Low carbon energy R&D portfolios that are robust when models and experts disagree

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Innovation and Climate Change Governance

Paris, France

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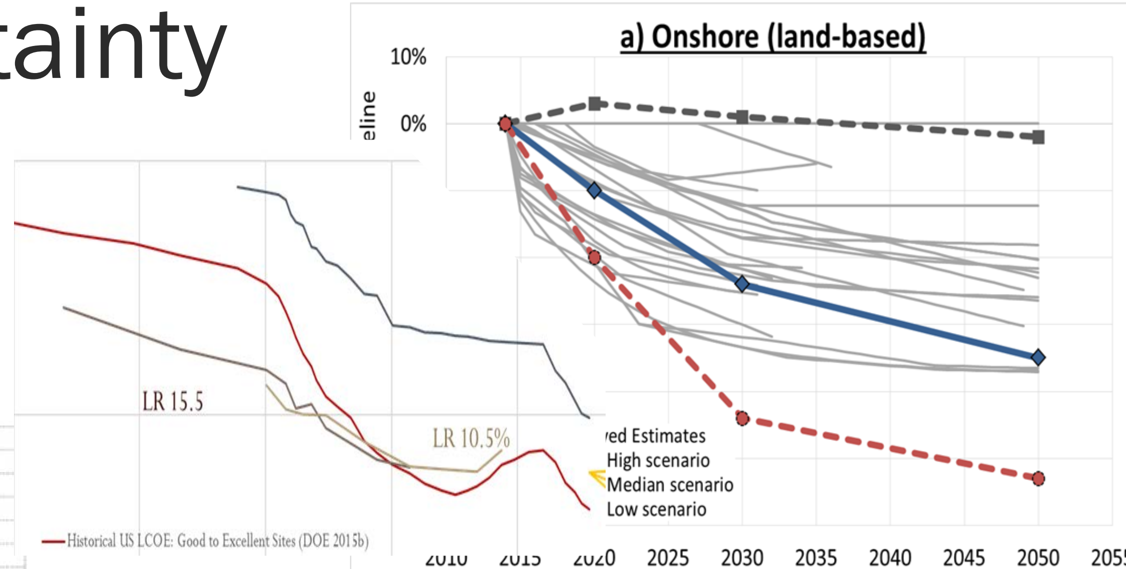
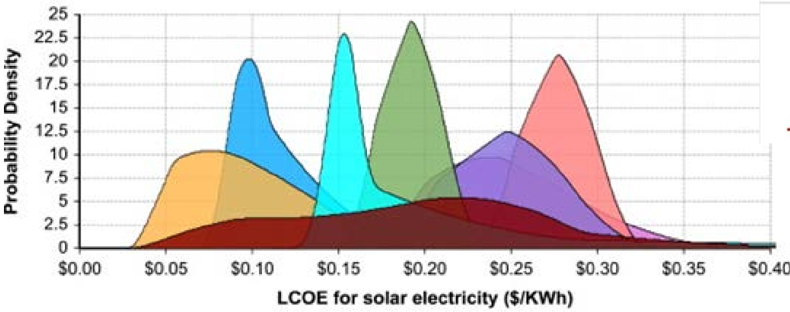
Energy Transition Institute @ UMass Amherst

