Finding common ground when experts disagree:

Robust Portfolio Decision Analysis

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COST IS1304 Conference
5 July 2017

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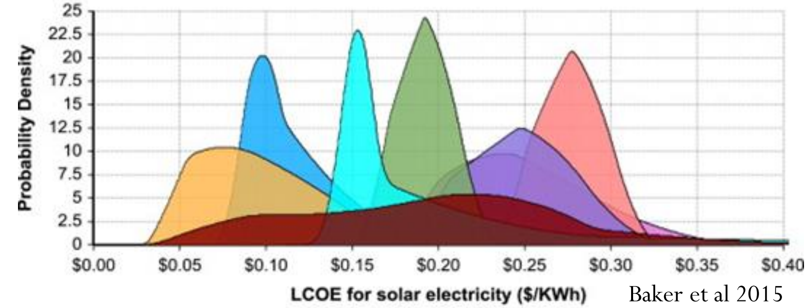
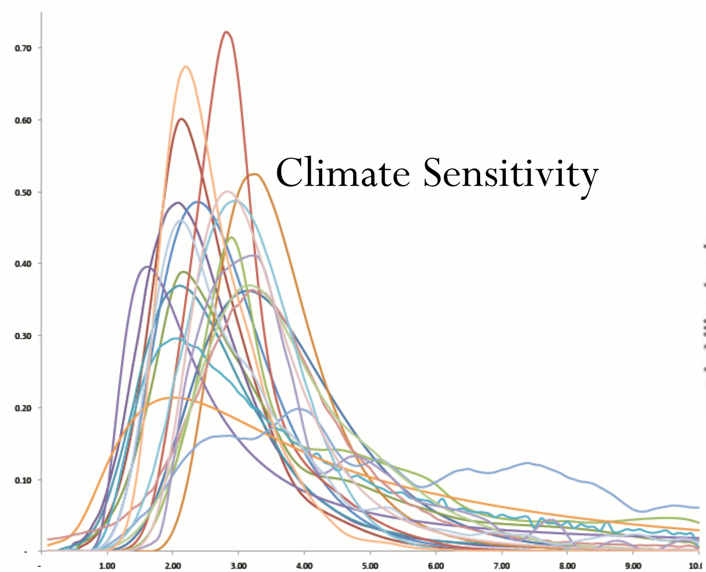
School of Science

Deep Uncertainty

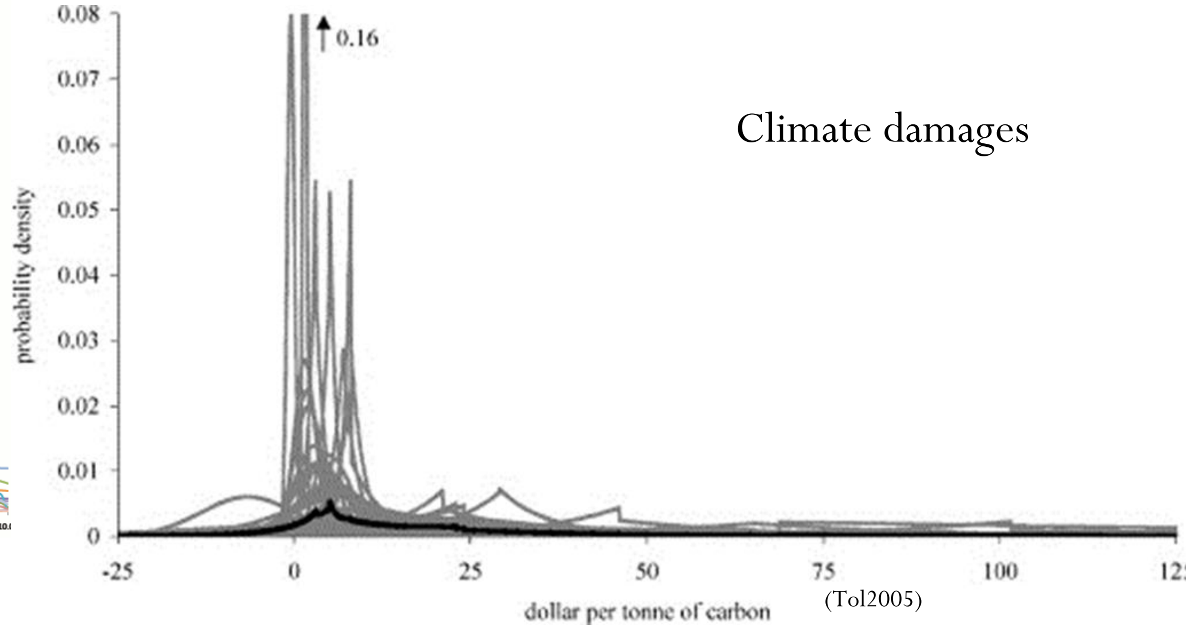
- Conflicting experts or models



Technical change

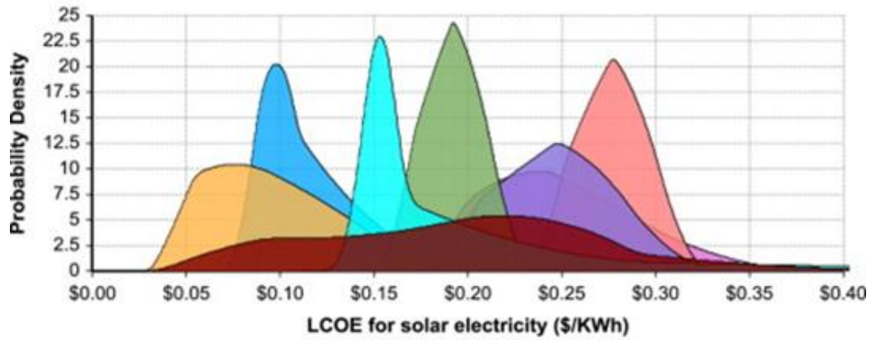


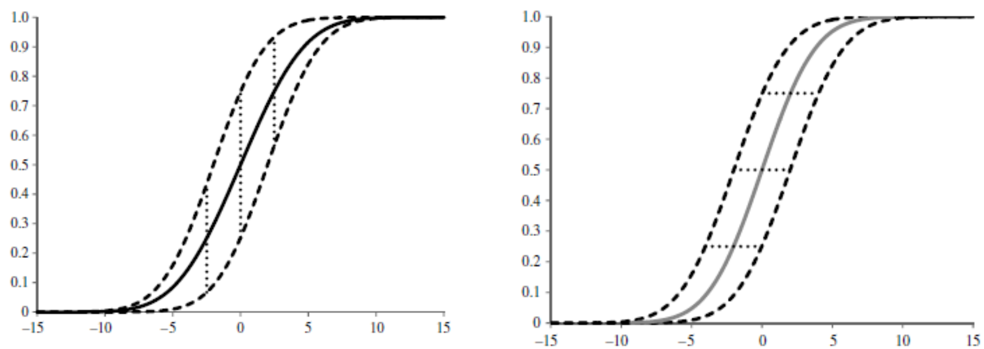
(Meinshausen et al. 2009)



