

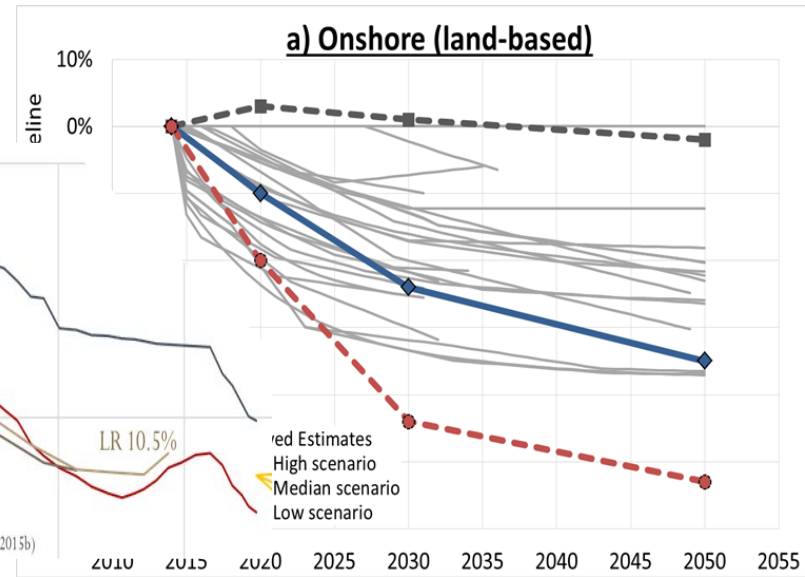
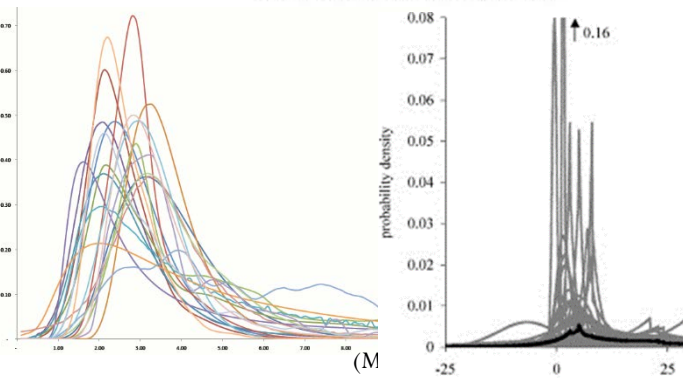
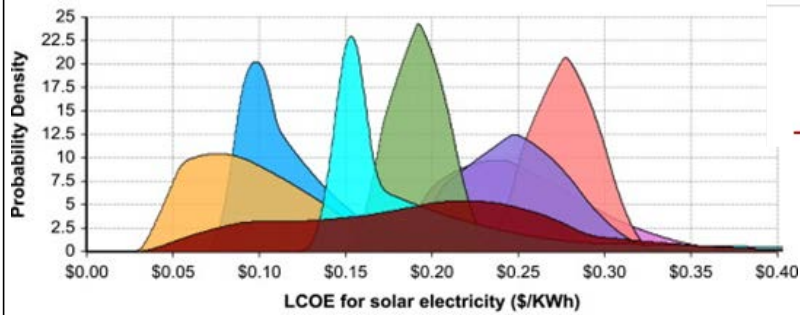
Robust Energy Technology Policy: Finding common ground

Erin Baker, University of Massachusetts, Amherst
Workshop on Distributed Energy Resources
Auckland, NZ
January 12, 2018

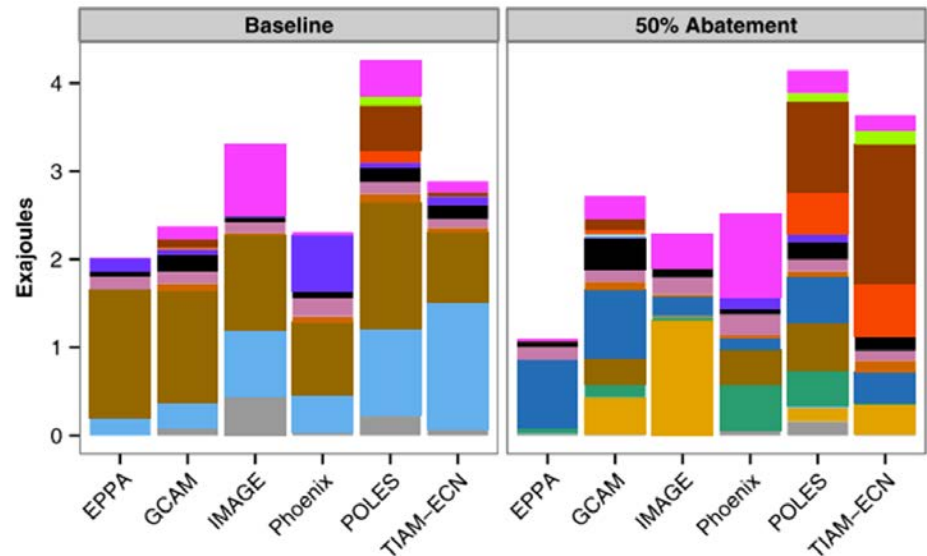


Deep Uncertainty

Conflicting Experts

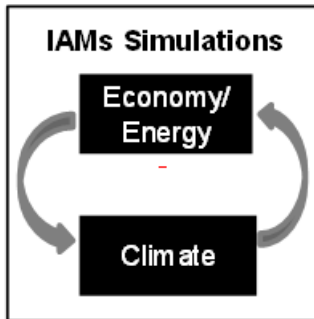
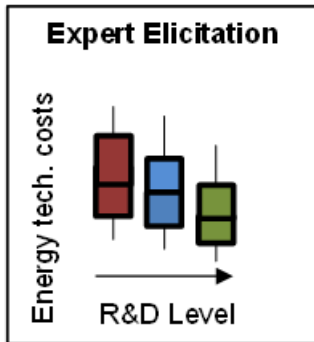


Conflicting Models

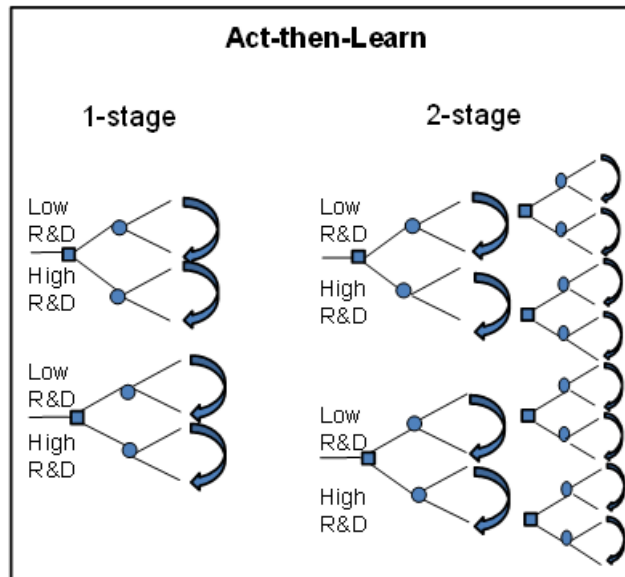
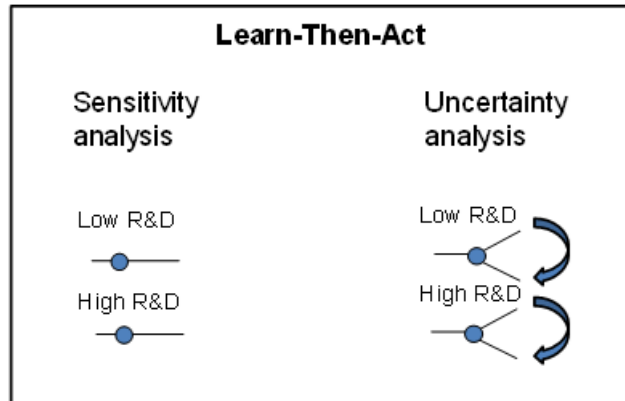


