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ENERGY TECHNOLOGY
INNOVATION POLICY

eRD3

July 6, 2011

Quantifying technology uncertainty and the impact of innovation policies on the distribution of environmental and security benefits of RD&D investments

30th International Energy Workshop, Stanford University

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Overview

- Motivation

- Methodology

- Results
  – Contribution of RD&D to meeting U.S. government goals
  – Returns to RD&D investments accounting for technical uncertainty
  – Optimization of RD&D allocation

- Conclusions

Calls for more energy RD&D in the United States are becoming more frequent

Year	Recommendation
1997	PCAST recommended $2.8 billion/year in 2010$ by 2003, which represented a doubling in "as spent" dollars from 1997, for efficiency, fission and fusion, fossil, and renewables.
1999	Schock *et al.* (mainly from national labs) estimated the value of U.S. low-carbon energy R&D to reduce climate change mitigation costs to $6.4-$9 billion/year in 2010$ (about 3X).
2004	NCEP recommended an increase from $2.0 billion 2010$ in 2004 to $3.7 billion 2010$ in 2010 (almost a doubling) for oil, efficiency, advanced coal, nuclear energy, and renewables.
2005	Nemet and Kammen recommended that $6.7-30.1 billion/year 2010$ be invested in low-carbon technology R&D using Schock et al. results from 550 ppmv CO_2 stabilization scenario.
2007	National Academies "Rising Above the Gathering Storm" report recommends the creation of ARPA-E.
2007	Nemet and Kammen recommended a 5-10 fold increase in energy RD&D from 2005 levels ($21-$41 billion/year in 2010$) using analogies with Manhattan and Apollo projects.
2008	APS recommended $250 million per year for buildings efficiency.
2010	▪ Brookings Institution, American Enterprise Institute, and Breakthrough Institute recommended $25 billion/year for a national network of innovation institutions, expanded U.S. DOD energy technology procurement, ARPA-E, and nuclear power ▪ American Energy Innovation Council recommended $16 billion/year in energy RD&D. ▪ PCAST also recommended annual expenditures on energy RDD&D of $16 billion.

Tools are needed to help make decisions about RD&D investments and complementary policies

- U.S. Department of Energy uses recommendations from individual technology programs and presidential priorities, but does not incorporate the uncertainty in technology outcomes (and benefits) or the interaction between technologies in the marketplace in a comprehensive manner

- Interested parties (coal, nuclear, environmentalists) lobby to increase government support for their area

- The decision-making process could be supported by an integrated and transparent assessment of:
  - The *distribution* of returns (benefits) to a portfolio of public RD&D investments to help determine an appropriate total level of investments
  - The optimal allocation by technology accounting for the competition between technologies in the market

Research question

- What can we say about the level and allocation of energy RD&D investment required to have acceptable results on metrics we care about:
    - CO_2 emissions
    - CO_2 prices (if climate policy adopted)
    - Clean Energy Standard (CES) prices (if CES policy adopted)
   - Oil imports

Methodology

- **Step 1: Estimating the impact of RD&D on technological change**
  - Factor decomposition: looking back (Nemet, 2007; McNerney, Farmer & Trancik, 2011)
  - Monitoring precursors: identifying changes early on (Martino, 1987)
  - Expert elicitation: looking forward (Henrion & Morgan 1990; Baker & Keisler, 2009)

- **Step 2: Determining the effect of technological change on societal benefits** (i.e., CO_2 emissions, oil imports, CO_2 prices, Clean Energy Standard credit prices)
  - Designing scenarios integrating results from different elicitations into multi-region U.S. MARKAL model

- **Step 3: Post-processing**
  - Role of RD&D vs. deployment
  - Return on investment accounting for uncertainty
  - RD&D allocation optimization

Expert elicitations covered a wide range of technologies

- 4 supply side technology areas
  - *Nuclear energy*: Gen III, Gen IV, modular reactors
  - *Fossil energy*: coal with and without CCS, natural gas with and w/o CCS
  - *Bioenergy:* gasoline, diesel, and jet fuel production through thermochemical and biochemical conversion pathways, and electricity
  - *Photovoltaic energy*: residential, commercial, and utility scale