Deep Uncertainty - Approaches

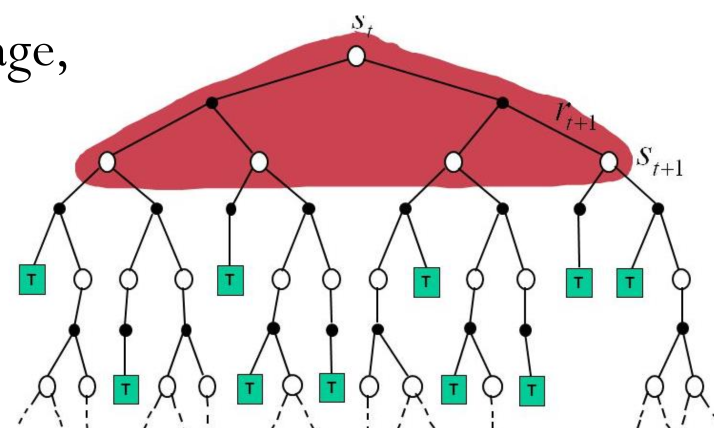
- Aggregate beliefs:
  Clemen & Winkler; Cooke; Lichtendahl et al





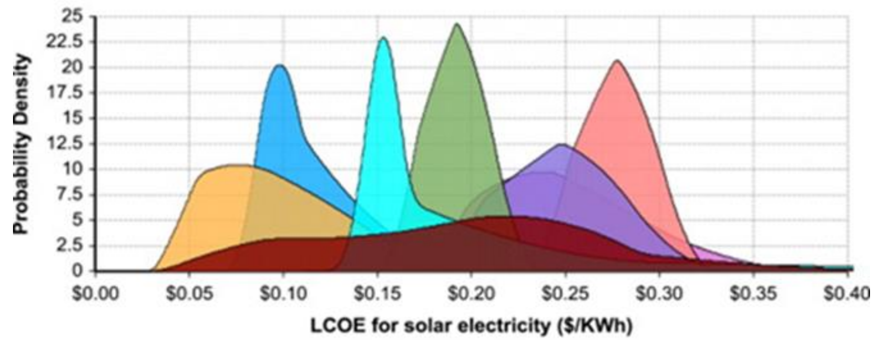
Lichtendalh et al 2013

- Expected Utility, von Neuman-Morgenstern, Savage,
- Dynamic Decision making under uncertainty and learning, : (Kolstad, Baker, Lemoine, Pyndyck)
- Criticism:
  - "lacking externally consistency"
  - Mathematically resolve disagreement resulting in a single best recommendation



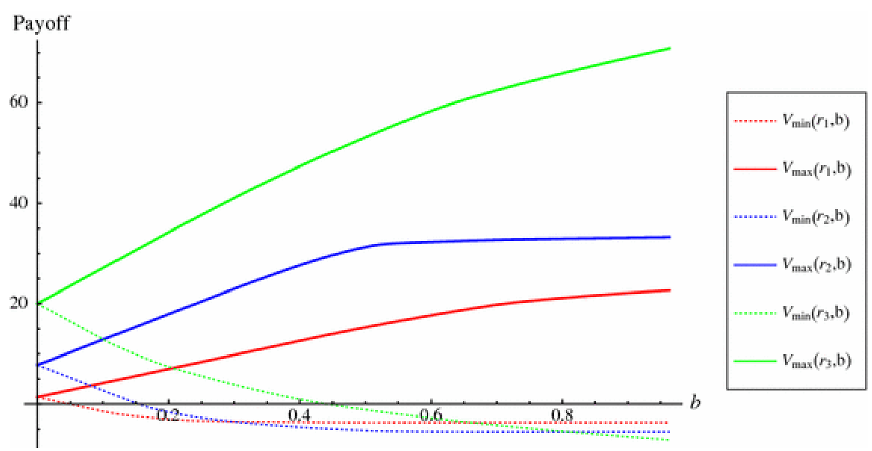
Deep Uncertainty - Approaches

Retain individual beliefs



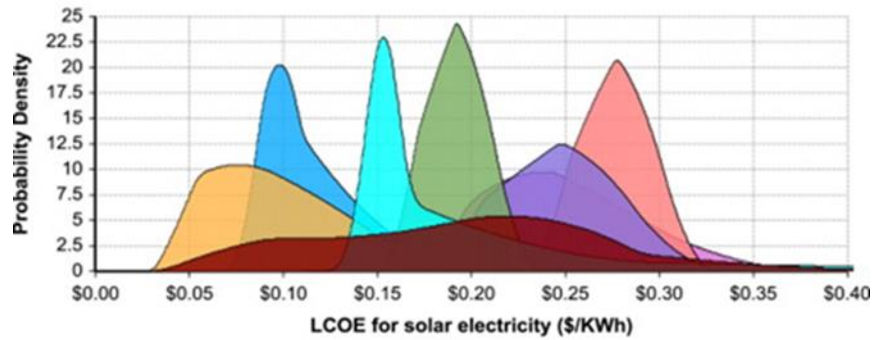
Synthesize in the context of a decision

- Ambiguity Aversion, robust optimization
  - Lacking internal consistency
  - Mathematically resolve disagreement resulting in a single best recommendation



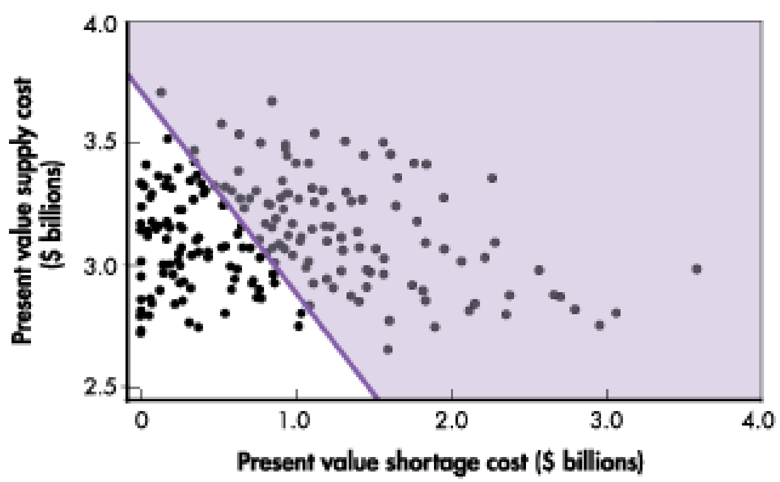
Deep Uncertainty - Approaches

Retain individual beliefs



Synthesize in the context of a decision

- Robust Decision Making
  - Evaluates a small number of alternatives
  - Iterates to develop alternatives



Our approach: Robust Portfolio Decision Analysis

- Considers *portfolios of alternatives* (technologies, policies)

possible portfolios

  - {high R&D into nuclear; solar subsides; 450ppm; cap&trade}
  - {low R&D into nuclear; solar subsidies; carbon tax}
- Results in a *set of "good" portfolios*
  - {*portfolio1, portfolio 7, portfolio 10*, ...}
- Provides insights about *good individual projects*
  - core projects = {solar subsidies, ...}

All sets on this slide are purely illustrative; these are not results.

