Finding common ground when experts and models disagree:

Belief dominance and Climate Change R&D Policy

Erin Baker, University of Massachusetts

Valentina Bosetti, Bocconi University and FEEM

Ahti Salo, Aalto University

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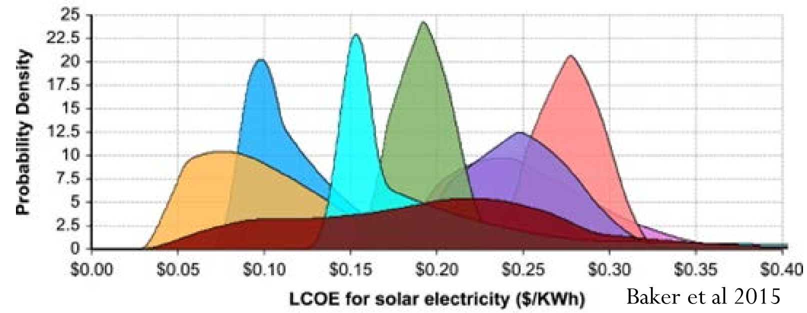
Deep Uncertainty

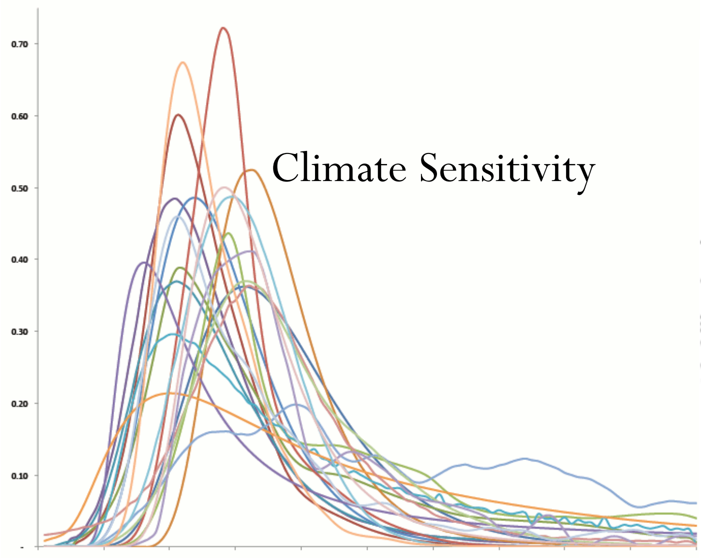
- Conflicting experts or models



Baker et al 2015

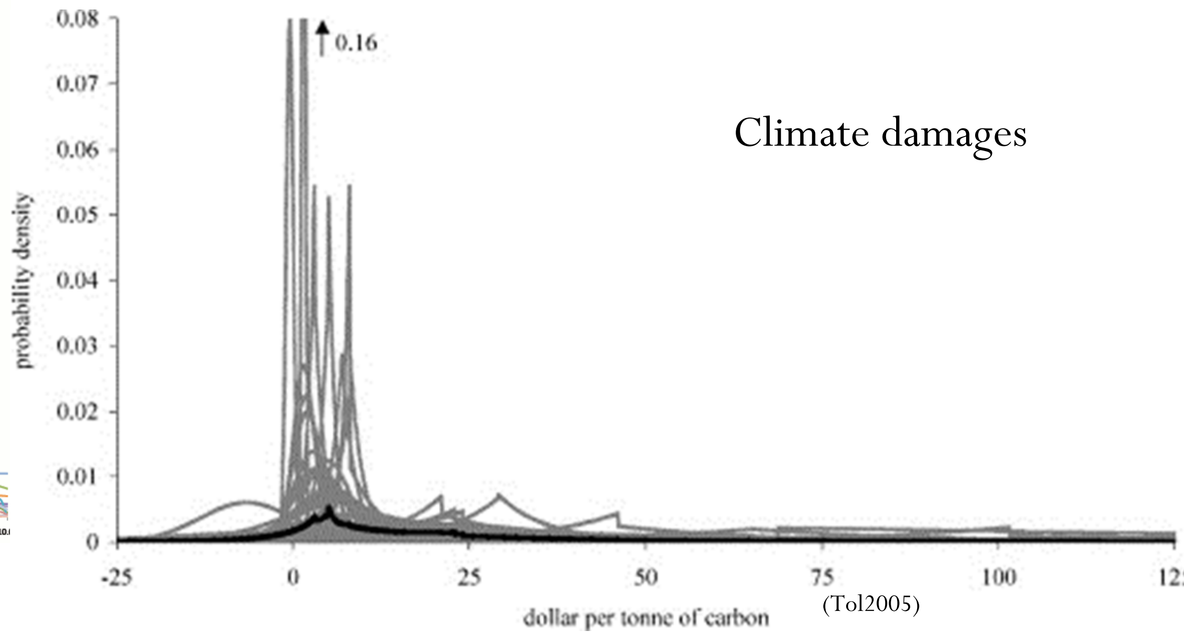
Technical change

Climate Sensitivity



(Meinshausen et al. 2009)