Decision Making Under Uncertainty

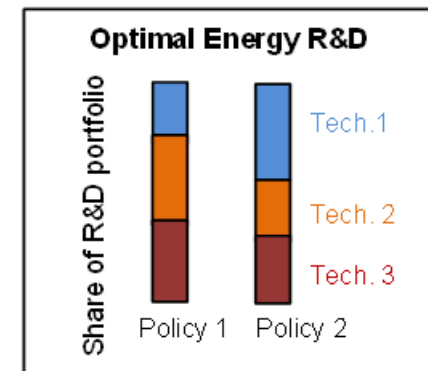
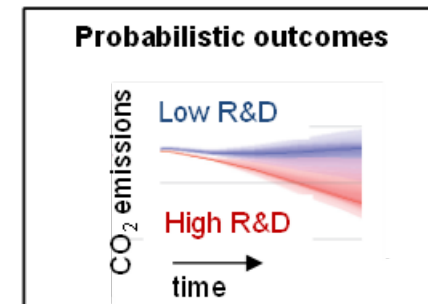
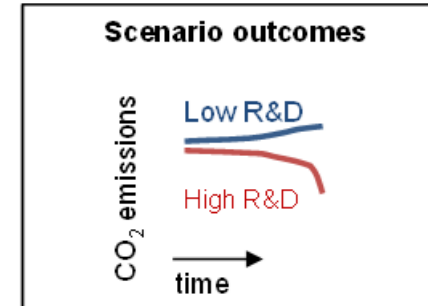
(a) Analytical Components