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May help to open up the dialogue on climate change. "Emphasize solutions and benefits".

Center for Research on Environmental Decisions and ecoAmerica. (2014). Connecting on Climate: A Guide to Effective Climate Change Communication. New York and Washington, D.C.

RPDA: theoretical framework

- Belief dominance: From a descriptive concept to a normative approach
- From non-dominated portfolios to robust individual alternatives

A descriptive concept

- Bewley (2002): “Knightian Decision Making”
- Gilboa et al (2010): “Objectively Rational”
- Stoye (2012): “Admissability”

Axioms of SEU *minus* completeness

“…rationalize many economic phenomena which otherwise seem difficult to explain…”

- Danan et al (2016):“Unambiguous Preferences”, applied to “Social Robust Decisions”

Belief Dominance: Terminology

- "Alternatives" x_i
- Uncertain outcomes z
- "Preferences" U(x,z)

Beliefs

	$\mathbf{x_1}$	$\mathbf{x_2}$	**…**	$\mathbf{x_n}$
f_1	$f_1(z,x_1)$	$f_1(z,x_2)$	…	$f_1(z,x_n)$
…	…	…	…	…
f_m	$f_n(z,x_1)$	$f_2(z,x_2)$	…	$f_2(z,x_n)$

Beliefs are exogenous if $f_1(z,x_i) = f_1(z,x_j)$ for all i,j

Belief Dominance

An alternative* $\mathbf{x}$ dominates an alternative $\mathbf{x}'$ over a set Φ of beliefs (probability distributions) if:

$$\int U(\mathbf{x};z)f(z;\mathbf{x})dz \geq \int U(\mathbf{x}';z)f(z;\mathbf{x}')dz \ \ \forall f \in \Phi$$

$\mathbf{x}$ is a vector of decision variables

z is a random variable with probability distribution f

U is an objective function

*An "alternative" may be a portfolio.

Belief Dominance (example)

An alternative* **x** dominates an alternative **x**’ over a set Φ of probability distributions if:

$$\int U(\mathbf{x}; z) f(z; \mathbf{x}) dz \geq \int U(\mathbf{x}'; z) f(z; \mathbf{x}') dz \quad \forall f \in \Phi$$

x is a vector of decision variables (investments into technology R&D, solar, nuclear,…)

Z is a random variable with probability distribution f (outcomes of technical change, such as cost; distribution depends on investment)

U is an objective function (The total cost of abatement, derived from an IAM)

*An “alternative” may be a portfolio.

Dominance Concepts

- *Belief*: fix U; alternative x dominates alternative x’

$$\int U(\mathbf{x};z)f(z;\mathbf{x})dz \geq \int U(\mathbf{x}';z)f(z;\mathbf{x}') \ \forall f \in \Phi$$

- *Stochastic*: fix x; distribution f dominates distribution g

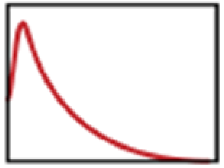
$$\int U(\mathbf{x};z)f(z)dz \geq \int U(\mathbf{x};z)g(z) \ \forall \mathrm{U} \in \mathrm{V}_S$$

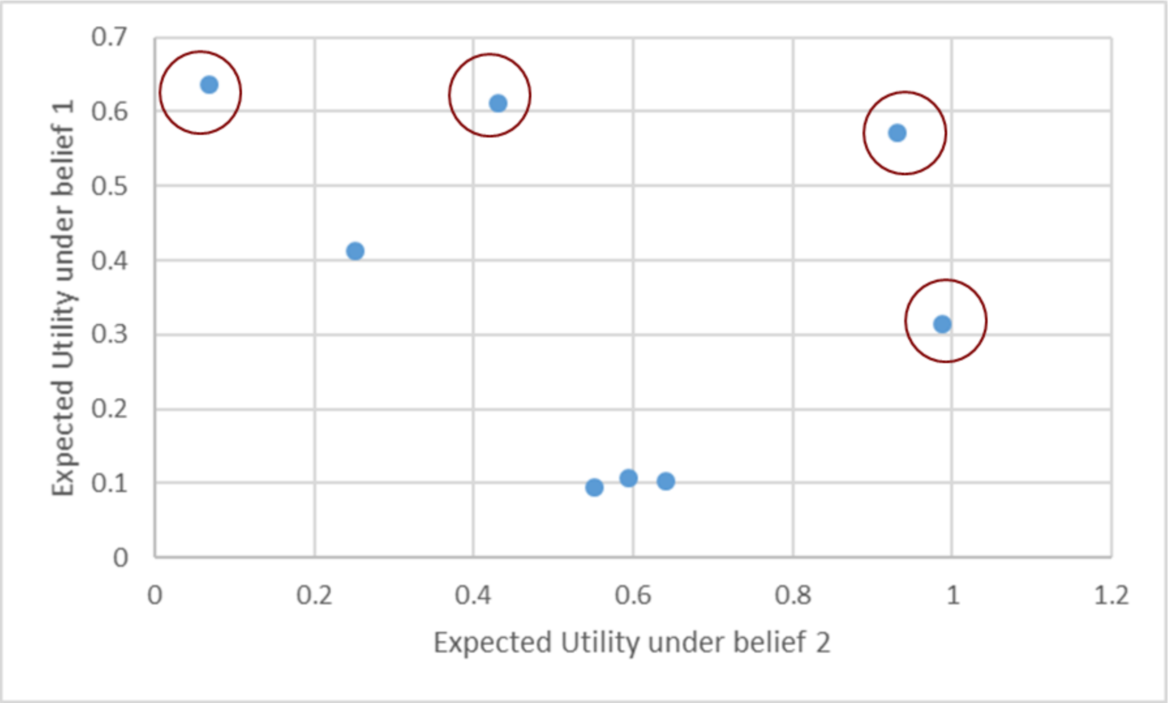
- *Pareto*: fix f; alternative x dominates alternative x’

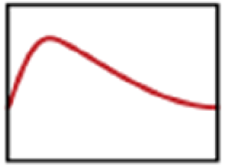
$$\int U(\mathbf{x};z)f(z)dz \geq \int U(\mathbf{x};z)f(z) \ \forall \mathrm{U} \in \mathrm{V}_P$$

Belief Dominance

An alternative is *non-dominated* if there is no other alternative that dominates it.

