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From elicitation to insights about energy RD&D investment portfolios

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Research question
From the perspective of using a risk analysis framework

- What can we say about the level and allocation of energy RD&D investment required to have acceptable results on metrics we care about:
  - CO₂ emissions
  - CO₂ prices (if climate policy adopted)
  - oil imports
  - geographic distribution of electricity cost that makes policies feasible

- Our approach is to incorporate technical uncertainty to allow us to quantify the uncertainty around the metrics (benefits) and use decision metrics such as:
  - Probability of CO₂ price below a reasonable level, e.g., $30/tonCO₂
  - Probability of a very high CO₂ price, e.g., $100/tonCO₂,
  - Mean and standard deviation of a resulting oil imports, etc.
  - … under a range of investment portfolios and assumptions
From elicitations to quantifying benefits of portfolios accounting for uncertainty

**Business as usual RD&D scenario**

- \(\text{CO}_2\) price
- $30/ton
- 2010 to 2050
- Time

**Enhanced RD&D scenario**

- \(\text{CO}_2\) price
- $30/ton
- 2010 to 2050
- Time

- e.g., 30% probability of carbon price in 2030 below $30/ton \(\text{CO}_2\)
- e.g., 70% probability of carbon price in 2030 below $30/ton \(\text{CO}_2\)
Outline

1. Elicitations
2. Technology cost distributions
3. Using information about uncertainty in multiple technologies
   - Dimensionality and computational constraints
   - Relationship between estimates across technologies and over time
4. Analysis
   - Investigating impact of budget for different experts
   - Market and policy sensitivity analysis
5. Other thoughts
   - Areas for input
   - Future work
Investment portfolios cover a wide range of technologies
Our elicitation cover 25 technologies and 4 RD&D budgets

- 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 ICE, electric vehicle, plug-in electric vehicle, hybrid vehicle, and fuel cell vehicle
  - Buildings: residential and commercial buildings, 6 levels of energy efficiency for heating and cooling
From 3 points to a full distribution to represent cost uncertainty
Elicitations ask for 10th, 50th, and 90th percentiles

- Fit normal functional form (could also use logistic for larger tails)
  - Half of normal distribution to 10th and 50th percentiles, truncated at 5% of the 10th percentile
  - Half of normal distribution to 50th and 90th percentiles

- If we asked “best guess,” 10th, and 90th, we could use a continuous skewed distribution

\[
F^{-1}(p|x_{10}, x_{50}, x_{90}) = \begin{cases} 
  x_{50} + s_1 \Phi^{-1}(p) & \text{if } 0 < p \leq 0.1 \\
  x_{50} + s_1 \Phi^{-1}(p) & \text{if } 0.1 < p \leq 0.5 \\
  x_{50} + s_2 \Phi^{-1}(p) & \text{if } 0.5 < p < 1 
\end{cases}
\]

\[
s_1 = \frac{x_{10} - x_{50}}{\Phi^{-1}(0.1)} \\
s_2 = \frac{x_{90} - x_{50}}{\Phi^{-1}(0.9)} \\
\alpha = 0.05 \times x_{10}
\]
Representing uncertainty and dealing with computational limits for a large number of technologies

- Latin Hypercube Sampling (LHS) algorithm from Iman and Conover (1982)
  - Each (marginal) distribution of technology costs is partitioned into equal probability strata. Within each strata, the (marginal) distribution strata is sampled exactly once in the entire analysis.
  - We believe that there is dependence between some technology costs, we design the study to select combinations of Latin Hypercube marginal distribution draws for each technology to have a desired (rank) correlation matrix.
  - Algorithm works stochastically, so we iterate until the maximum absolute difference in any one specified rank correlation is below a specified threshold (0.05 for 400 runs).

- Sampling done either with traditional LHS or with van der Waerden scores version of LHS - i.e., samples at median of strata
  - no major differences; Morgan and Henrion (1990) recommend van der Waerden

- 400 samples per scenario define distributions in our implementation

Morgan and Henrion (1990) and Webster et al. (2004)
Accounting for the fact that improvements in some technologies are likely to be related (across-technology rank correlation)

- Sampling distribution for electric and plug-in hybrid vehicles
  - Drawn using LHS with Iman and Conover method to induce Gaussian copula dependence for $\rho = 0.8$
  - Marginal distributions (provided by experts) are preserved
Clusters of technologies where improvements are likely to be related

**Cluster 1**
Liquid fuels and electricity from coal and biomass through thermochemical processes

**Cluster 2**
Liquid fuels from biomass using biochemical processes

**Cluster 3**
Nuclear Gen III/III+, Gen IV technologies and modular nuclear reactors

**Cluster 4**
Photovoltaic for residential, commercial, and utility scale applications

**Cluster 5**
Different types of compressed air energy storage technologies

**Cluster 6**
Vehicles and batteries for utility scale energy storage
Quantifying the relationship between technology outcomes
Current and possible approaches

- Relationship between outcome in technology A and B
  - In some technologies, a good outcome for technology A is likely to be associated with a good outcome for technology B

- Methodology used for determining correlations
  - Discussion of team members
    - Do technology A and B have similar processes or unit operations (e.g., gasification processes for biomass and coal, lithium batteries for vehicles and utility scale storage)?
    - Approximately, what fraction of the cost do “common” processes represent?
    - Do technology A and B require similar components (e.g., electronics for different types of vehicles, materials for high temperatures in nuclear reactors)?
  - Assignment of correlations
  - Comparison and adjustment of correlations to ensure consistency

- Going forward (options)
  - Integration in elicitation (done in the case of vehicles)
  - Convening expert group
A low cost in 2010 is likely to be associated with a low cost in 2030
Example: coal with carbon capture and storage
From elicitation of costs in 2010 & 2030, to annual costs to 2050

Interpolations and extrapolations

- Increasing cost: linear
- Decreasing cost: exponential
- Increasing performance: linear and constant
- Decreasing performance: linear and constant
Picking representative experts to model wide range of uncertainty
Middle-of-the-road, optimistic, and pessimistic “expert types”
Evaluating the benefits of different budgets and how they change by “expert type” and policy and market conditions

- Evaluating the benefits of different budgets
  - Business-as-usual
  - ½ recommended budget
  - Recommended budget
  - 10 times recommended budget
    - and robustness of benefits depending on “expert types” to bound the problem

- Impact under different conditions:
  - Policies (examples)
    - Carbon price (with and without international offsets)
    - Clean electricity standard
  - Markets (examples)
    - High oil and gas prices
    - High oil and low gas prices
Areas for input and future work

Areas for input
- Functional form of distributions (this affects elicitation)
- Estimating dependence across technologies and over time
- Estimating functional form of inter- and extrapolations
- Defining “expert type” scenarios (including combining all experts for one technology into one distribution)
- Defining other scenarios (e.g., budgets, input prices)
- Defining characteristics of metrics of interest we care about (for budget and not budget uses)

Possibilities for future work
- Creating continuous cost distributions as a function of RD&D
  - Interpolating between ½ budget, recommended budget, and 10X budgets to endogenize RD&D
- Dynamic evolution of investments over time
  - How would incorporating learning allow you to update your decision rules of investment? And how would this affect “benefits” we care about and decisions today?
- Integrating the global dimension
  - Innovation in other countries and technology transfer
Thank you for your attention

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