(b) Decision Frameworks

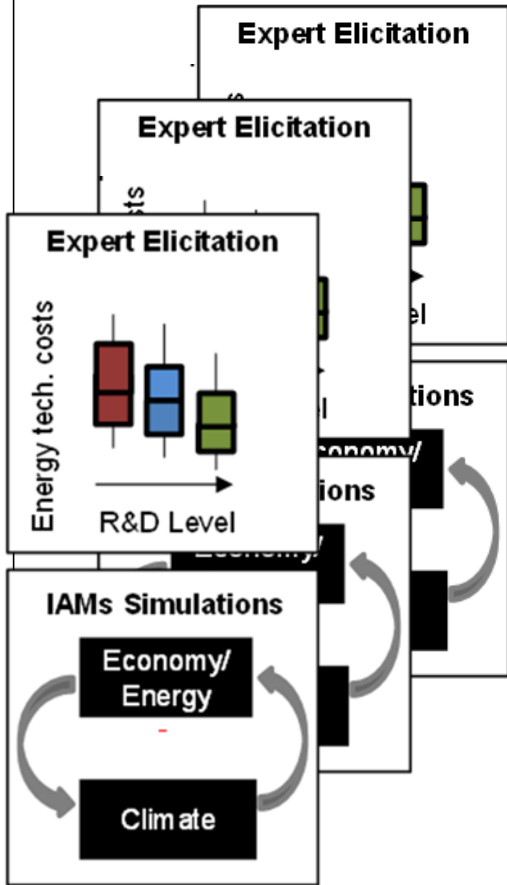


(c) Types of Results

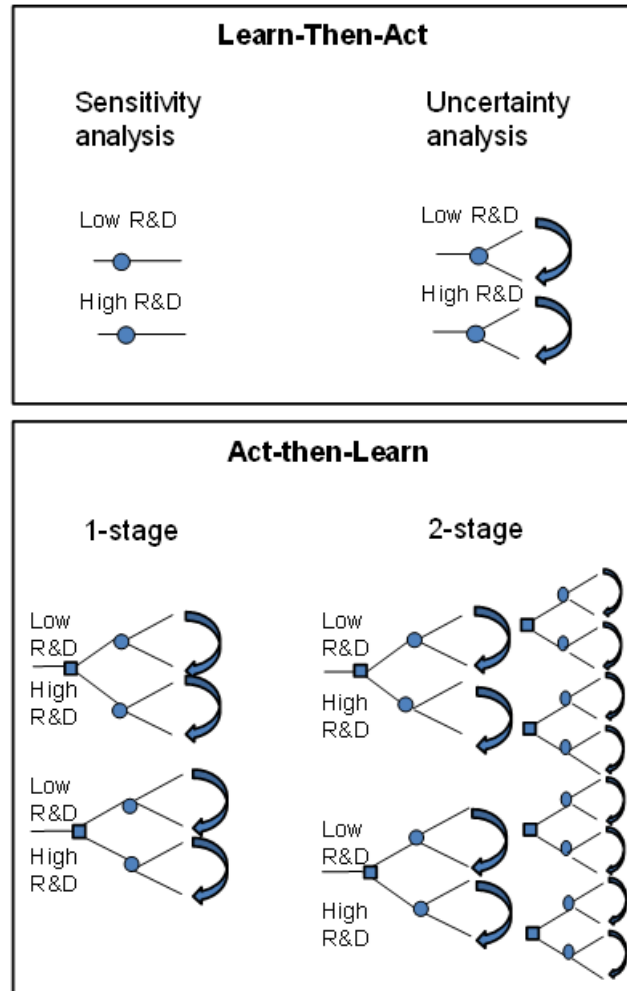


Decision Making Under *Deep* Uncertainty

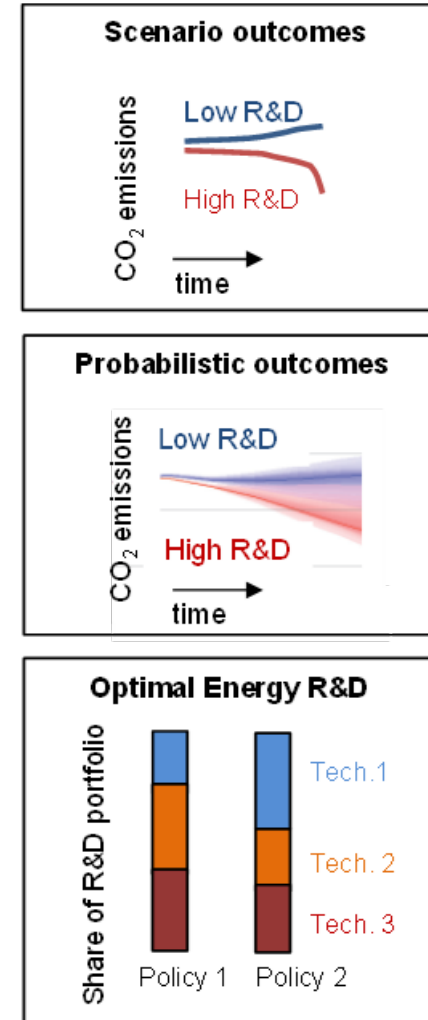
(a) Analytical Components



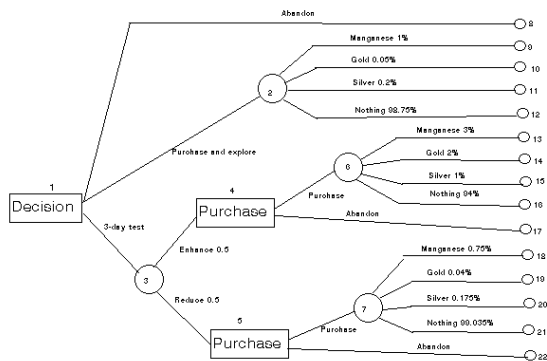
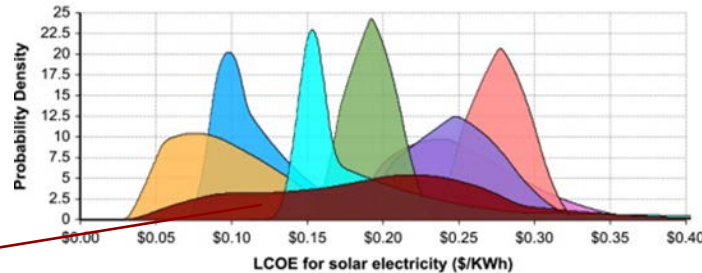
(b) Decision Frameworks



(c) Types of Results



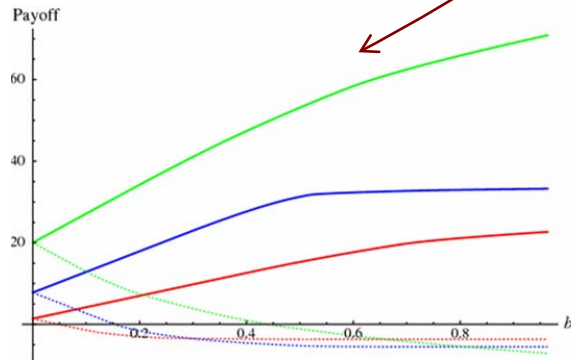
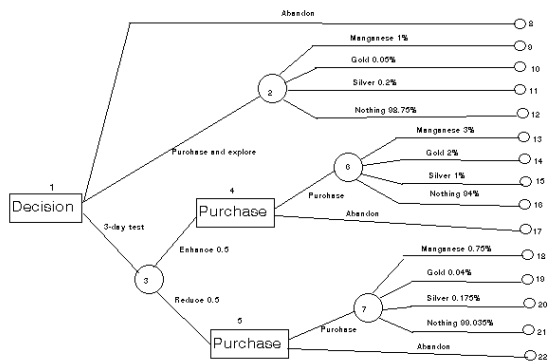
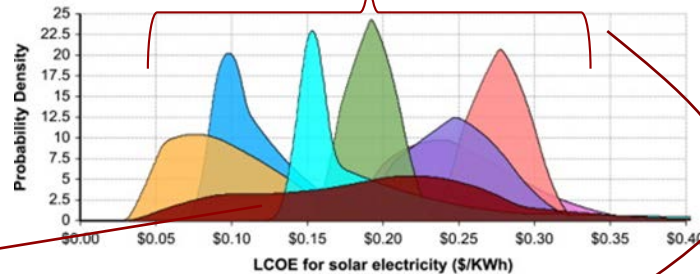
Deep Uncertainty - Approaches



- Traditional:
 - “lacking externally consistency”

*Mathematically resolve disagreement
resulting in a single best recommendation*

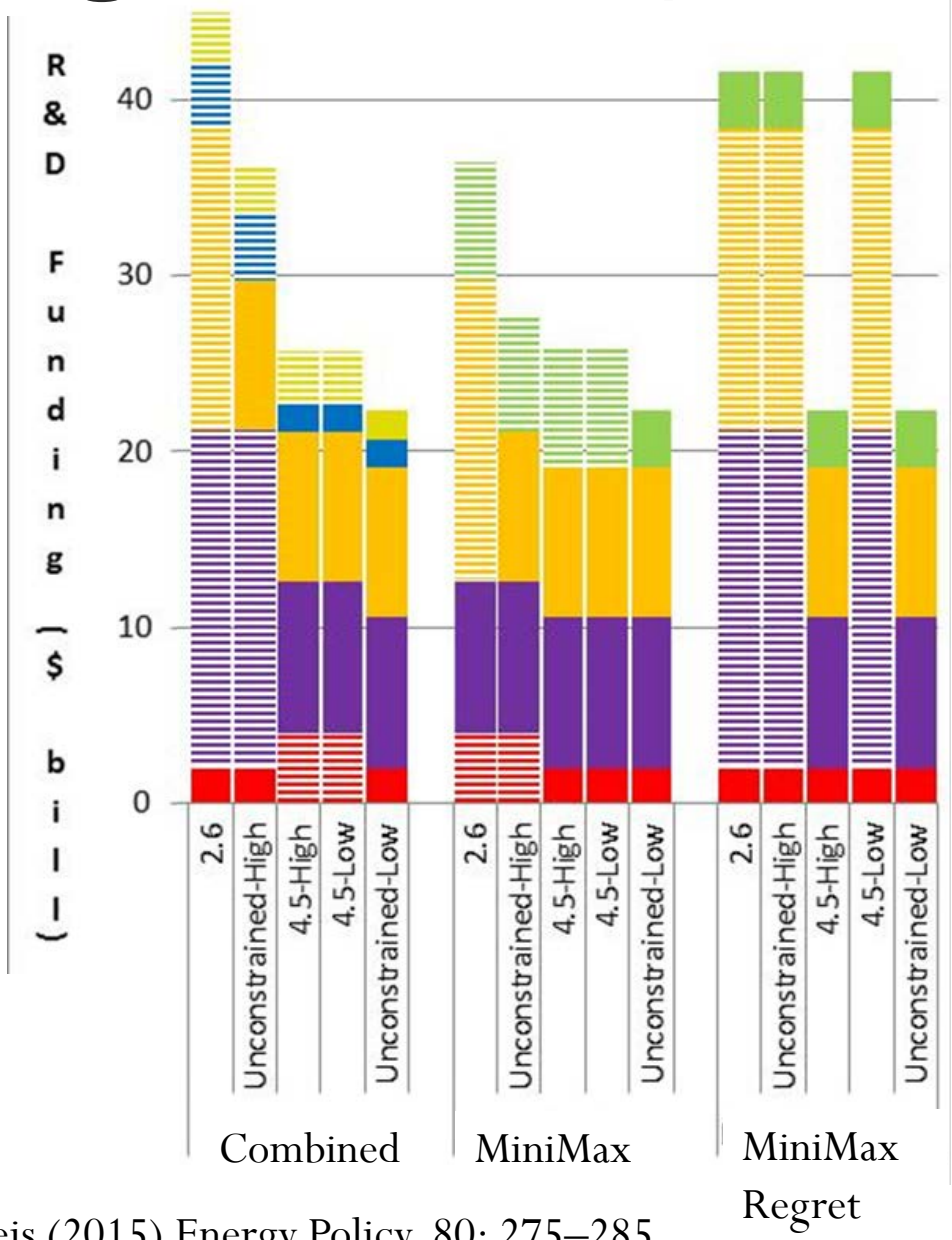
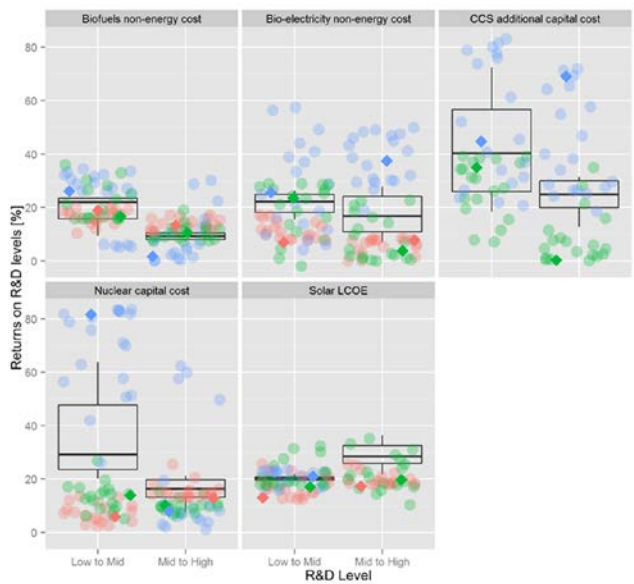
Deep Uncertainty - Approaches