- 1 enabling technology area
  - *Utility scale energy storage*: compressed air storage, 2 types of batteries, flow batteries

- 2 demand side technology areas
  - *Vehicle types*: advanced internal combustion engine vehicle, electric vehicle, plug-in electric vehicle, hybrid vehicle, and fuel cell vehicle
  - *Buildings*: commercial buildings, 6 levels of energy efficiency for heating and cooling

➔ *We covered 25 technologies under 4 budget scenarios*

➔ *Insights from 100 technical experts and 23 high-level reviewers*

Example results from nuclear expert elicitation
Picking 'representative' experts to model uncertainty

Anadon, Bosetti, Bunn, Catenacci & Lee (2011)
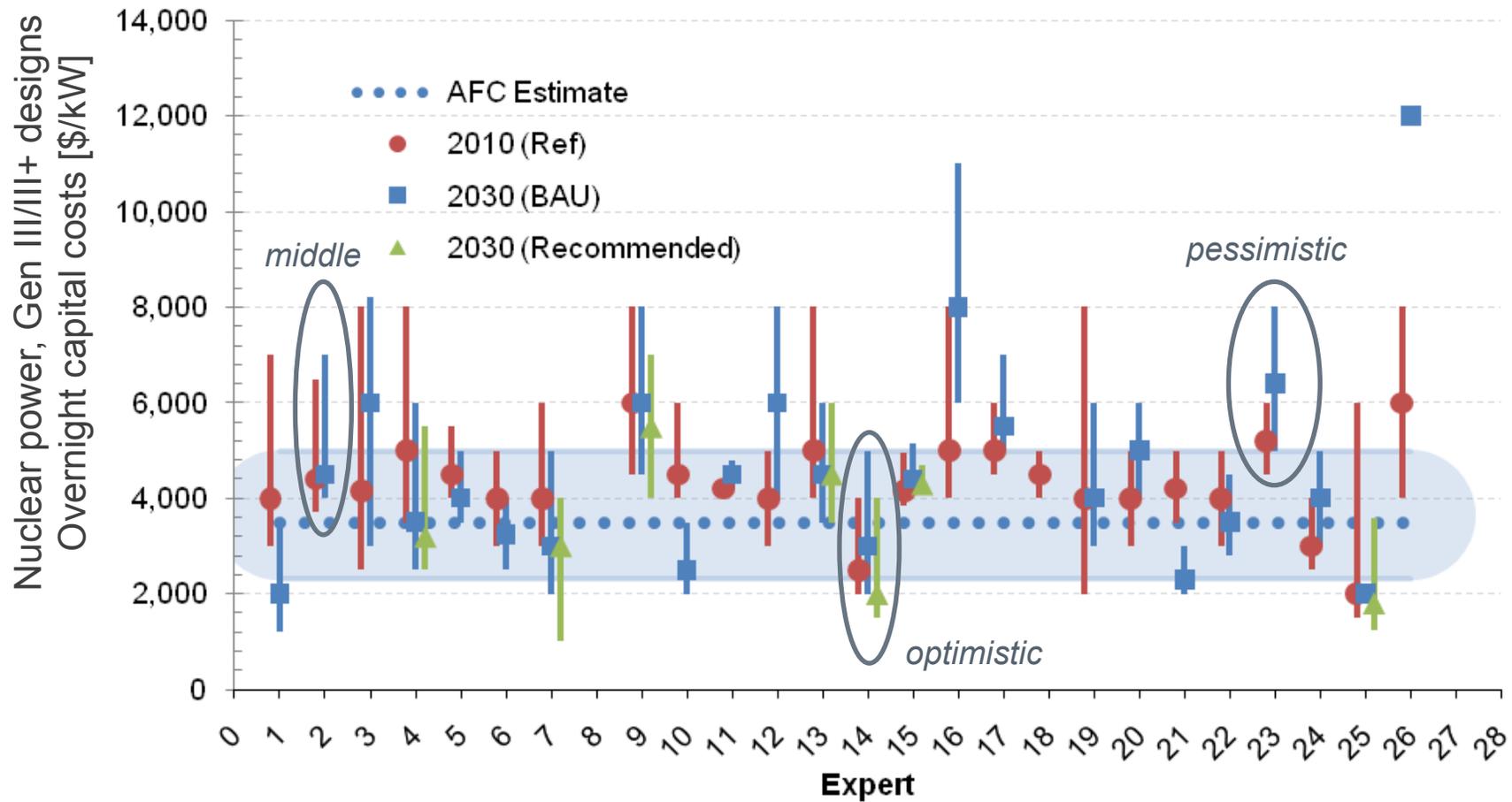
# Experts consistently expected decreasing marginal returns to RD&D