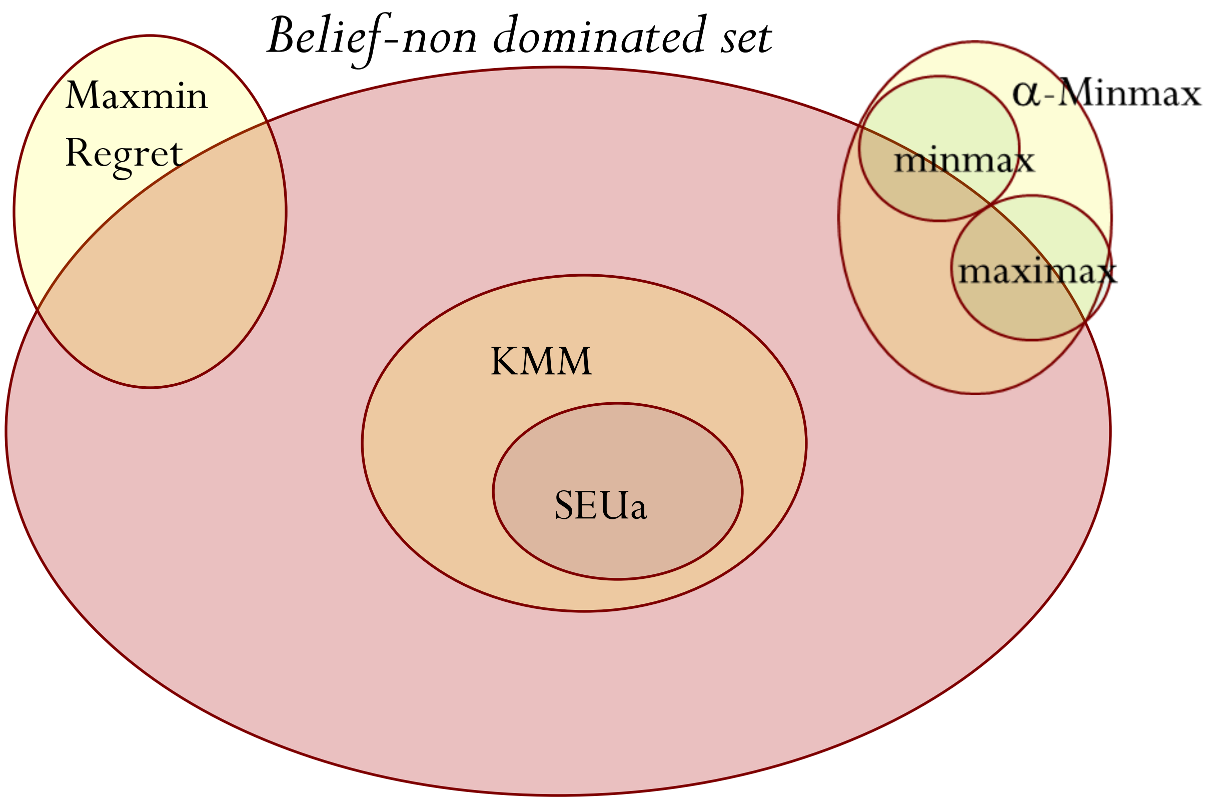






Belief non-dominance encompasses robustness concepts

Theorem: At least one optimal solution to robustness concept C is in the belief-non-dominated set.



From portfolios to individual alternatives

- Each portfolio is made up of individual projects i=1..I
- Define x_i=1 if project i is funded and 0 otherwise
- Define a portfolio $\vec{x} \equiv (x_1, \ldots, x_N)$
- Let ND = {non-dominated portfolios}

$$core \equiv \{ i \mid x_i = 1 \ \forall \vec{x} \in ND \}$$

$$ext \equiv \{ i \mid x_i = 0 \ \forall \vec{x} \in ND \}$$

$$bord \equiv \{ i \mid i \notin core \text{ and i} \notin ext \}$$

non-dominated portfolios

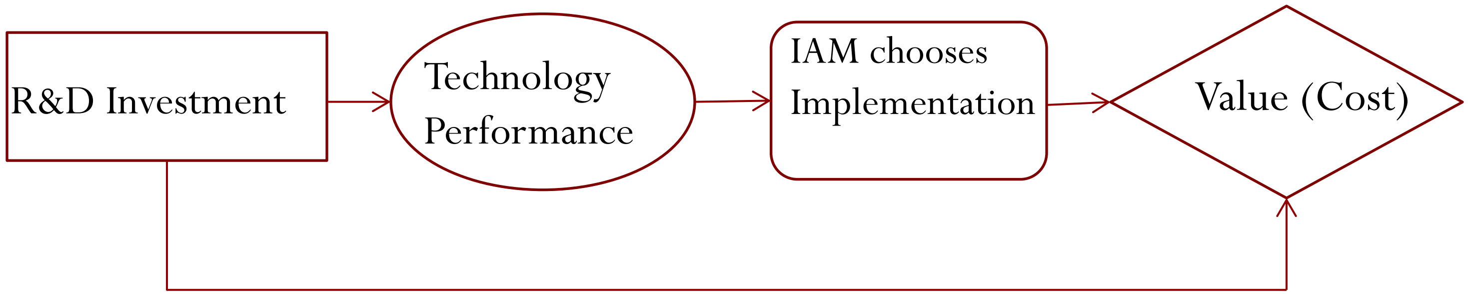
a	b	c	d	e	f
1	0	0	1	1	0
1	0	1	1	1	0
1	0	0	1	1	0
0	0	1	1	0	1
0	0	0	1	0	1
0	0	1	1	0	1