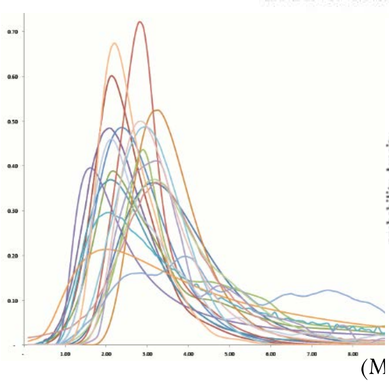
Deep Uncertainty

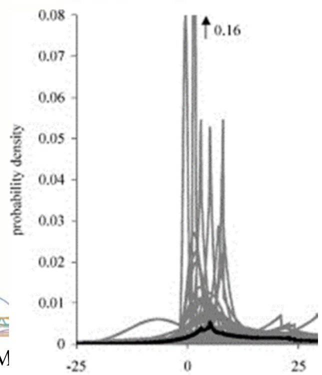
Conflicting forecasting methods



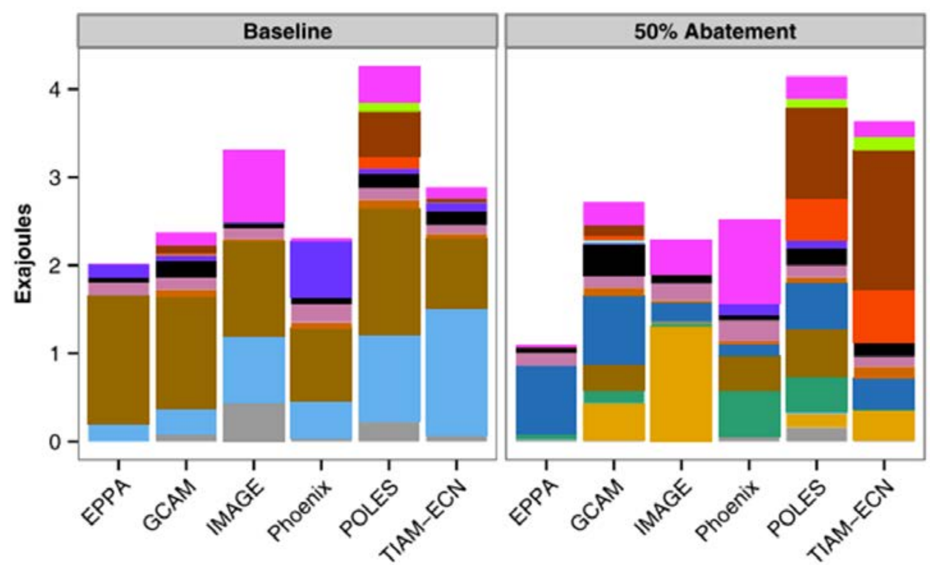
Conflicting Experts



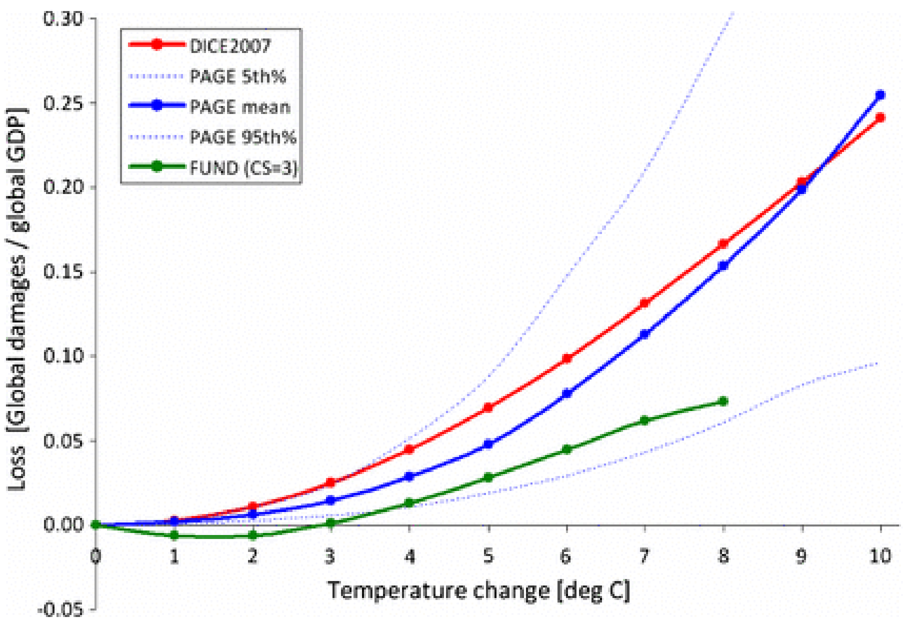