Ratio of the overnight capital cost of Gen IV reactors in 2030 under different RD&D scenarios and that under the BAU scenario
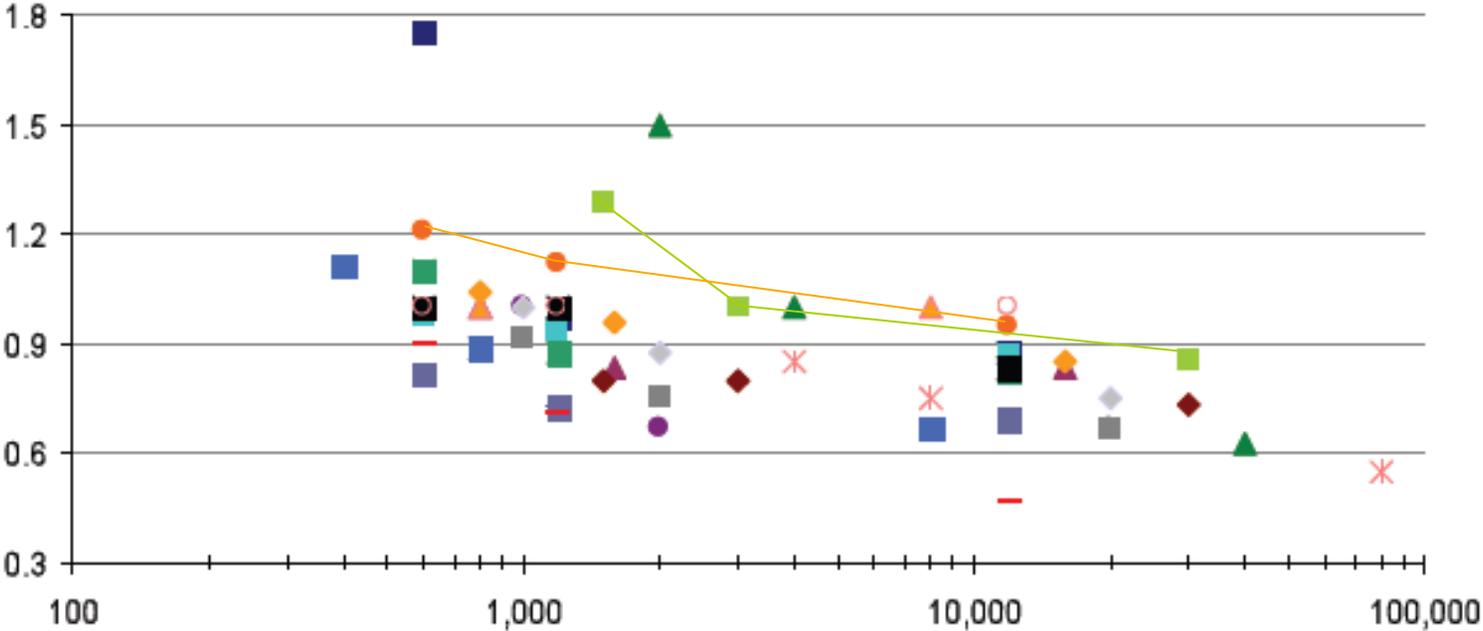
Public funding for nuclear RD&D: ½ recommended, recommended, and 10X recommended [million U.S.2010$]

Introducing expert elicitation results in MARKAL - dealing with computational limits

- Feeding 25 probability distribution functions of technology costs into MARKAL using conventional Monte Carlo would be computationally prohibitive

- Latin Hypercube Sampling (LHS) algorithm from Iman and Conover (1982) was used to decrease the number of runs needed to define a scenario to 400