project **b** is in exterior; project **d** is in core

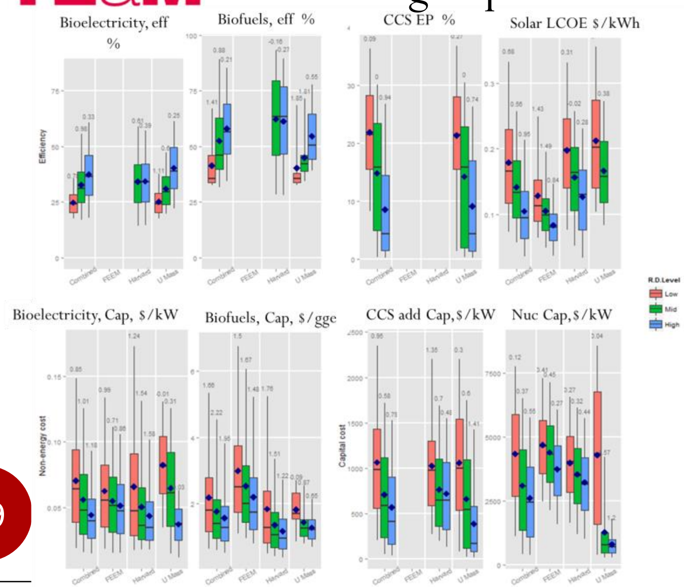
Proof of concept: Public energy technology R&D portfolios

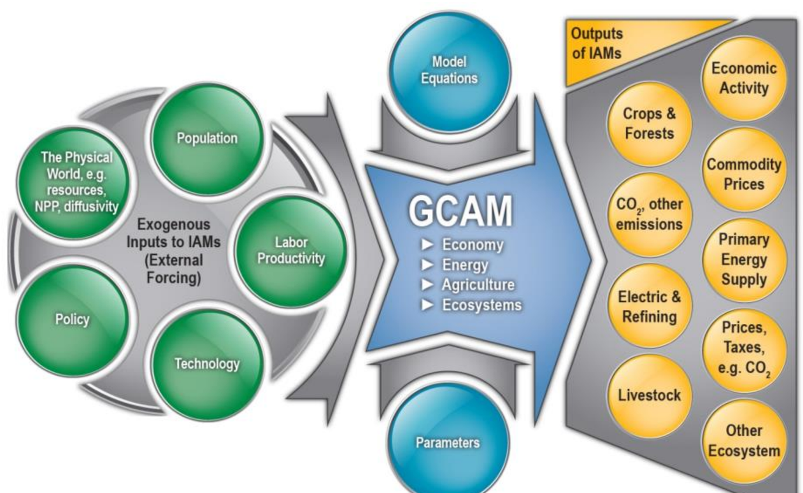
Proof of concept: Energy Technology R&D Portfolio in Response to Climate Change.

Given a Representative Concentration Pathway (RCP) of **2.6 w/m^2 (~450ppm):**



3 sets of elicitations on 5 technologies plus combined





The computational model

$$H(\mathbf{x},\tau) \equiv \sum_{l=1}^{1000} p_\tau(\mathbf{z}_l;\mathbf{x})\, TAC(\mathbf{z}_l, s) + \kappa B(\mathbf{x})$$

For s = 2.6 (~450ppm)

$$\text{s.t.} \sum_j x_{ij} = 1 \quad \forall i$$

- x belief dominates x’ if $H(\mathbf{x},\tau) \le H(\mathbf{x}',\tau) \quad \forall \tau$

$x_{ij} = 1$ if technology i is invested in at the jth funding level; 0 otherwise

i = solar, nuclear, CCS, bio-elec, bio-fuel

j = low, mid, high

TAC(z,s) = total abatement cost for stabilization s, tech outcome z

B(x) = total R&D investment for portfolio x

κ = opportunity cost of investment

p_τ is the discrete probability of outcome z_l given investment x. We use importance sampling to estimate p_τ .

Results: non-dominated portfolios

Portfolios	Technologies					Objectives ENPV(Cost in billions of $2005)			
	Solar	Nuc	BF	BE	CCS	Combined	Harvard	FEEM	UMass
1	Low	High	High	High	Mid	20736	21770	24327	15509
2	Low	Mid	High	High	Mid	20768	21654	24188	15720
3	Low	High	Mid	High	Mid	20838	21929	24525	15301
4	Mid	High	High	High	Mid	20889	21588	24345	15813
5	Low	Mid	Mid	High	Mid	20912	21806	24434	15213
6	Mid	Mid	High	High	Mid	20922	21513	24163	16162
7	Mid	High	Mid	High	Mid	21084	21741	24548	15509
8	Low	High	Low	High	Mid	21135	21417	24307	20029
9	High	Mid	Low	High	High	21136	21325	22747	20003
10	Mid	Mid	Mid	High	Mid	21144	21659	24379	15528
11	High	High	Low	High	High	21320	21581	22901	19324
12	Low	High	Mid	High	Low	21334	22744	25468	15153
13	Low	Mid	Mid	High	Low	21491	22671	25442	15142

13 out of 243 total are non-dominated

Results: non-dominated portfolios

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	Solar	Nuc	BF	BE	CCS	Combined	Harvard	FEEM	UMass
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10	Mid	Mid	Mid	High	Mid	21144	21659	24379	15528
11	High	High	Low	High	High	21320	21581	22901	19324
12	Low	High	Mid	High	Low	21334	22744	25468	15153
13	Low	Mid	Mid	High	Low	21491	22671	25442	15142

Optimal under combined distribution

Results: non-dominated portfolios

Portfolios	Technologies					Objectives ENPV(Cost in billions of $2005)			
	Solar	Nuc	BF	BE	CCS	Combined	Harvard	FEEM	UMass
1	Low	High	High	High	Mid	20736	21770	24327	15509
2	Low	Mid	High	High	Mid	20768	21654	24188	15720
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4	Mid	High	High	High	Mid	20889	21588	24345	15813
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12	Low	High	Mid	High	Low	21334	22744	25468	15153
13	Low	Mid	Mid	High	Low	21491	22671	25442	15142

Optimal under Minmax Regret

Results: non-dominated portfolios

Portfolios	Technologies					Objectives ENPV(Cost in billions of $2005)			
	Solar	Nuc	BF	BE	CCS	Combined	Harvard	FEEM	UMass
1	Low	High	High	High	Mid	20736	21770	24327	15509
2	Low	Mid	High	High	Mid	20768	21654	24188	15720
3	Low	High	Mid	High	Mid	20838	21929	24525	15301
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12	Low	High	Mid	High	Low	21334	22744	25468	15153
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Optimal under Harvard, FEEM, Maxmin