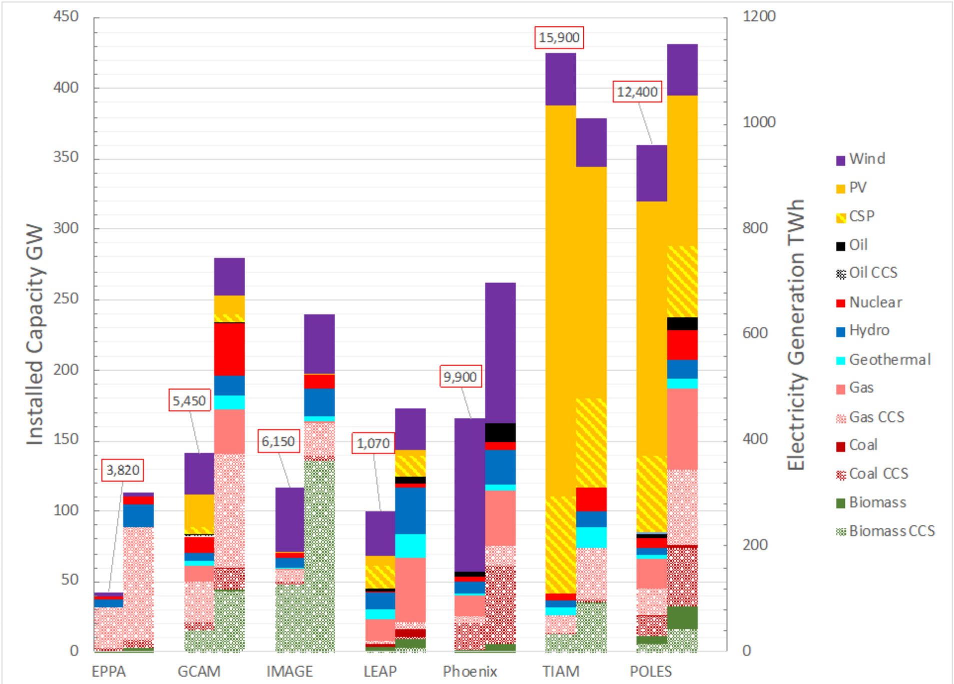
Conflicting Models



Model uncertainty



Interagency Working Group on Social Cost of Carbon. (2010). Technical support document: Social cost
of carbon for regulatory impact analysis under executive order 12866.