Morgan and Henrion (1990) and Webster et al. (2004)
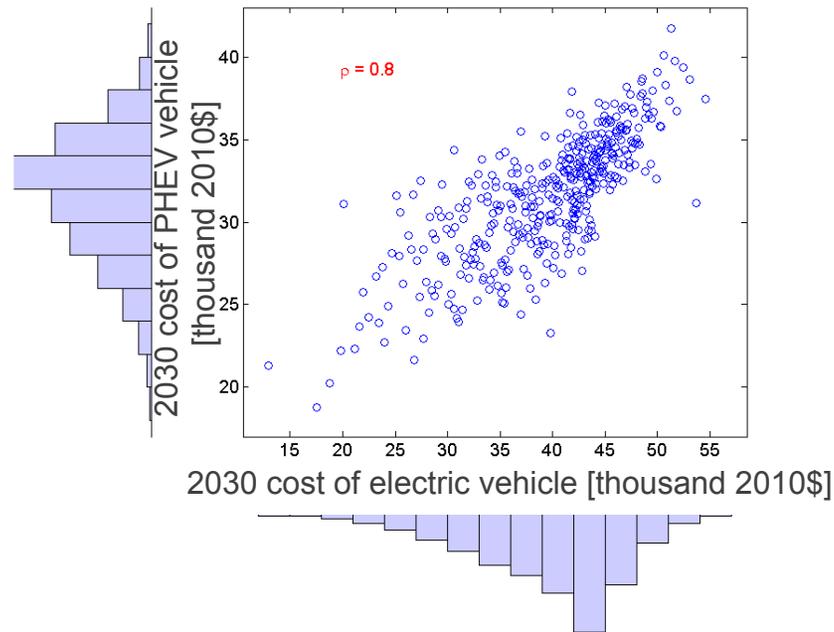
Evaluating the benefits of RD&D by "expert type" and policy and market conditions

- Evaluating the benefits of different budgets:
    - Business-as-usual
    - Recommended budget
    - 10 times recommended budget

    … and robustness of benefits depending on "expert types" (middle, optimistic, and pessimistic) bound the problem

- Impact under different policy and market conditions:
    - Policies (examples)
        - Cap and trade (83% reductions in CO_2 emissions in 2050 compared to 2005)
        - CES (President Obama's goal of 80% clean power by 2035)
    - Markets (examples)
        - High oil and gas prices
        - High oil and low gas prices

Using the variation in CO_2 price results to optimize RD&D allocation for 6 technology areas

Create a continuous function of experts' 10th/50th/90th cost percentiles and RD&D

- using estimates under 3 different RD&D levels

Estimate most likely RD&D level for technology costs in each of the 400 runs using a loss function approach

- matrix of 400 sets of technology costs, each with RD&D for 6 areas

Estimate relationship between RD&D levels for 6 areas and CO_2 prices using overfit least squares regression

Combine CO_2 prices for each of the 400 runs with the 400 sets of RD&D for 6 areas

Minimize CO_2 price subject to budget constraint using non-linear multivariate optimization

Conclusions

1. Incorporating elicitations and technical uncertainty makes the case about the need to put in place complementary demand-side policies stronger
   – Large increases in RD&D will not be sufficient to achieve current U.S. emissions reduction and oil import reduction goals, even if the best outcomes materialize

2. Increasing annual funding from $2 billion to $5-$8 billion for the technology areas investigated results in significant *expected* emissions reductions of by 2050 under a no policy case, and CO_2 price reductions

3. Beyond the recommended RD&D levels, all benefits exhibit decreasing marginal returns under all policies cases

   - The magnitude and probability of positive returns depends on policy; i.e., benefits of RD&D are more certain under the CO_2 policy than under the CES policy

4. Our modeling and analysis allows estimation of the optimal allocation of RD&D investments subject to a budget constraint accounting for interaction between technologies in the marketplace
   – This last allocation step does not take into account the uncertainty around RD&D and this would be a natural next step in our work

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Thank you for your attention,
Tom Alfstad, Paul Friley, and Savvas Politis for their work in MARKAL,
the ERD3 Advisory Board and the rest of the team for advice,
and the Doris Duke Charitable Foundation for financial support.