- Traditional:
 - “lacking externally consistency”
- Ambiguity Aversion, robust optimization
 - Lacking internal consistency

Mathematically resolve disagreement resulting in a single best recommendation

Decision Making Under Deep Uncertainty



Finding common ground when experts and models disagree: Robust Portfolio Decision Analysis

Erin Baker, University of Massachusetts

Valentina Bosetti, Bocconi University and FEEM

Ahti Salo, Aalto University



Our approach: Robust Portfolio Decision Analysis

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

possible portfolios {

- {high R&D into nuclear; solar subsidies; 450ppm; cap&trade}
- {low R&D into nuclear; solar subsidies; carbon tax}

- Results in a *set of “good” alternatives*

- {*portfolio 1, portfolio 7, portfolio 10, ...*}

- Provides insights about *good individual projects*

- core projects = {solar subsidies, ...}

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 - {*portfolio 1, portfolio 7, portfolio 10, ...*}
- Provides insights about *good individual projects*
 - core projects = {solar subsidies, ...}

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



Belief Dominance: Terminology

- “Alternatives” x_i
- Uncertain outcomes z
- “Preferences” $U(x,z)$



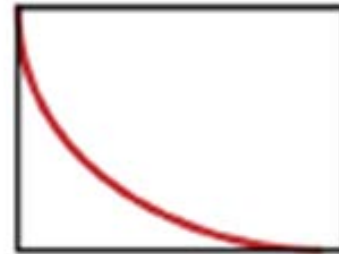
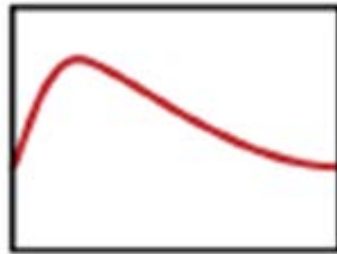
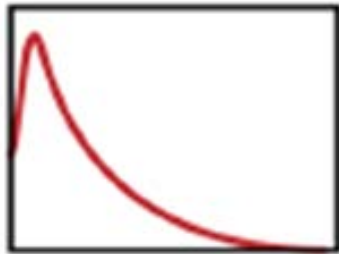
		x_1	x_2	...	x_n
Beliefs	f_1	$f_1(z, x_1)$	$f_1(z, x_2)$...	$f_1(z, x_n)$

	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, A dominates another B , if A is better than B under all beliefs



$$E[u(A)] > E[u(B)] \quad E[u(A)] = E[u(B)] \quad E[u(A)] > E[u(B)]$$

A is a better choice than B no matter the belief. Therefore A Belief-Dominates B

$$E[u(C)] > E[u(D)] \quad E[u(C)] = E[u(D)] \quad E[u(C)] < E[u(D)]$$

Whether C or D is a better choice depends on the belief. There is no dominance between C & D.

Belief Dominance

An alternative, A dominates another B , if A is better than B under all beliefs



$E[u(A)] > E[u(B)]$ $E[u(A)] = E[u(B)]$ $E[u(A)] > E[u(B)]$
A is a better choice than B no matter the belief. Therefore A Belief-Dominates B

$E[u(C)] > E[u(D)]$ $E[u(C)] = E[u(D)]$ $E[u(C)] < E[u(D)]$
Whether C or D is a better choice depends on the belief. There is no dominance between A & B.

Belief Dominance

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

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

\mathbf{x} is a vector of decision variables

Z is a random variable with probability distribution f

U is an objective function

Dominance Concepts

- *Belief*: fix U ; alternative \mathbf{x} dominates alternative \mathbf{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*: fix \mathbf{x} ; distribution f dominates distribution g

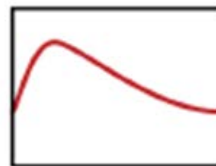
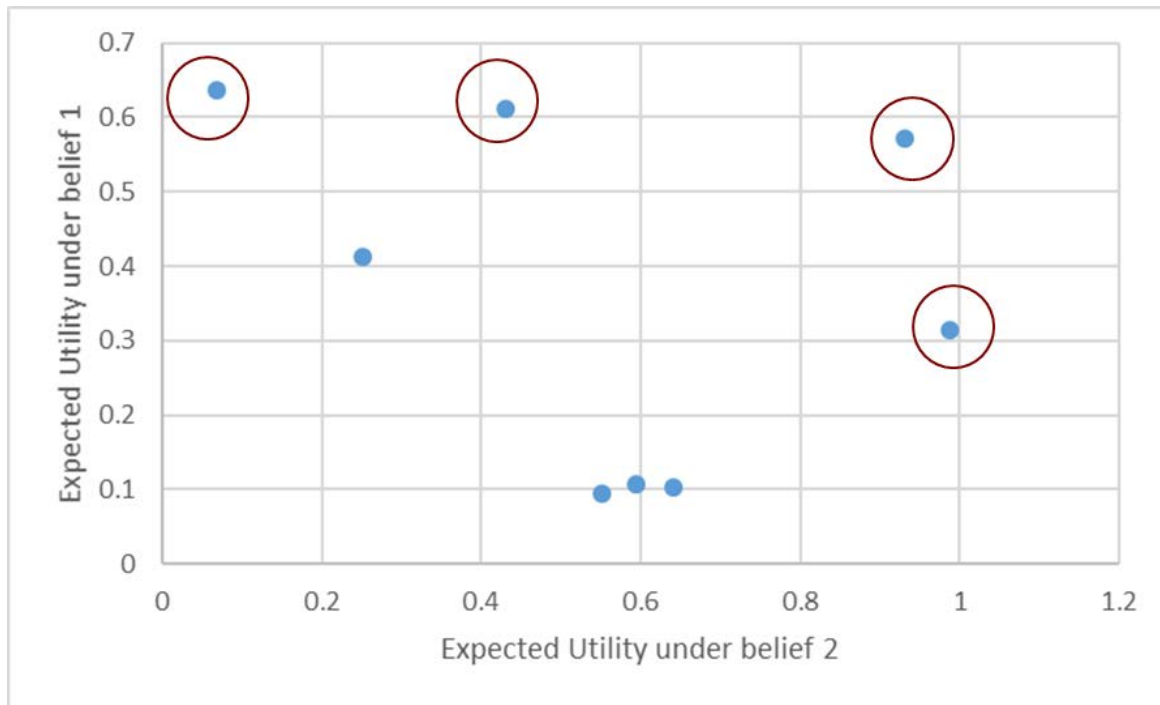
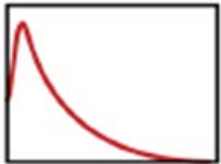
$$\int U(\mathbf{x}; z) f(z) dz \geq \int U(\mathbf{x}; z) g(z) \quad \forall U \in V_S$$