Results: non-dominated portfolios

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	Solar	Nuc	BF	BE	CCS	Combined	Harvard	FEEM	UMass
1	Low	High	High	High	Mid	20736	21770	24327	15509
2	Low	Mid	High	High	Mid	20768	21654	24188	15720
3	Low	High	Mid	High	Mid	20838	21929	24525	15301
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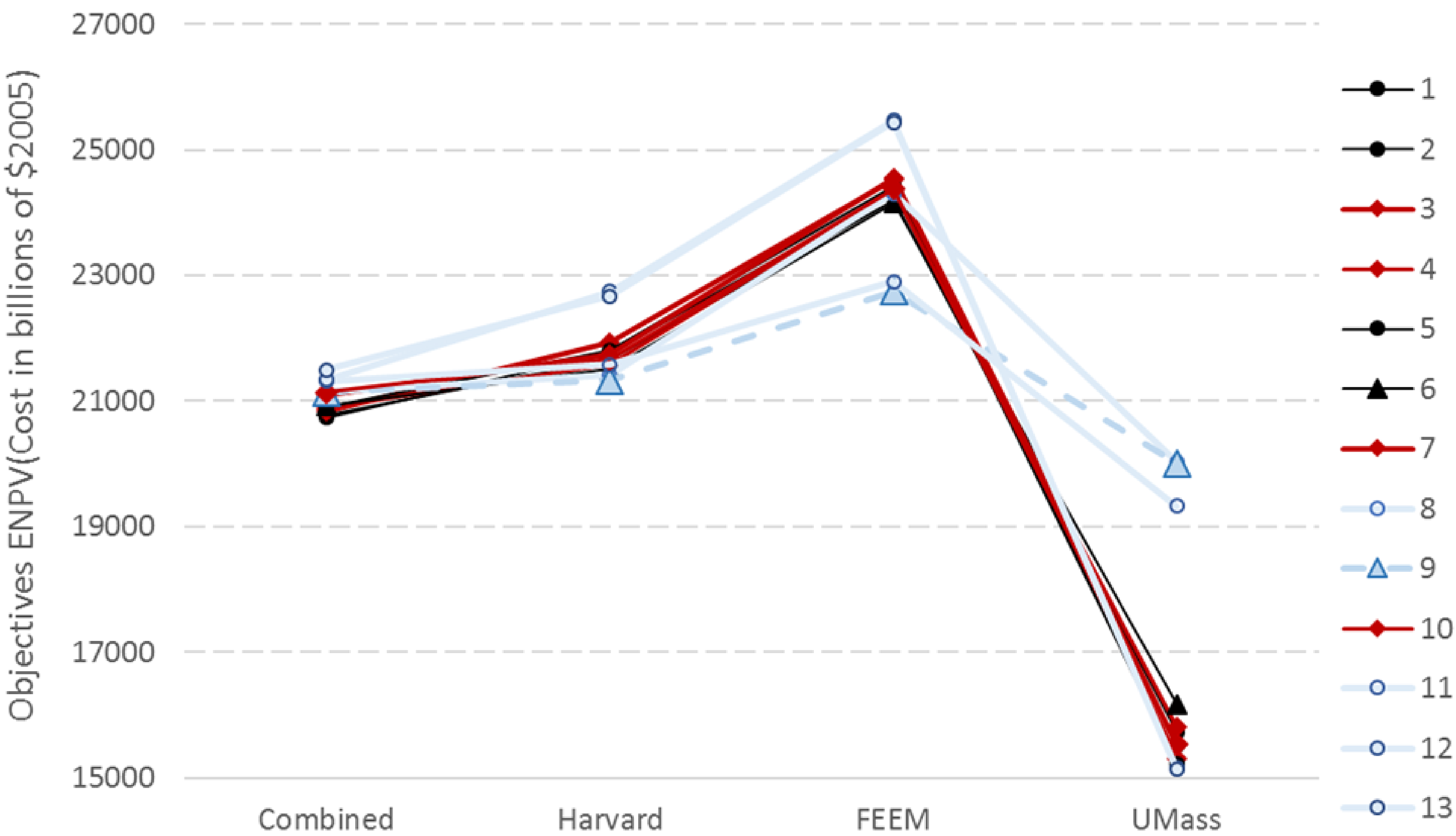
10	Mid	Mid	Mid	High	Mid	21144	21659	24379	15528
11	High	High	Low	High	High	21320	21581	22901	19324
12	Low	High	Mid	High	Low	21334	22744	25468	15153
13	Low	Mid	Mid	High	Low	21491	22671	25442	15142

Optimal under UMass and Maximax

Portfolios	Robustness Concepts		
	SEUa	α-maxmin	KMM
1	Combined distribution		
2	Equal weight	$\alpha = 0.7$	Higher Ambiguity Tolerance
3			
4			
5	Equal weight: Harvard, FEEM, UMass	$\alpha = 0.1$-0.6	
6		Minmax Regret	
7			
8			
9	FEEM, Harvard	$\alpha = 0.9,\ 1$ (Maxmin)	Lower Ambiguity Tolerance
10			
11		$\alpha = 0.8$	
12			
13	UMass	$\alpha = 0$ (Maximax)	

Portfolios	Robustness Concepts		
	SEUa	α-maxmin	KMM
1	Combined distribution		
2	Equal weight	$\alpha = 0.7$	Higher Ambiguity Tolerance
3			
4			
5	Equal weight: Harvard, FEEM, UMass	$\alpha = 0.1$-0.6	
6		Minmax Regret	
7			
8			
9	FEEM, Harvard	$\alpha = 0.9,\ 1$ (Maxmin)	Lower Ambiguity Tolerance
10			
11		$\alpha = 0.8$	
12			
13	UMass	$\alpha = 0$ (Maximax)	

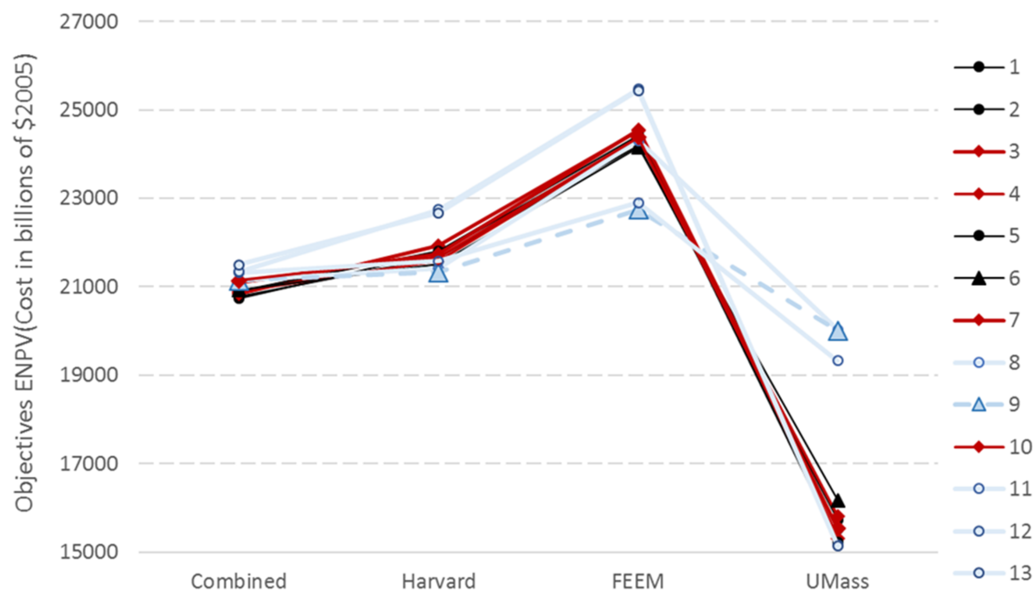
The non-dominated portfolios



NPV of the cost of each portfolio. Red portfolios not solution to other concepts Portfolio 6 is MinMax Regret; 9 is MinMax