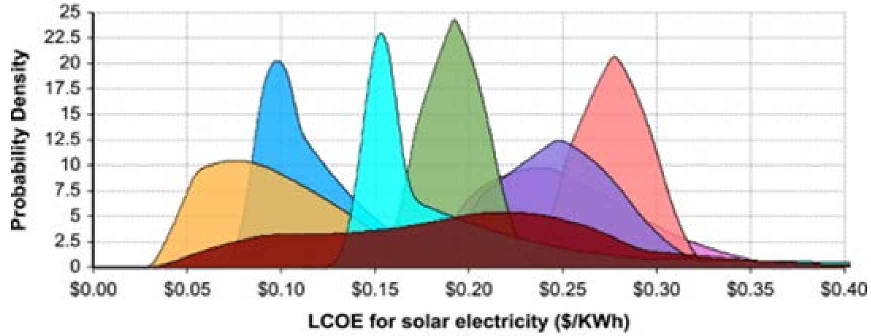
Climate damages

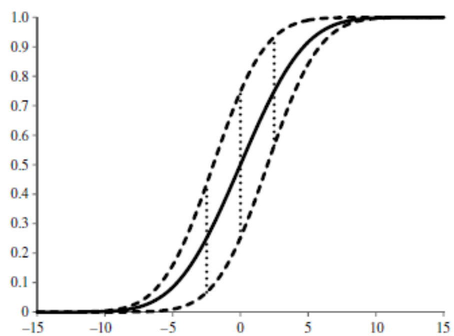


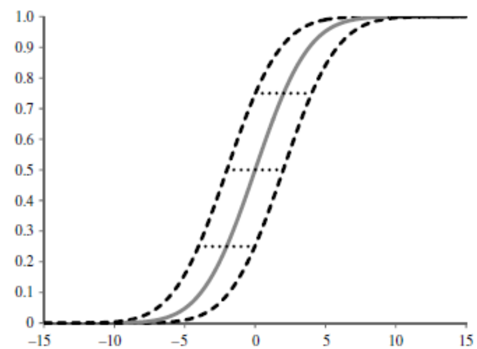
(Tol2005)

Deep Uncertainty - Approaches

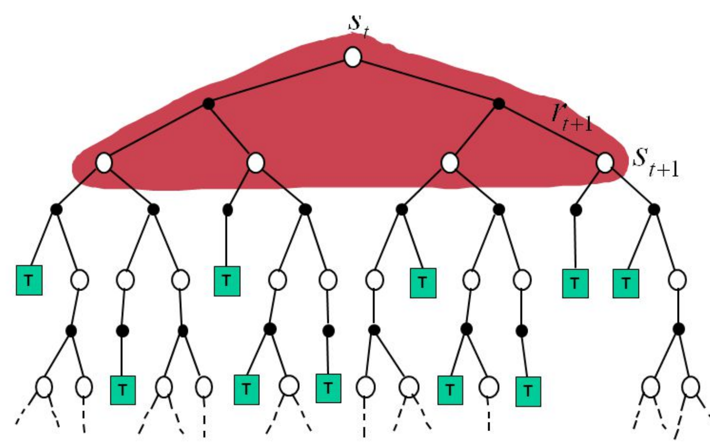
- Aggregate beliefs:
  Clemen & Winkler; Cooke; Lichtendahl et al





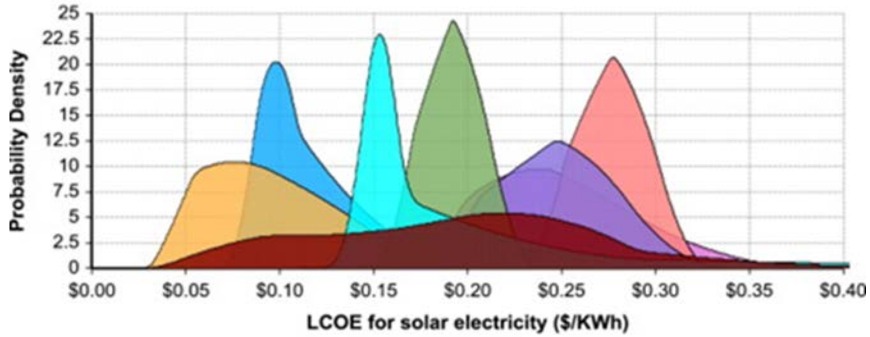


- Dynamic Decision making under uncertainty and learning: (Kolstad, Baker, Lemoine, Pyndyck)
- Criticism:
  - "lacking externally consistency"
  - Mathematically resolve disagreement resulting in a single best recommendation