- *Pareto*: fix f ; alternative \mathbf{x} dominates alternative \mathbf{x}'

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

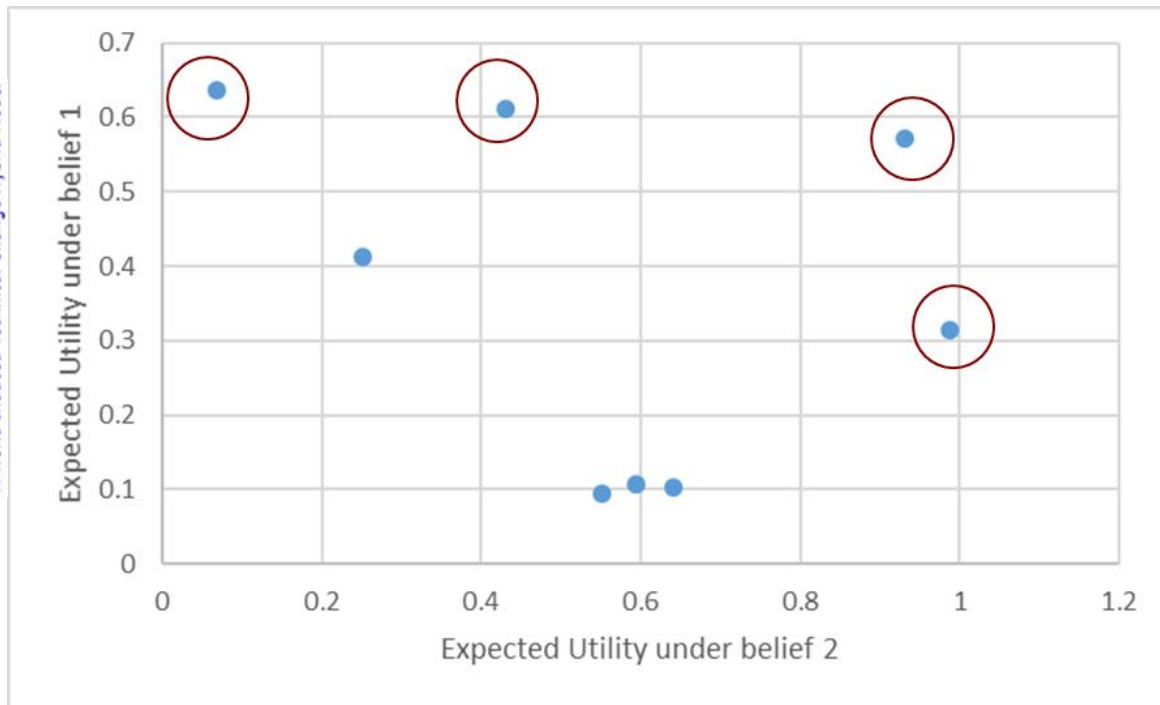
Belief Dominance

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



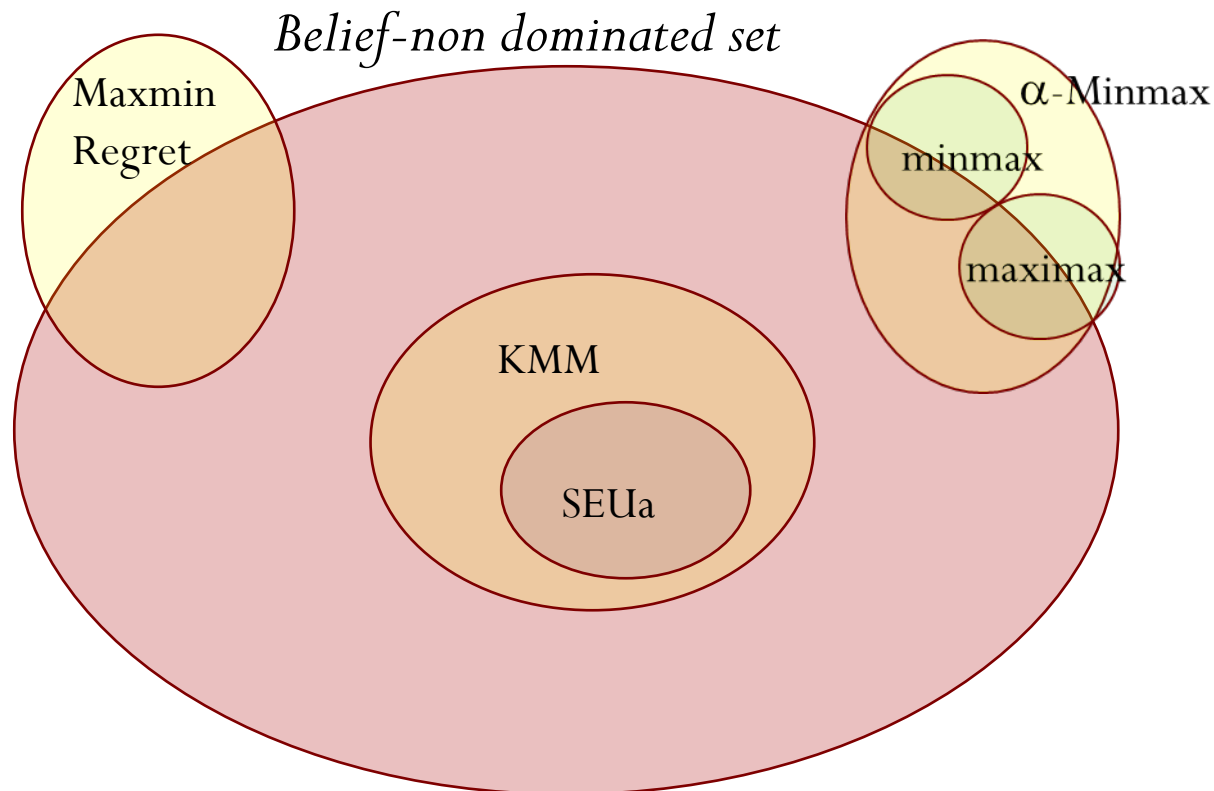
Belief Dominance

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 $\vec{x} \equiv (x_1, \dots, x_N)$
- Let $ND = \{\text{non-dominated portfolios}\}$