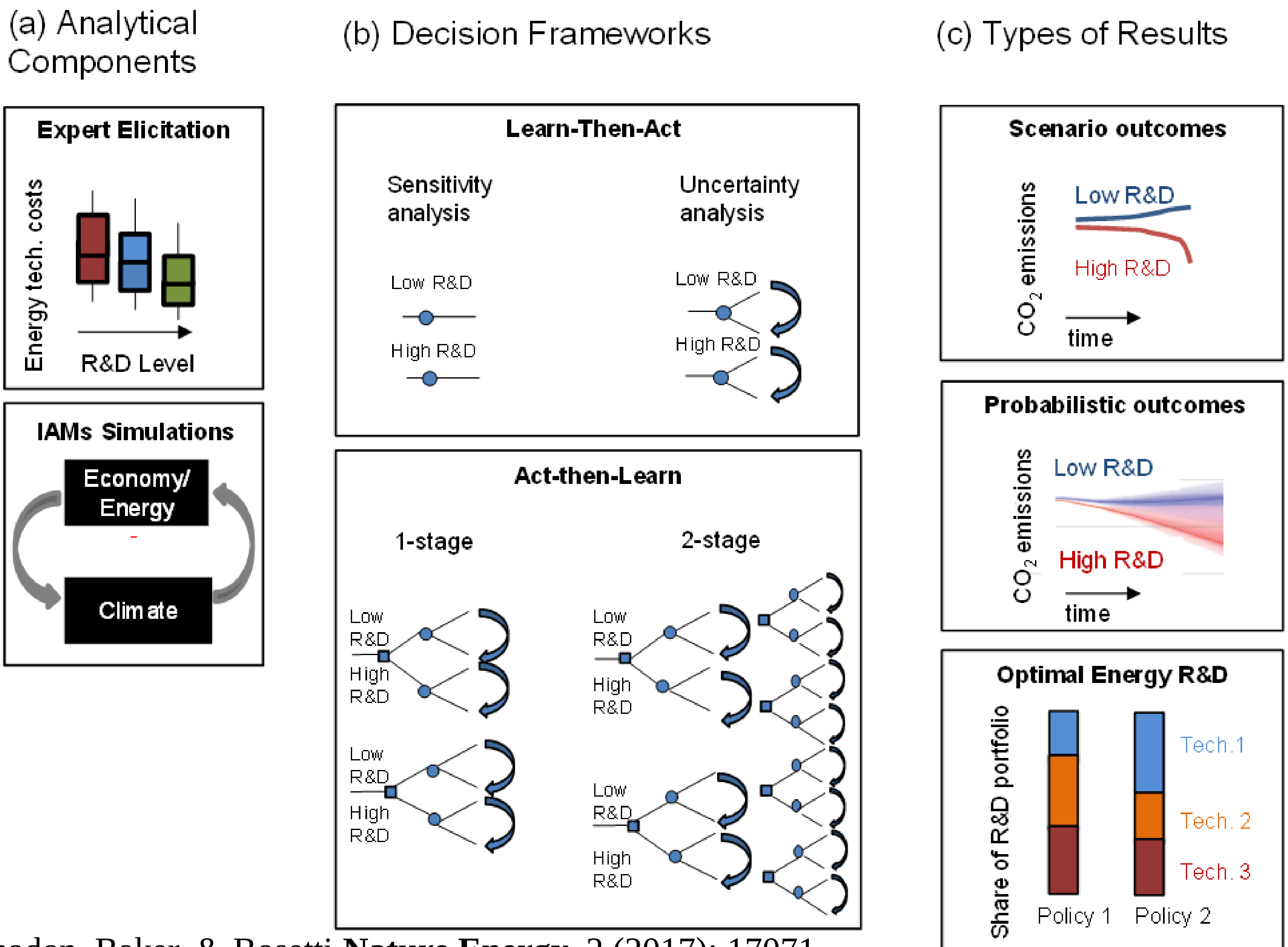
Mercado Fernandez, R., 2020. Robust and Sustainable Energy Pathways to Reach Mexico's Climate Goals.