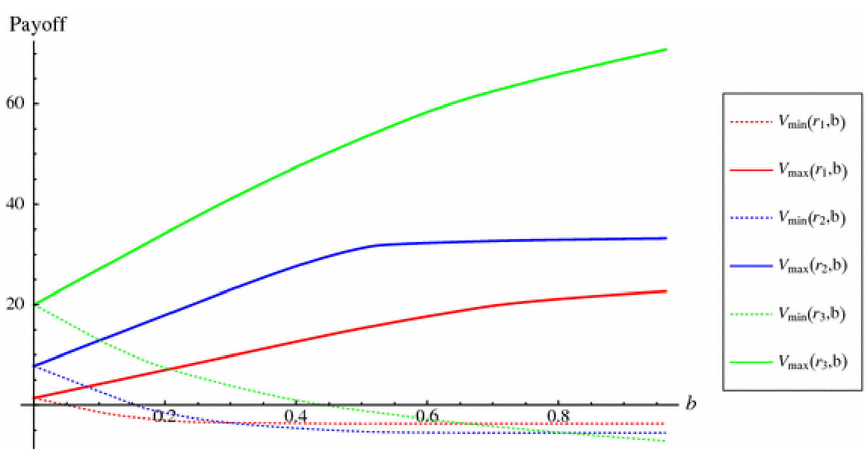
Deep Uncertainty - Approaches

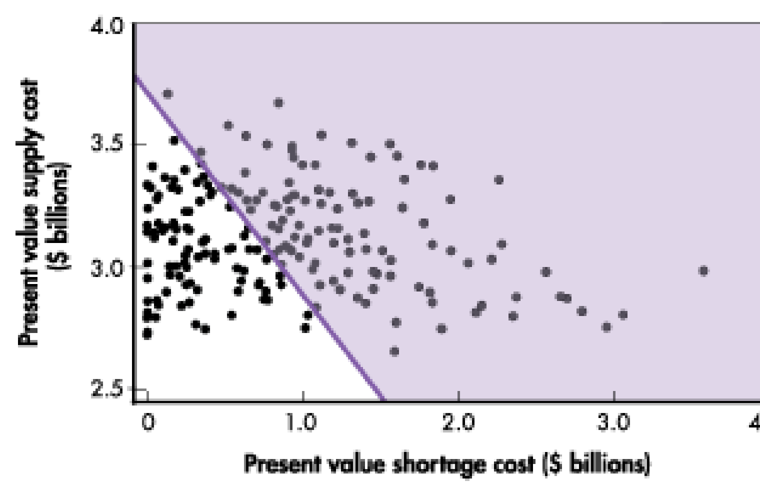
Retain individual beliefs



Synthesize in the context of a decision

- Ambiguity Aversion, robust optimization
  - Lacking internal consistency
  - Mathematically resolve disagreement resulting in a single best recommendation
- 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" alternatives*
  - $\{portfolio1, portfolio\ 7, portfolio\ 10, \ldots\}$
- 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".

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

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 non-dominated portfolios to robust individual alternatives

Belief Dominance

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

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

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:

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

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*: alternative x dominates alternative x’

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

- *Stochastic*: distribution f dominates distribution g

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

- *Pareto*; alternative x dominates alternative x’

$$\int U_i(\mathbf{x};z) f(z)\,dz \geq \int U_i(\mathbf{x};z) f(z) \quad \forall \mathrm{U}_i$$

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

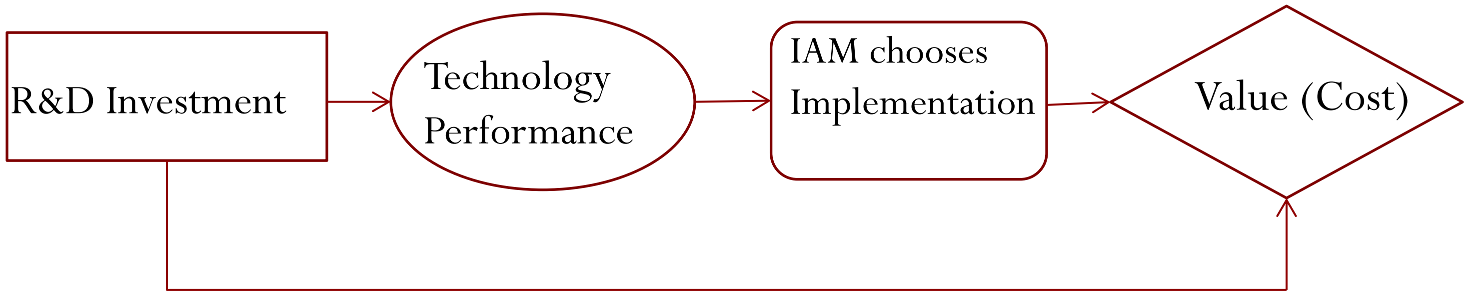
a	b	c	d	e	f
1	0	0	1	1	0
1	0	1	1	1	0
1	0	0	1	1	0
0	0	1	1	0	1
0	0	0	1	0	1
0	0	1	1	0	1

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

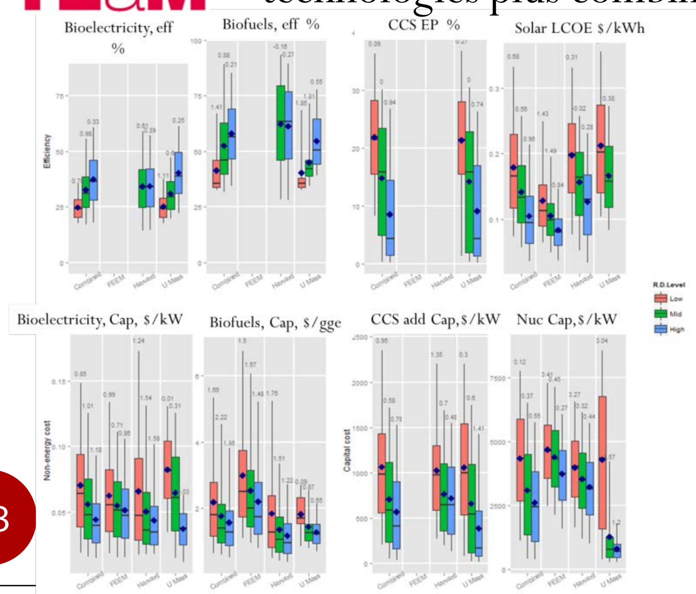
Proof of concept: Public energy technology R&D portfolios

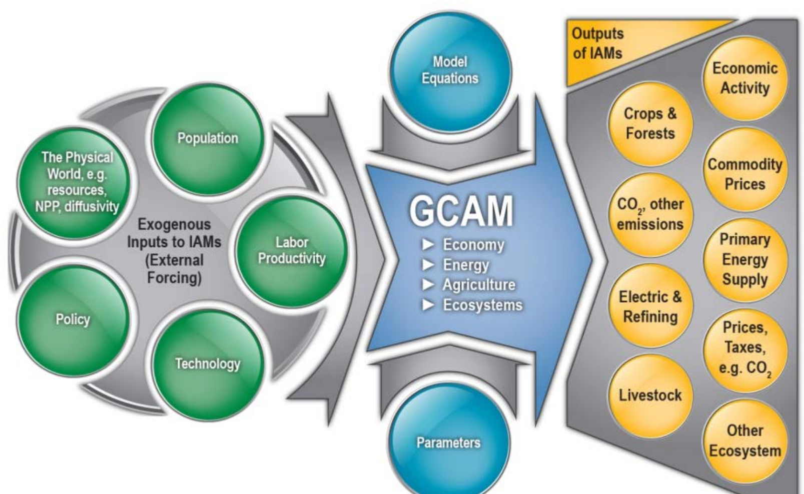
Proof of concept: Energy Technology R&D Portfolio in Response to Climate Change.