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

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

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

non-dominated portfolios

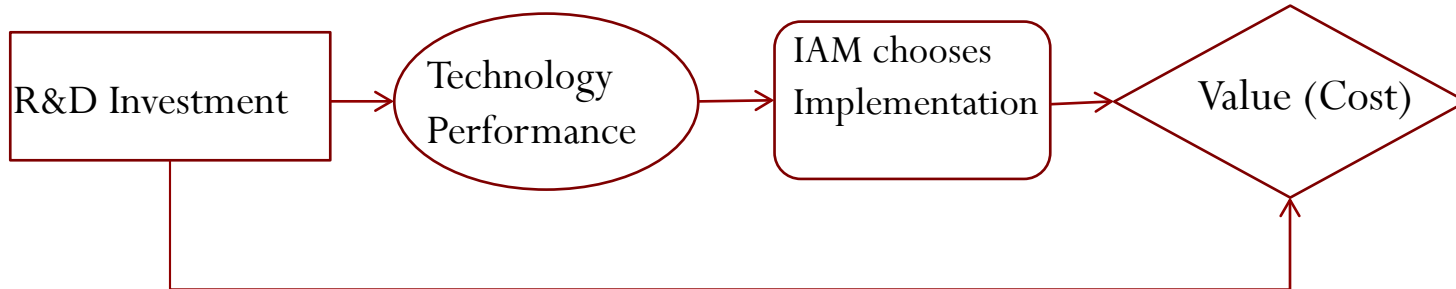
a	b	c	d	e	f
1	0	0	1	1	0
1	0	1	1	1	0
1	0	0	1	1	0
0	0	1	1	0	1
0	0	0	1	0	1
0	0	1	1	0	1

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

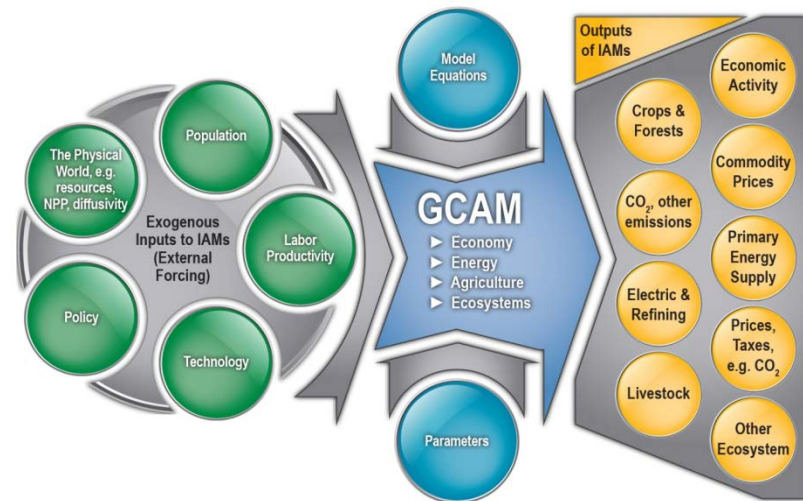
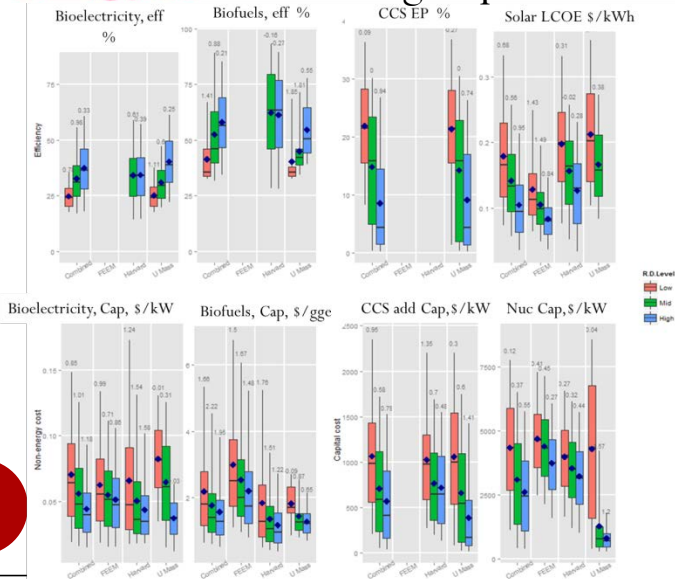
Proof of concept: Public energy technology R&D portfolios

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 ($\sim 450\text{ppm}$):



3 sets of elicitations on 5 technologies plus combined



The computational model

$$H(\mathbf{x}, \tau) \equiv \sum_{l=1}^{1000} p_{\tau}(\mathbf{z}_l; \mathbf{x}) TAC(\mathbf{z}_l, s) + \kappa B(\mathbf{x}) \quad \text{For } s = 2.6 (\sim 450\text{ppm})$$

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

- \mathbf{x} belief dominates \mathbf{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 j th funding level; 0 otherwise

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

$j =$ low, mid, high

$TAC(\mathbf{z}, s) =$ total abatement cost for stabilization s , tech outcome \mathbf{z}

$B(\mathbf{x}) =$ total R&D investment for portfolio \mathbf{x}

$\kappa =$ opportunity cost of investment

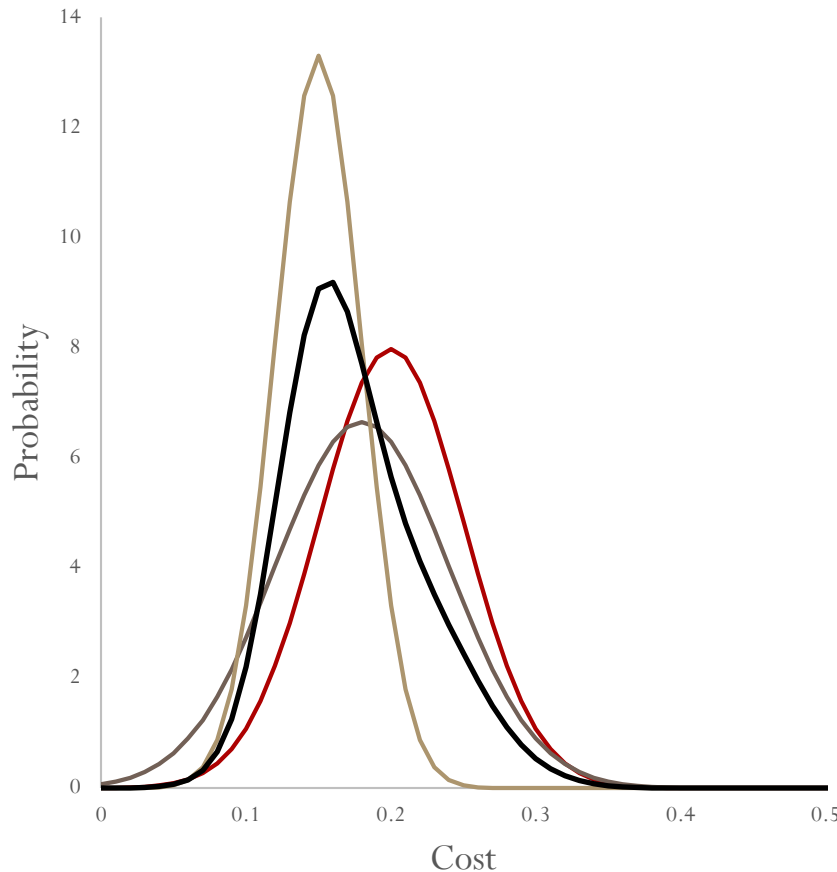
p_{τ} is the discrete probability of outcome \mathbf{z}_1 given investment \mathbf{x} . We use importance sampling to estimate p_{τ} .