A subset of more robust portfolios

Portfolio	Technologies					R&D(millions $2005/yr)	Objectives ENPV(Cost in billions of $2005)			
	Solar	Nuc	BF	BE	CCS		Combined	Harvard	FEEM	UMass
1	1%	76%	9%	7%	7%	234	20736	21770	24327	15509
2	2%	26%	27%	22%	23%	75	20768	21654	24188	15720
3	1%	82%	2%	8%	8%	218	20838	21929	24525	15301
4	2%	75%	9%	7%	7%	237	20889	21588	24345	15813
5	3%	33%	6%	29%	29%	59	20912	21806	24434	15213
6	5%	25%	26%	22%	22%	78	20922	21513	24163	16162
7	2%	81%	2%	8%	8%	220	21084	21741	24548	15509
10	7%	32%	6%	28%	28%	61	21144	21659	24379	15528



Results: core and exterior projects

Portfolios	Technologies					Objectives ENPV(Cost in billions of $2005)			
	Solar	Nuc	BF	BE	CCS	Combined	Harvard	FEEM	UMass
1	Low	High	High	High	Mid	20736	21770	24327	15509
2	Low	Mid	High	High	Mid	20768	21654	24188	15720
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12	Low	High	Mid	High	Low	21334	22744	25468	15153
13	Low	Mid	Mid	High	Low	21491	22671	25442	15142

BE high is in core; Nuc low is in exterior

Results: core and exterior projects among “robust” group

Portfolio	Technologies					R&D(millions $2005/yr)	Objectives ENPV(Cost in billions of $2005)			
	Solar	Nuc	BF	BE	CCS		Combined	Harvard	FEEM	UMass
1	1%	76%	9%	7%	7%	234	20736	21770	24327	15509
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6	5%	25%	26%	22%	22%	78	20922	21513	24163	16162
7	2%	81%	2%	8%	8%	220	21084	21741	24548	15509
10	7%	32%	6%	28%	28%	61	21144	21659	24379	15528

Solar high excluded

Nuc low excluded

Biofuels low excluded

Bio-electricity high and CCS mid in the core

Future work – When Models Disagree

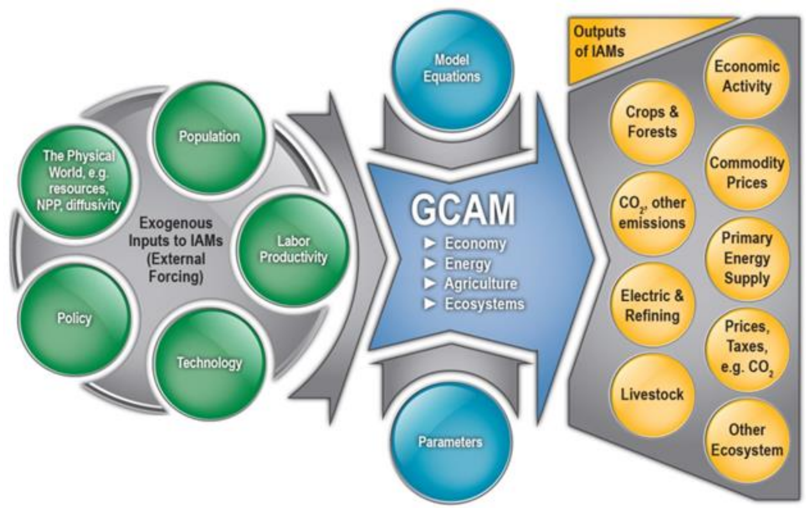
- Model uncertainty and parametric uncertainty

$$\mathrm{H}(\mathbf{x};\tau,m)=\sum_{i=1}^{1000} p_{\tau\mathbf{x}}(\mathbf{z}_i)\left[TAC_m(\mathbf{z}_i;s)\right]+\kappa \mathrm{B}_{\mathbf{x}}$$

  - τ is beliefs over parametric uncertainty; *m* represents individual models
  - portfolio x belief dominates x’ if: $\mathrm{H}(\mathbf{x};\tau,m)\le \mathrm{H}(\mathbf{x}';\tau,m)\ \forall \tau,m$