damage functions from FUND, PAGE, DICE

Capacity and energy portfolios for Mexico in 2050 based on 7 IAMs

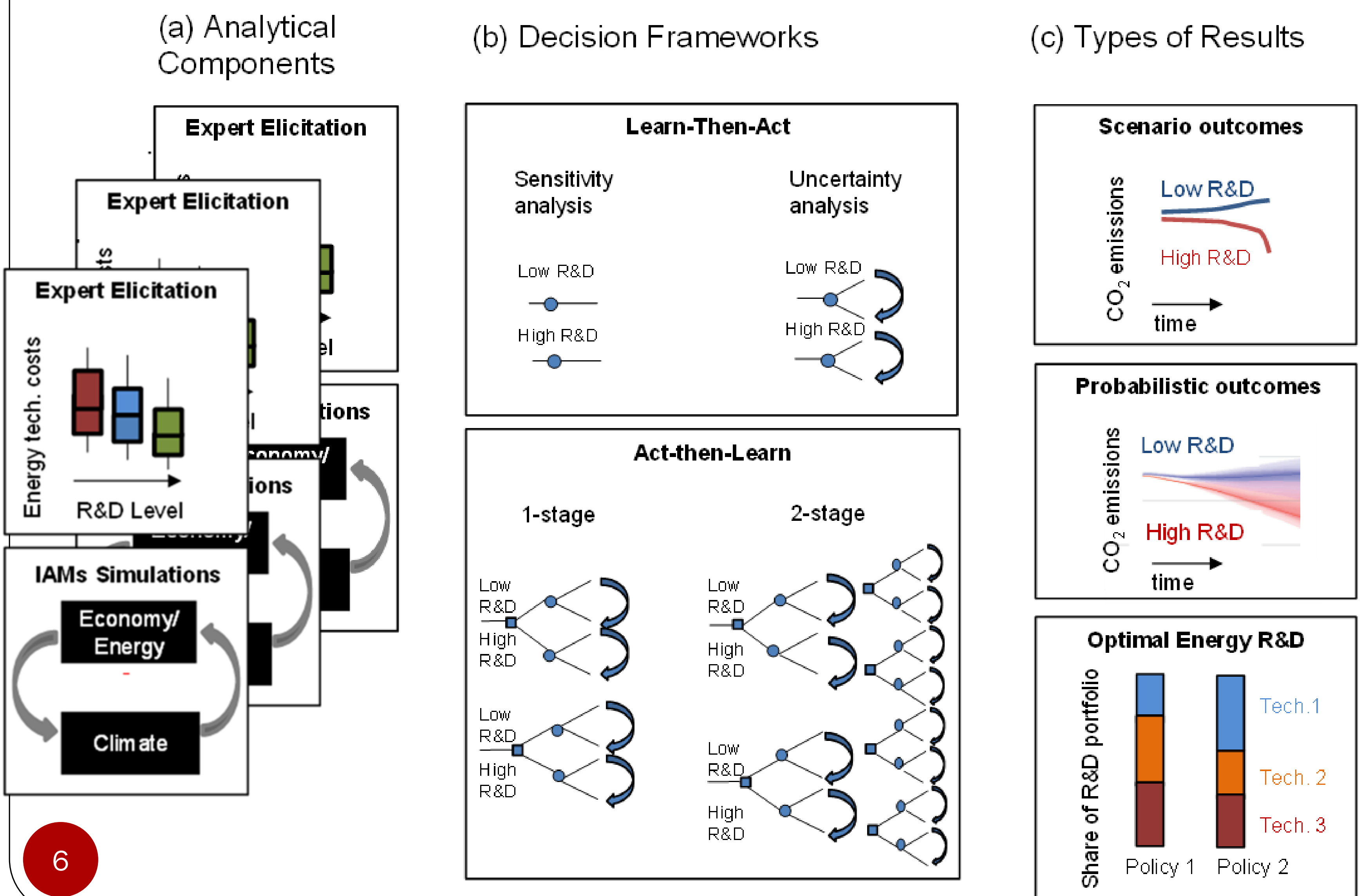
Decision Making under Deep Uncertainty

Decision Making Under Uncertainty

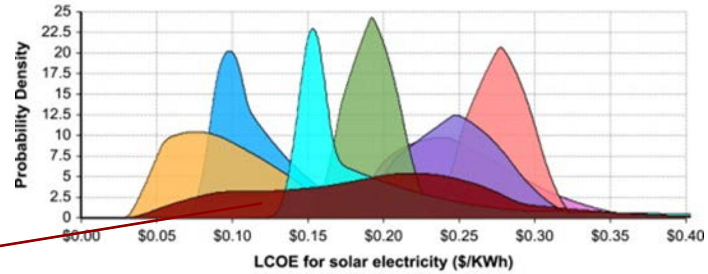


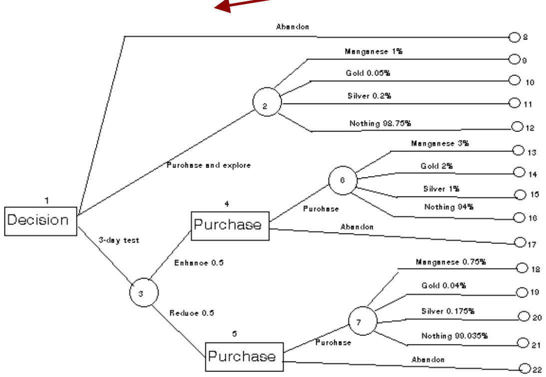
Anadon, Baker, & Bosetti **Nature Energy**, 2 (2017): 17071

Decision Making Under *Deep* Uncertainty



Deep Uncertainty - Approaches