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.



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

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Optimal under combined distribution

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Results: non-dominated portfolios

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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
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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)	

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
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12	Low	High	Mid	High	Low	21334	22744	25468	15153
13	Low	Mid	Mid	High	Low	21491	22671	25442	15142

Results conditional on climate goal and IAM. Budgets vary by portfolio

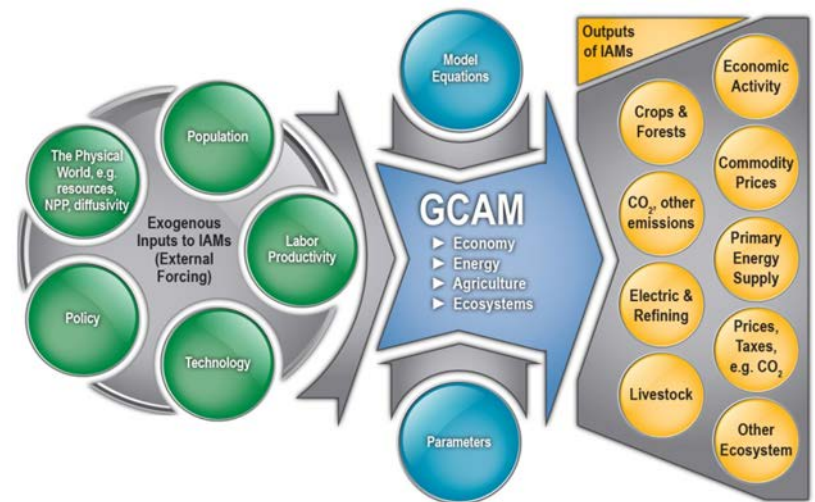
Portfolio	Technologies					Total R&D(Cost in millions of \$2005)	Objectives ENPV(Cost in billions of \$2005)			
	Solar	Nuc	BF	BE	CCS		Combin ed	Harvar d	FEEM	UMass
1	1%	76%	9%	7%	7%	234	20736	21770	24327	15509
2	2%	26%	27%	22%	23%	75	20768	21654	24188	15720
3	1%	82%	2%	8%	8%	218	20838	21929	24525	15301
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
8	1%	83%	1%	8%	8%	215	21135	21417	24307	20029
9	14%	8%	1%	7%	70%	239	21136	21325	22747	20003
10	7%	32%	6%	28%	28%	61	21144	21659	24379	15528
11	8%	45%	0%	4%	42%	398	21320	21581	22901	19324
12	1%	87%	2%	8%	3%	206	21334	22744	25468	15153
13	4%	41%	8%	36%	11%	47	21491	22671	25442	15142

Future work – When Models Disagree

- Model uncertainty and parametric uncertainty

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

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



Conclusions

- Deep uncertainty – hard to put probabilities, multiple stakeholders, communication of degree of disagreements
- Rational decision-centric approaches
 - Beyond making model more accurate or precise, toward more decision-relevant
 - Methods that use analysis to avoid mistakes and shine light on tradeoffs and disagreements
- 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.