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



3 sets of elicitations on 5 technologies plus combined





The general model

$$\min_{\boldsymbol{x}} \int \left\{ TAC\left(\boldsymbol{z}, s\right) + \kappa B\left(\boldsymbol{x}\right) \right\} f_{\tau}\left(\boldsymbol{z}; \boldsymbol{x}\right) d\boldsymbol{z}$$

For s = 2.6 (~450ppm)

$$\sum_j x_{ij} = 1 \quad \forall i$$

$x_{ij} = 1$ 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

$f_{\tau}\left(z; x\right)$ = pdf of z from team τ given investment portfolio x

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 $H(\mathbf{x},\tau) \leq H(\mathbf{x}',\tau) \quad \forall \tau$

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

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

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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	U Mass
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	**High**	**Mid**	**Low**	**High**	**High**	21136	**21325**	**22747**	20003
8	Mid	Mid	Mid	High	Mid	21144	21659	24379	15528
9	High	High	Low	High	High	21320	21581	22901	19324
10	**Low**	**Mid**	**Mid**	**High**	**Low**	21491	22671	25442	**15142**

10 out of 243 total are non-dominated

Results: core and exterior projects

Portfolios	Technologies					Objectives ENPV (cost in billions of $2005)			
	Solar	Nuc	BF	BE	CCS	Combined	Harvard	FEEM	U Mass
1	Low	High	High	High	Mid	20736	21770	24327	15509
2	Low	Mid	High	High	Mid	20768	21654	24188	15720
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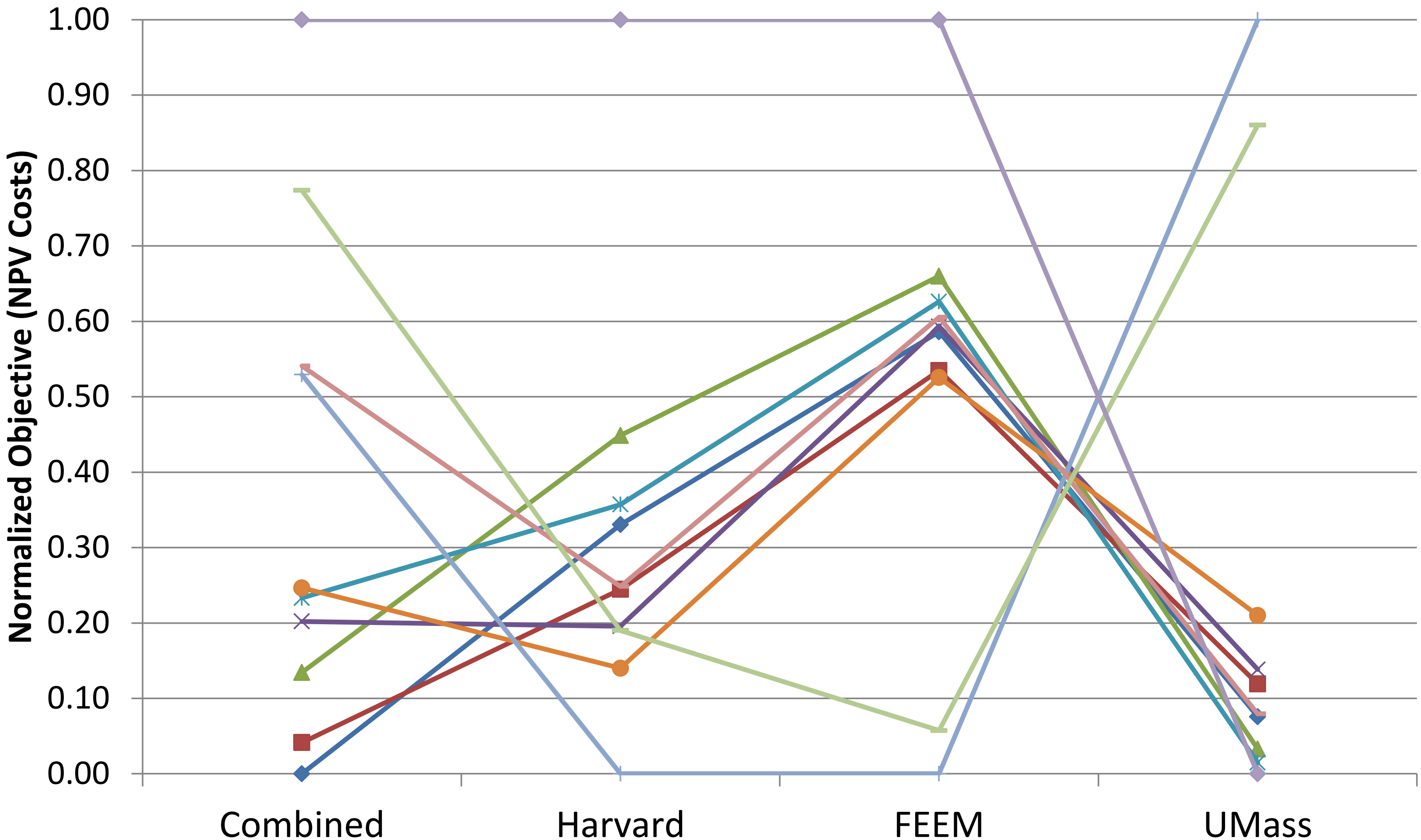
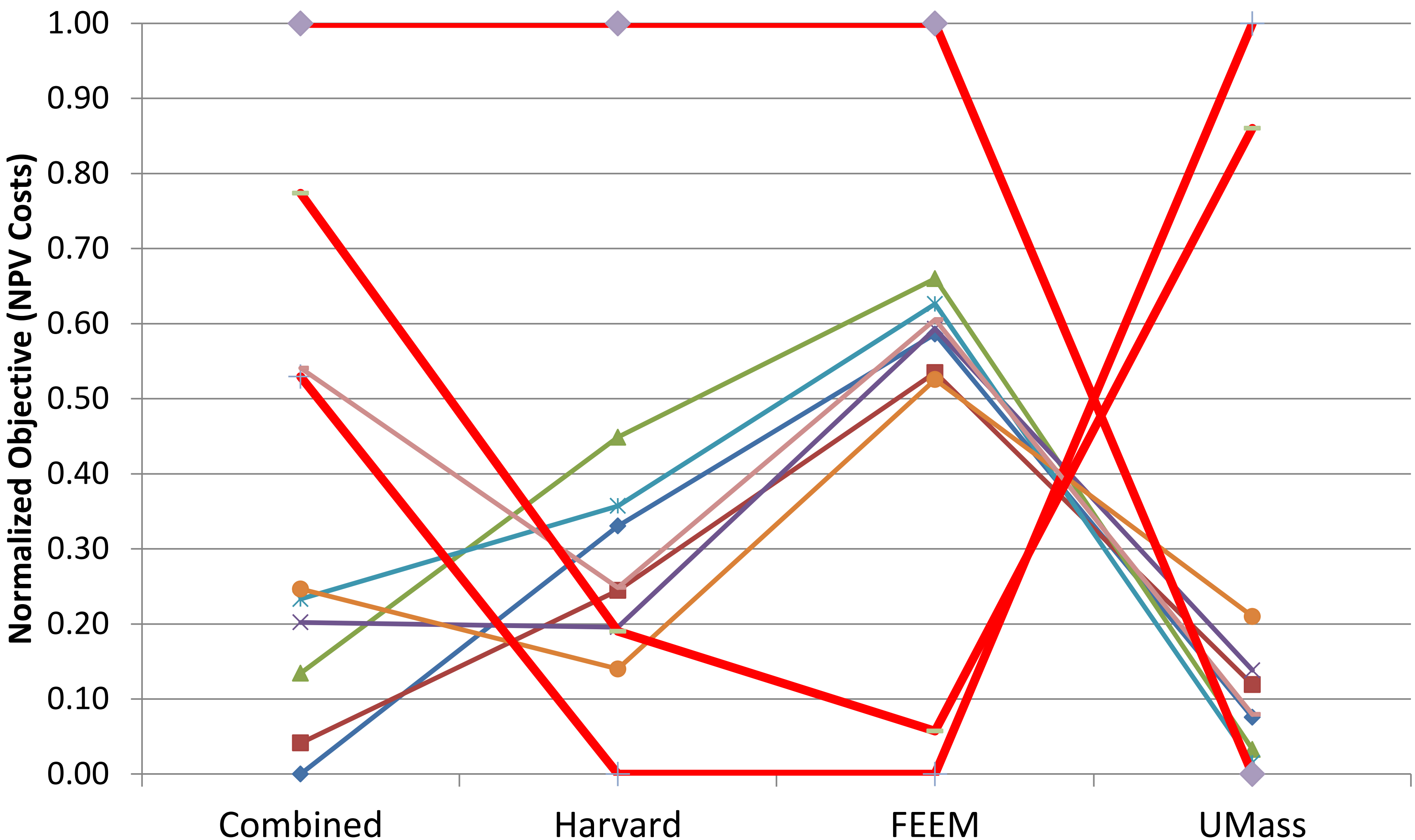
9	High	High	Low	High	High	21320	21581	22901	19324
10	Low	Mid	Mid	High	Low	21491	22671	25442	15142