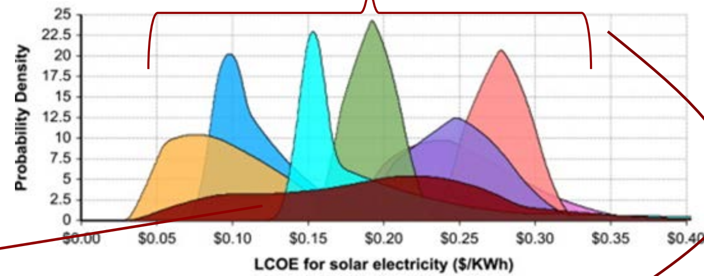


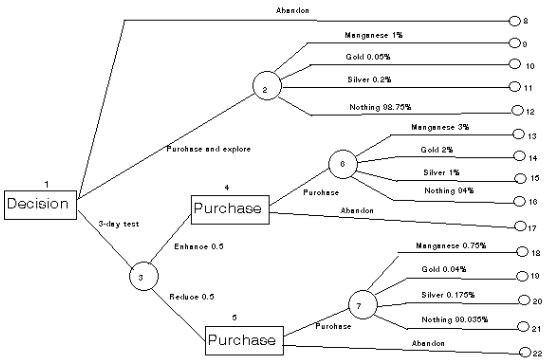


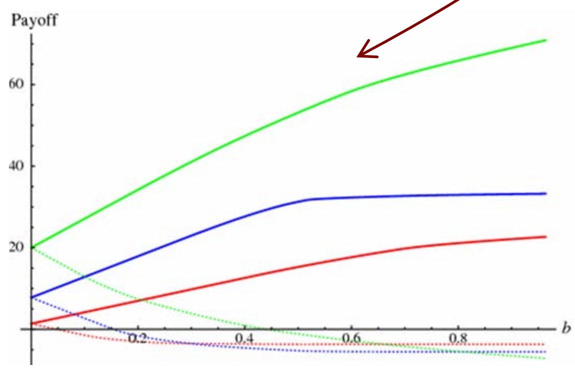
- Traditional:
  - "lacking externally consistency"

Mathematically resolve disagreement resulting in a single best recommendation

Deep Uncertainty - Approaches







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  - Lacking internal consistency

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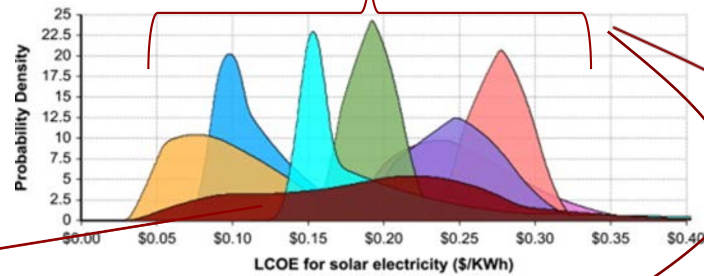