A World Induced Technical Change Hybrid Model

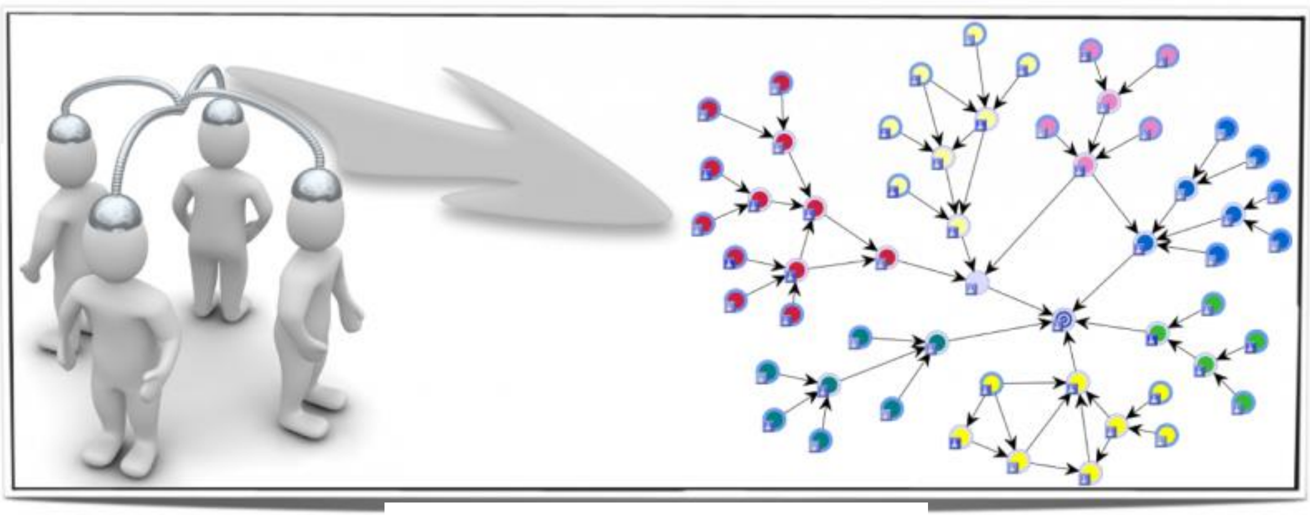
IIASA
MESSAGE



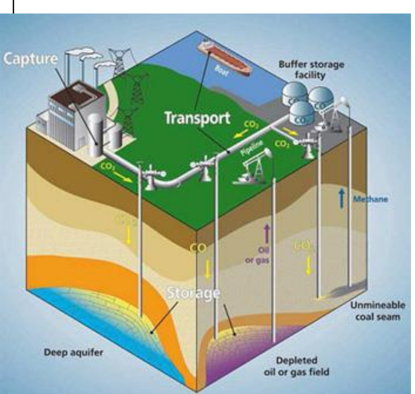
Conclusions

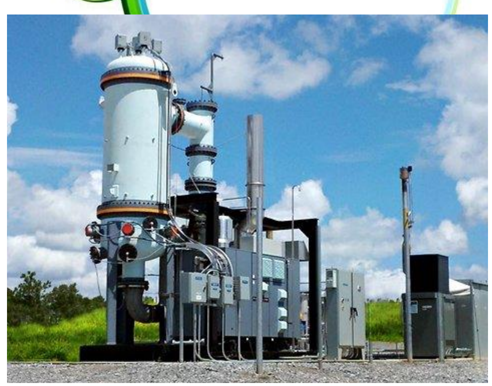
- Belief Dominance operationalizes a descriptive concept, allowing analysts to derive a set of good alternatives under conflicting beliefs.
  - Synthesizes beliefs in a decision context
  - Avoids worst-case analysis
- RPDA leads to implications about individual alternatives
  - Example: A high investment into bio-electricity was robust across all beliefs
- By focusing on a set of good alternatives, RPDA uses the best available knowledge to support decision making in a way that preserves flexibility for decision makers.

Expert Elicitation on energy technologies

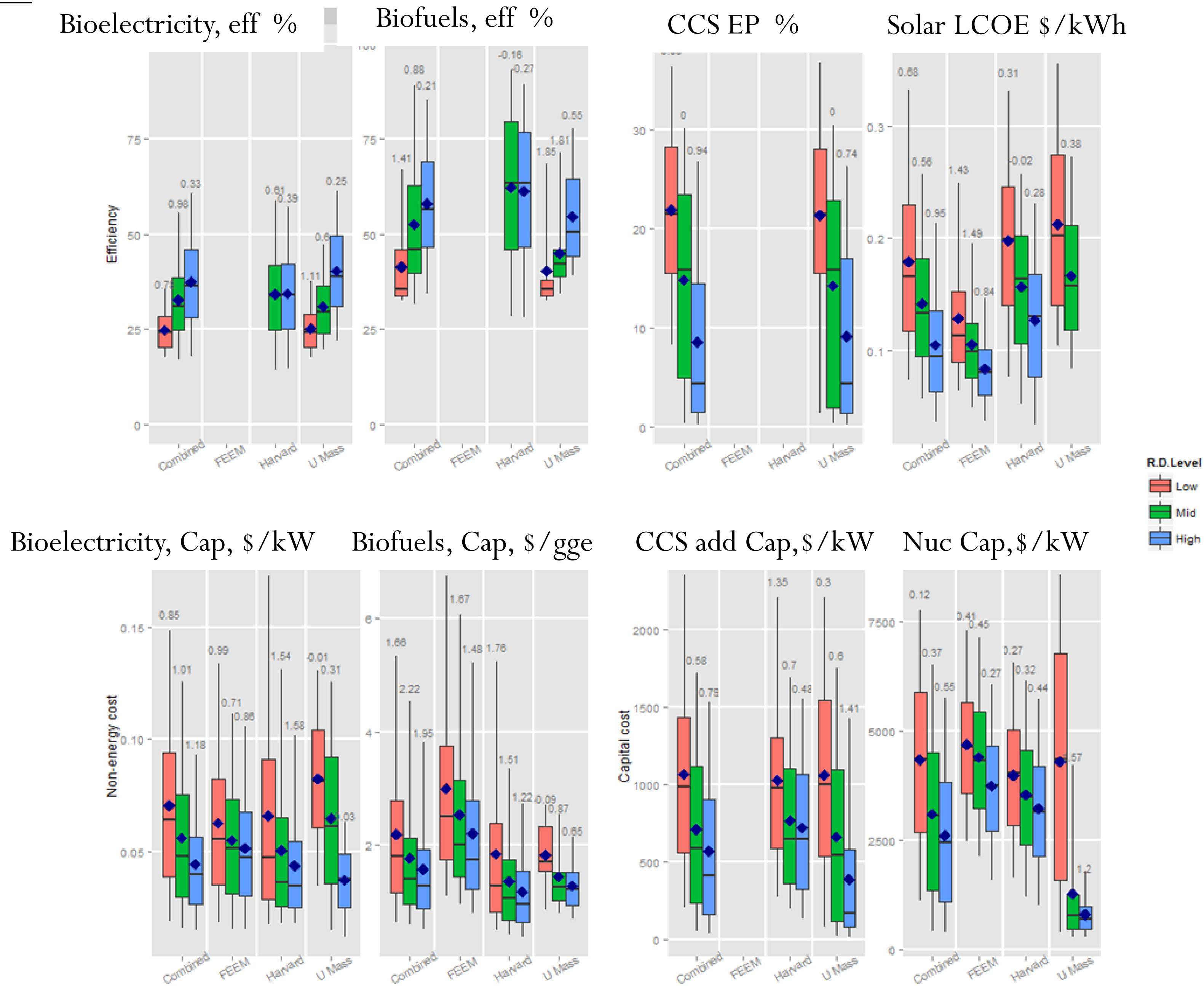


A structured process for eliciting subjective probability distributions from experts about items of interest to decision makers.





TEaM Results



Solar LCOE			Nuclear capital cost			Biofuels combined			Bio-electricity combined			CCS combined		
Low	Mid	High	Low	Mid	High	Low	Mid	High	Low	Mid	High	Low	Mid	High
6.7	16	132	25	77	713	5.7	15	81	5.8	12	68	21	68	673