BE high is in core; Nuc low is in exterior

Normalized ENPV of TAC by team



Normalized ENPV of TAC by team: some are less robust



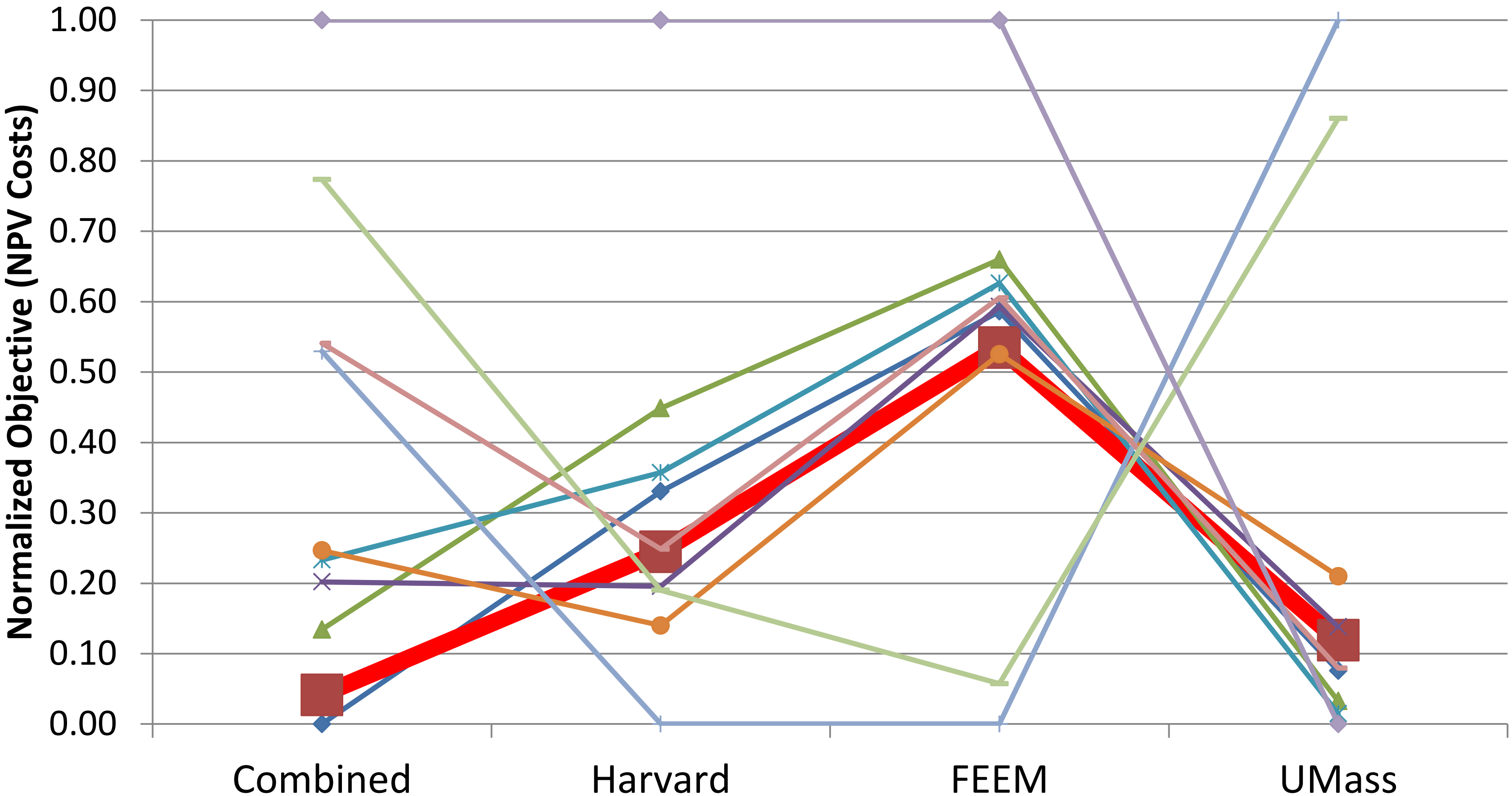
Results: core and exterior of "robust" non-dominated

Portfolios	Technologies					Objectives ENPV (cost in billions of $2005)			
	Solar	Nuc	BF	BE	CCS	Combined	Harvard	FEEM	U Mass
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
8	Mid	Mid	Mid	High	Mid	21144	21659	24379	15528

core = {BE high; CCS mid}

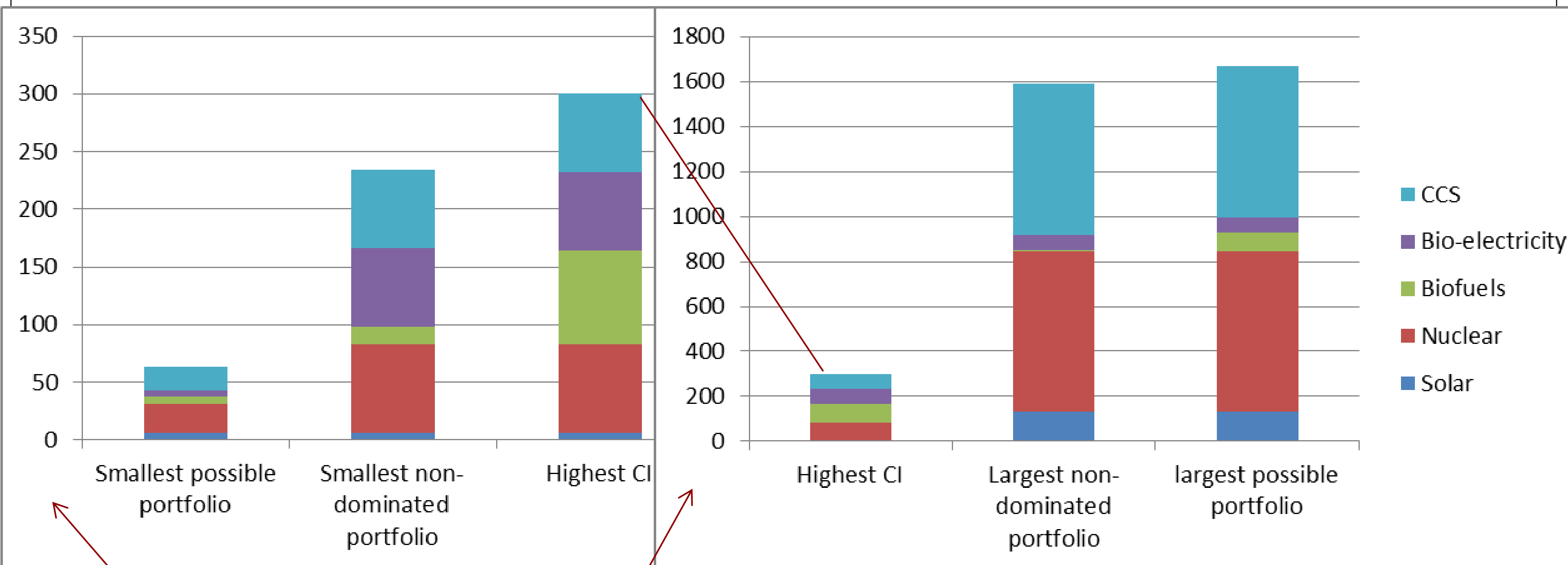
exterior = {Solar high; nuclear low; BF low}

