half a century of subsidies. Thus, in formulating the answer, the lessons of half a century of nuclear power should be kept in mind.

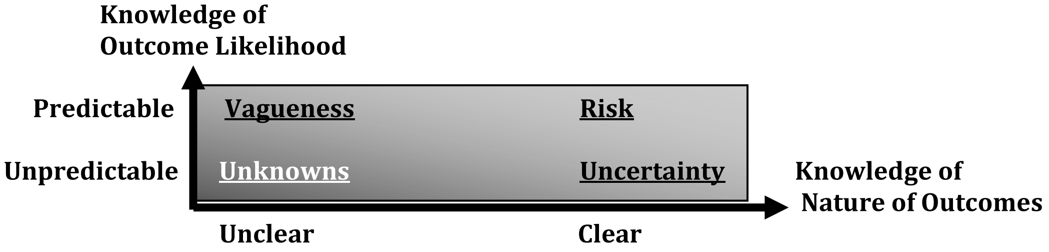
Nuclear power is a non-market phenomenon: It is certainly true that economics has decided, and will likely continue to decide, the fate of nuclear power. The fiction that investors and markets can make decisions about nuclear power in a vacuum is dangerous. Given the massive economic externalities of nuclear power (not to mention the national security and environmental externalities), policy-makers decide the fate of nuclear power by determining the rate of profit through subsidies.

Learn from history: Sound economic analysis requires that sunk costs be ignored, but the mandate for forward-looking analysis does not mean that the analyst should ignore history. Utilities claim that the cost of completing a new reactor or repairing an old one is lower than the cost of pursuing an alternative from scratch. The problem is that utilities are just as likely to underestimate and be unable to deliver on the promised "to-go" costs in the future as they have been in the past. Regulators must exercise independent judgment and take the risk of cost overruns into consideration.

Match risks and rewards: If the goal is to have cost-efficient decisions, risks must be shifted onto those who earn rewards. By reducing the rate of profit that utilities earn from subsidized project, policy-makers can offset the bias that subsidies (such as loan guarantees and advanced cost recovery) introduce into utility decision-making.

EXHIBIT ES-5: CONFRONTING AMBIGUITY IN THE INCREASINGLY COMPLEX TERRAIN OF KNOWLEDGE:

THE REGIONS OF KNOWLEDGE



TOPOGRAPHIC MAPS AND NAVIGATION TOOLS FOR THE REGIONS OF KNOWLEDGE

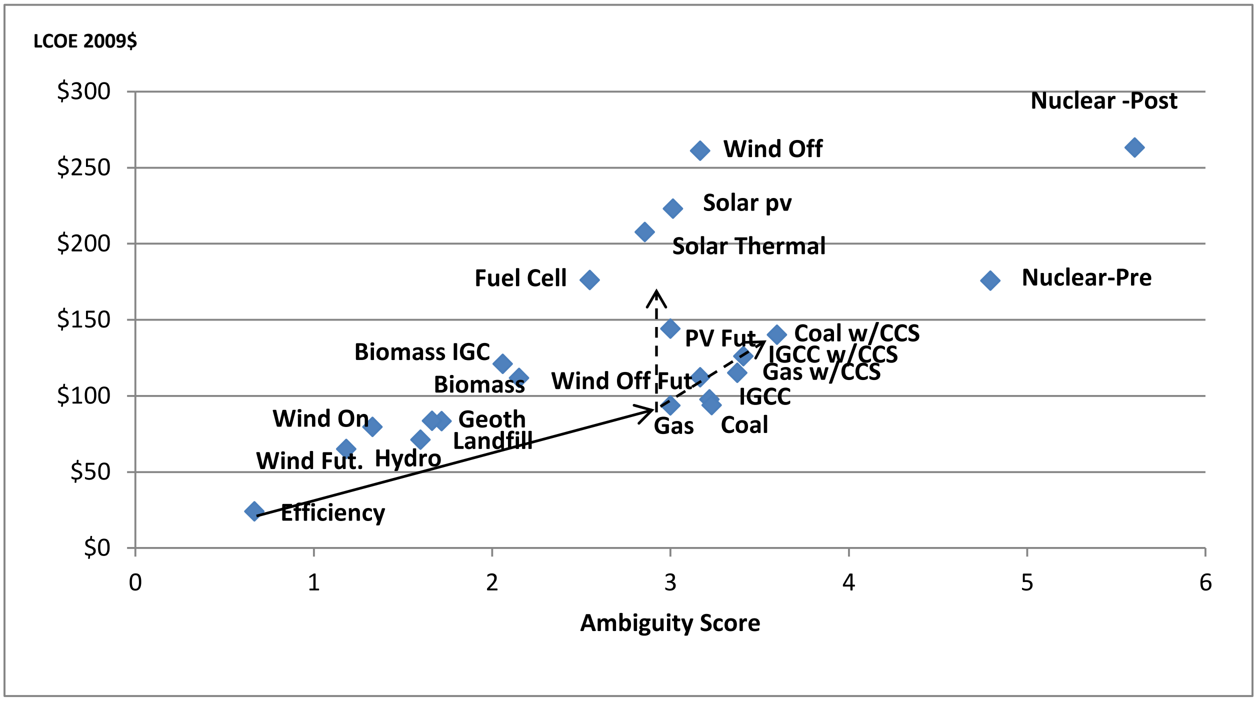
	UNKNOWNS	VAGUENESS	UNCERTAINTY	RISK
TOPOGRAPHIC MAPS				
Technology Risk Assessment				
Challenges	Unanticipated effects	Contested framing	Nonlinear systems	Familiar systems
Outcomes	Unclear	Unclear	Clear	Clear
Probabilities	Unpredictable	Predictable	Unpredictable	Predictable
Black Swan Theory				
Challenges	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
NAVIGATION TOOLS				
Analytic frameworks				
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 Alternative Instrument Sufficiency	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 Ccapital
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: Nassim Nicholas Taleb, *The Black Swan* (New York: Random House, 2010), Postscript; 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.; 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.

Buy time: Given the severe problems that retrofitting poses and the current conditions of extreme uncertainty about changes in safety regulation, it is prudent to avoid large decisions that are difficult to reverse or modify. Flexibility is a valuable attribute of investments, and mistakes should be kept small.

Applying this approach to resource acquisition leads to clear pathways to the future built on resources that have attractive characteristics even in a carbon constrained world (see Exhibit ES-6).. The clearest finding is that nuclear does not belong on the near-term supply-curve and it does not appear to be an attractive resource for the long-term, in light of the potential availability of future renewables and carbon capture technologies. This is the same conclusion suggested by Exhibit ES-4, but it is much sharper when the other sources of ambiguity are incorporated into the analysis.

EXHIBIT ES-6: RESOURCE ACQUISITION PATHS BASED ON MULTI-CRITERIA EVALUATION



Sources: Mark Cooper, "Prudent Resource Acquisition in a Complex Decision Making Environment: Multidimensional Analysis Highlights the Superiority of Efficiency," ***Current Approaches to Integrated Resource Planning, 2011 ACEEE National Conference on Energy Efficiency as a Resource*****, Denver, September 26, 2011**

To be sure, the burning question is whether the nations that have relied on nuclear power to a significant extent will be able to shift the resources base. There is no doubt that this is a significant technological and economic challenge that will not be easy. It is important to keep in mind that the outcome of the analysis can certainly vary from nation to nation because the natural resource endowments of nations vary. However, Fukushima reminds us that nuclear power is not easy either and embodies significant challenges that have been repeatedly underestimated or ignored.