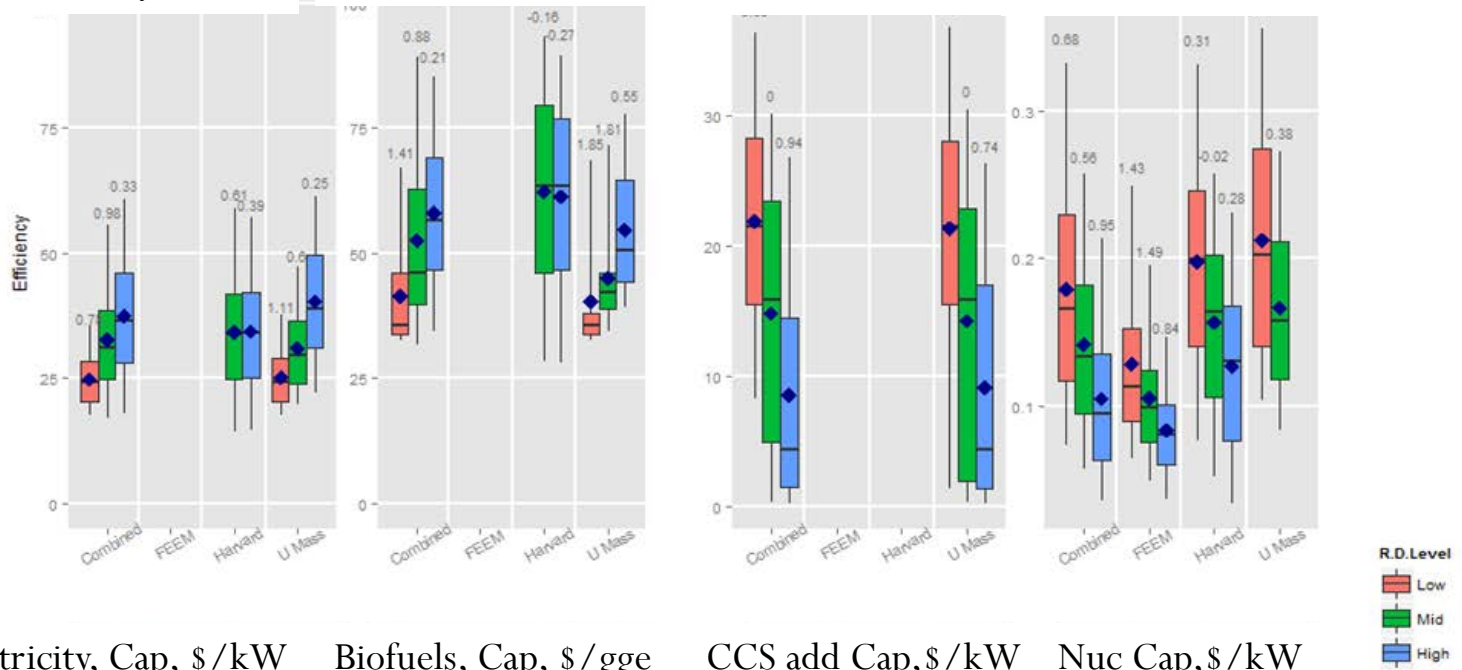
TEaM Results

Bioelectricity, eff %

Biofuels, eff %

CCS EP %

Solar LCOE \$/kWh

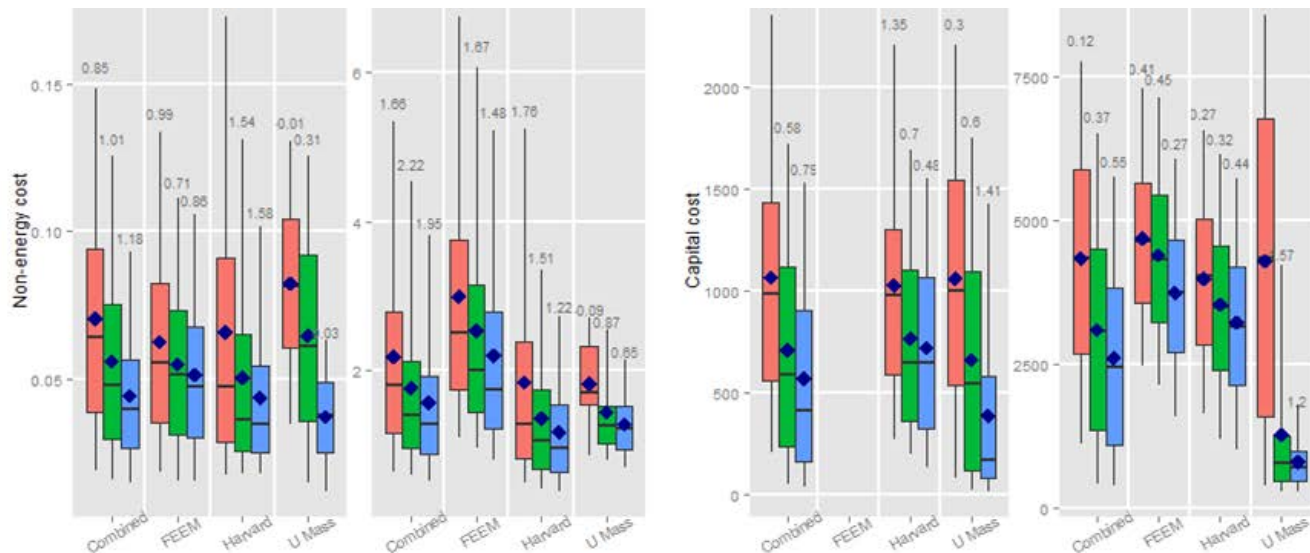


Bioelectricity, Cap, \$/kW

Biofuels, Cap, \$/gge

CCS add Cap, \$/kW

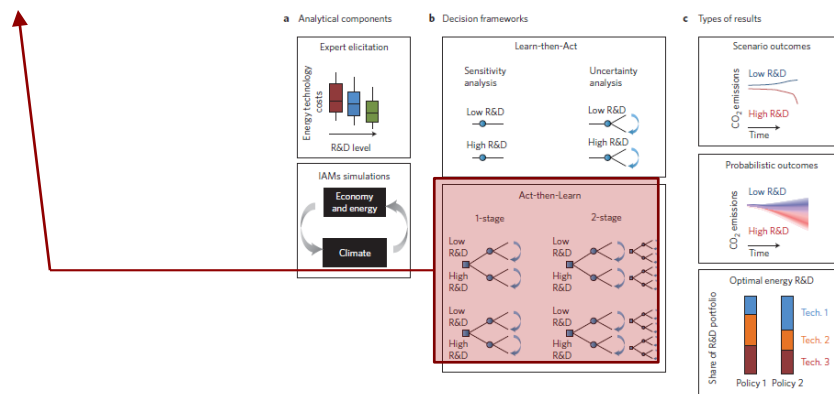
Nuc Cap, \$/kW



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

Decision Making under Deep Uncertainty

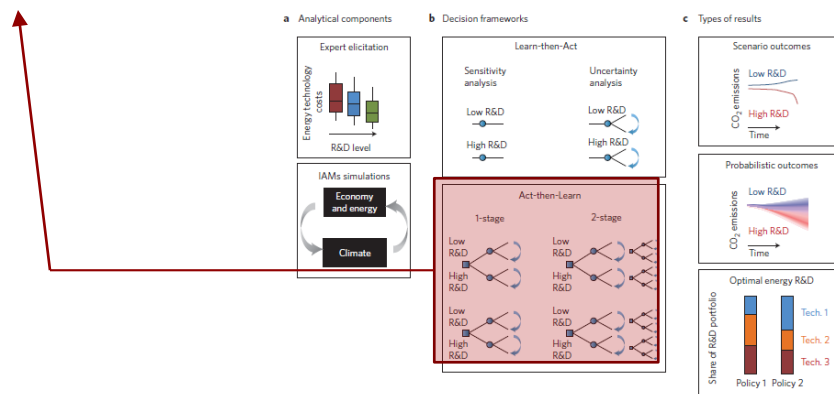
	IIA	Ind	Sym	INA	Complete
Bayes/SEU	X	X			X
Maxmin	X		X		X
α -Maxmin	X	c	X		X
Minimax Regret		X	X	X	X
Klibinoff-M-M	?	?	X	?	X
Admissibility	X	X	X		



Adapted from Stoye (2012) Annu. Rev. Econ. 4.1: 257-282.

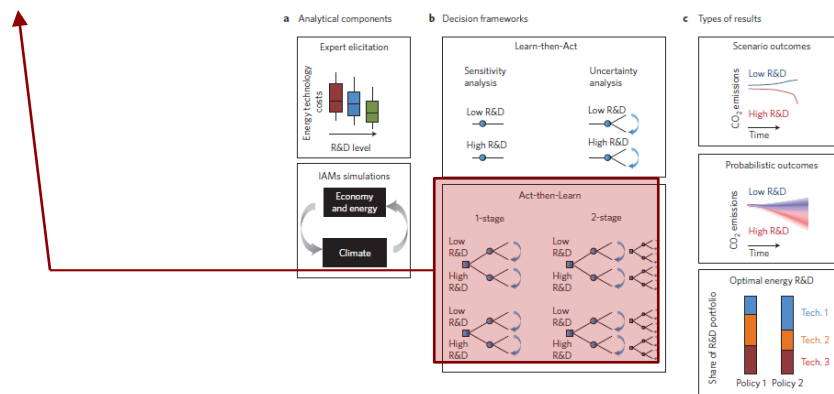
Decision Making under Deep Uncertainty

	IIA	Ind	Sym	INA	Complete
Bayes/SEU	X	X			X
Maxmin	X		X		X
α -Maxmin	X	c	X		X
Minimax Regret		X	X	X	X
Klibinoff-M-M	?	?	X	?	X
Admissibility	X	X	X		



Decision Making under Deep Uncertainty

	IIA	Ind	Sym	INA	Complete
Bayes/SEU	X	X			X
Maxmin	X		X		X
α -Maxmin	X	c	X		X
Minimax Regret		X	X	X	X
Klibinoff-M-M	?	?	X	?	X
Admissibility	X	X	X		



Decision Making under Deep Uncertainty

	IIA	Ind	Sym	INA	Complete
Bayes/SEU	X	X			X
Maxmin	X		X		X
α -Maxmin	X	c	X		X
Minimax Regret		X	X	X	X
Klibinoff-M-M	?	?	X	?	X
Admissibility	X	X	X		