Portfolio with most common funding levels



Portfolios	Technologies				
	Solar	Nuc	BF	BE	CCS
2	Low	Mid	High	High	Mid

Comparison of budgets



in millions of dollars per year

Future work – When Models Disagree

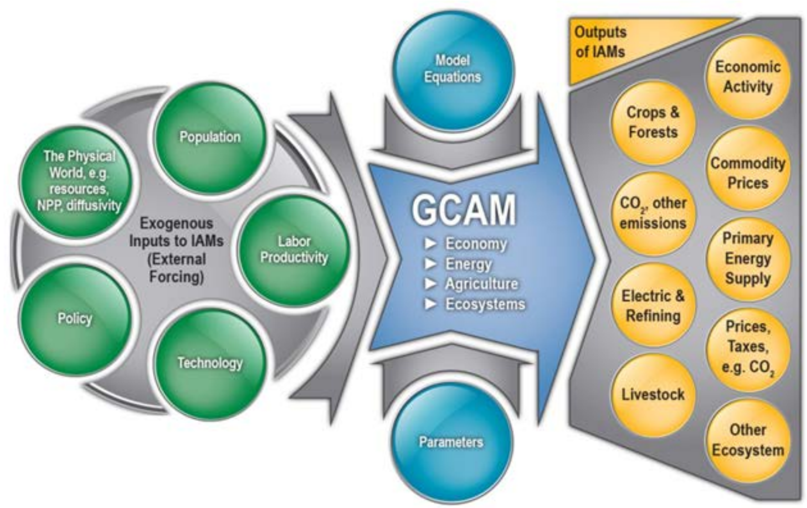
- Model uncertainty and parametric uncertainty

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

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

A World Induced Technical Change Hybrid Model

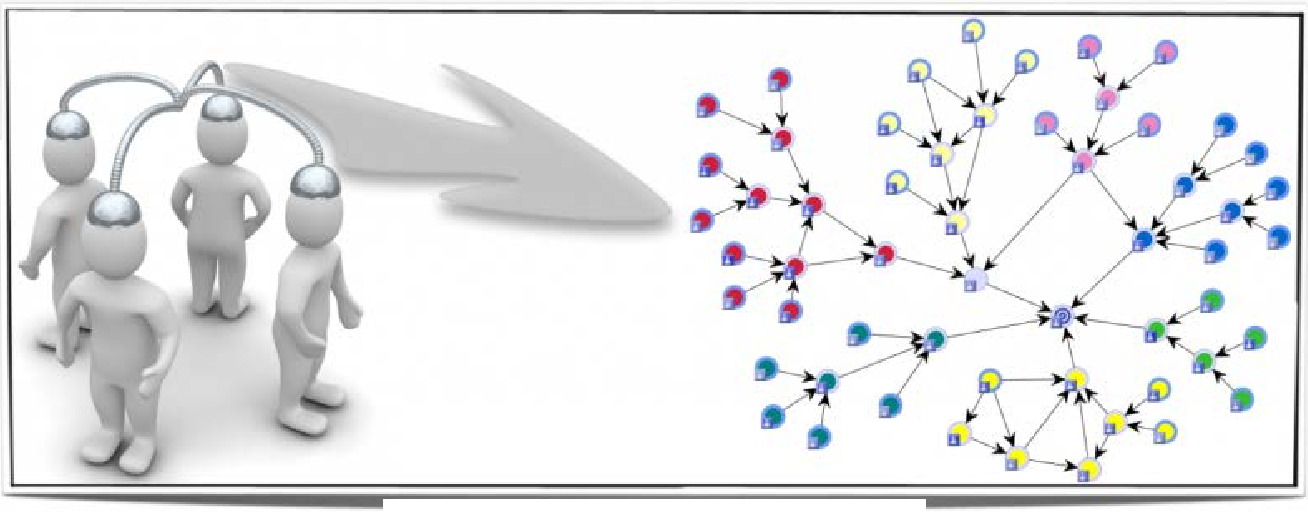
MESSAGE



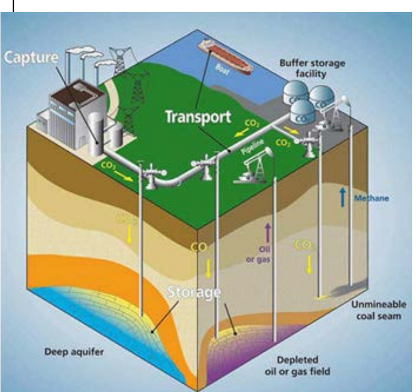
Conclusions

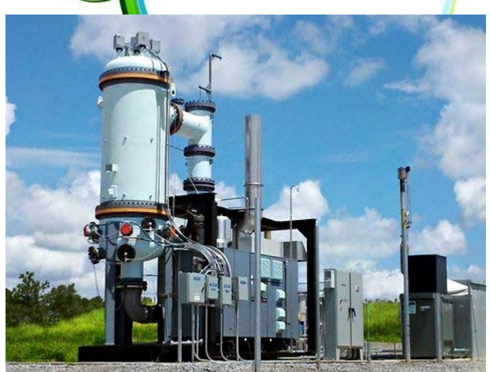
- Belief Dominance is a new concept that allows analysts to derive a set of good alternatives under conflicting beliefs.
  - Synthesizes beliefs in a decision context
  - Avoids worst-case analysis
- RPDA leads to implications about individual alternatives
  - Example: A high investment into bio-electricity 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



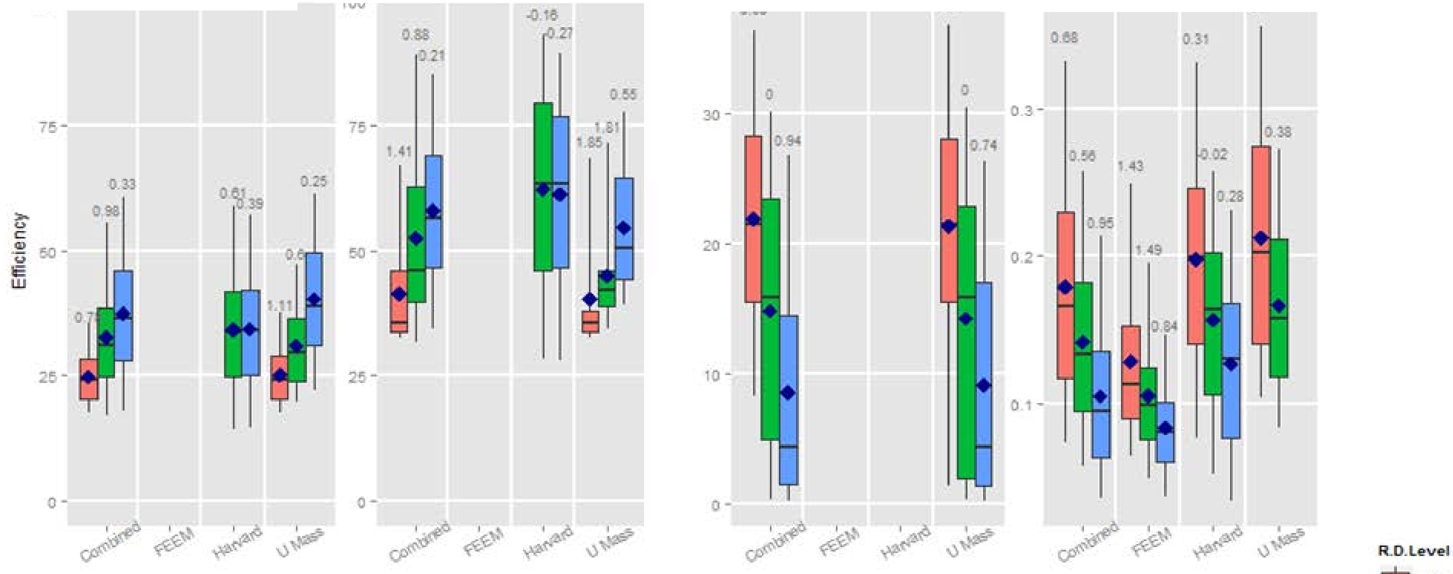
A structured process for eliciting subjective probability distributions from experts about items of interest to decision makers.



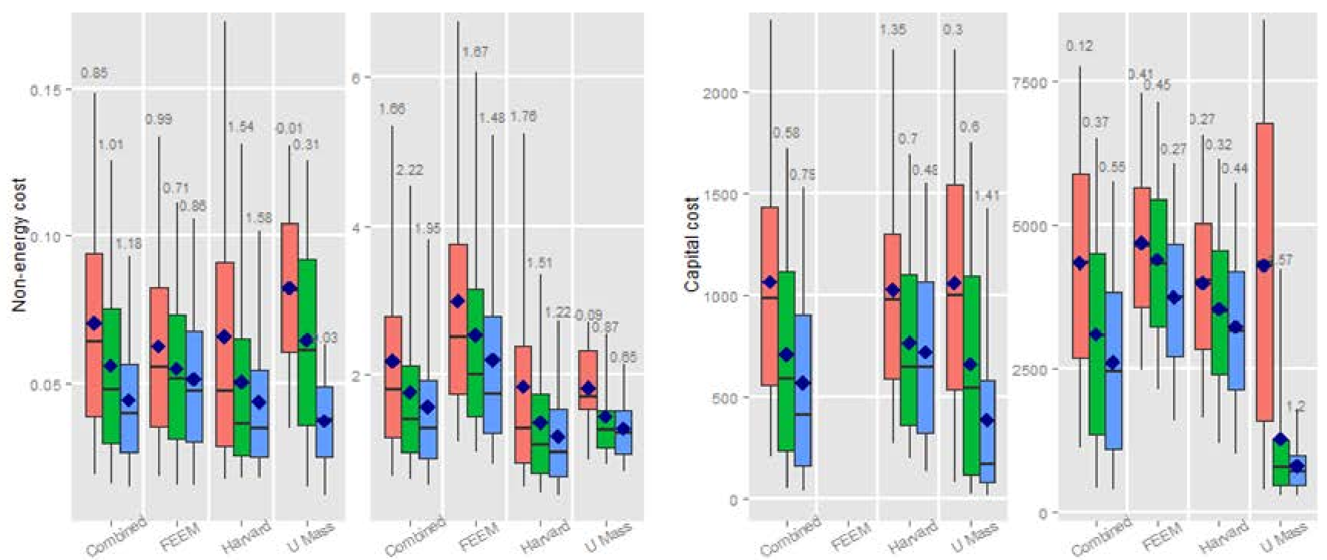


TEaM Results

Bioelectricity, eff % | Biofuels, eff % | CCS EP % | Solar LCOE $/kWh



Bioelectricity, Cap, $/kW | Biofuels, Cap, $/gge | CCS add Cap,$/kW | Nuc Cap,$/kW



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

Covering Distributions with Importance Sampling

Nominal (elicited) distributions $q_{ij}(x_i)$

Covering (importance) distribution $p_{i(x_i)}$ chosen to span the range of nominal distributions and sample from the area of interest.

Sampling distribution is multiplied by the likelihood ratio q_i/p_i to remove sampling bias.