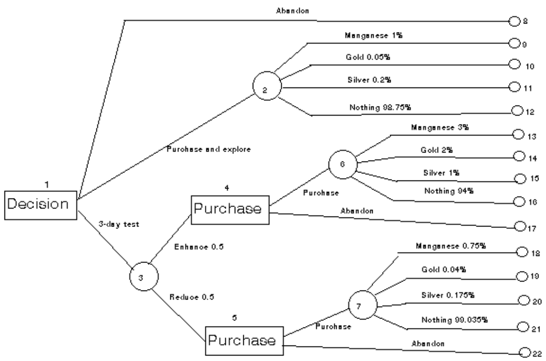

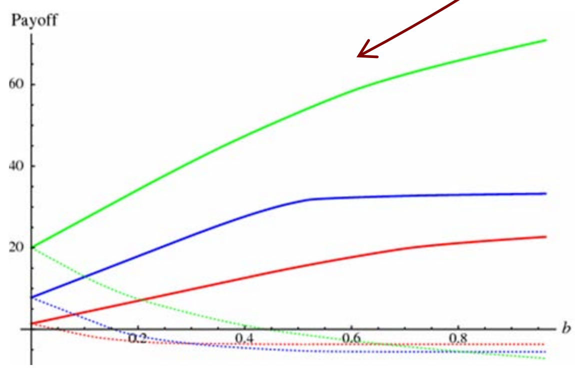

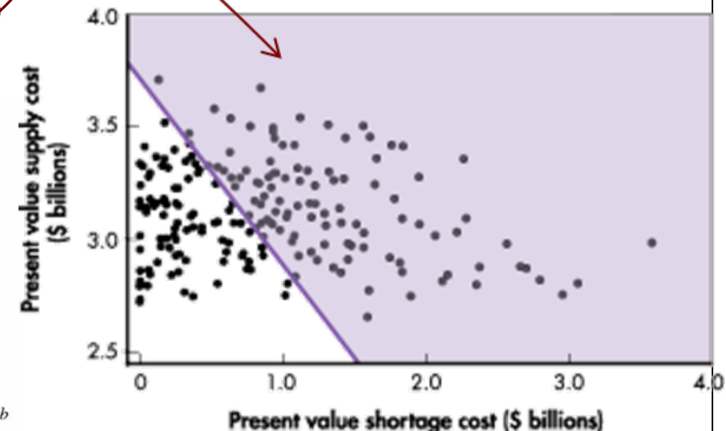

- Traditional:
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“Robust Decision Making”

- Evaluates a small number of alternatives
- Iterates to develop alternatives

Mathematically resolve disagreement resulting in a single best recommendation

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

Baker, E., Bosetti, V. and Salo, A., 2020. Robust portfolio decision analysis: An application to the energy research and development portfolio problem. European Journal of Operational Research, 284(3), pp.1107-1120.

Aalto University
School of Science

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,*…}
- 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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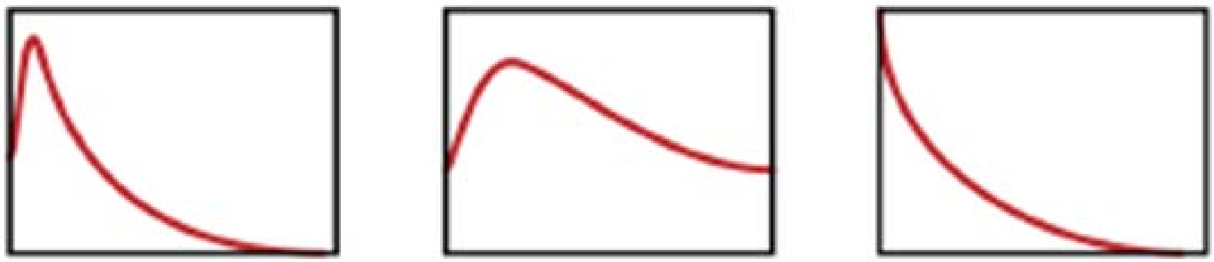
May help to open up the dialogue on climate change. "Emphasize solutions and benefits".

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.

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 Belief-Dominates B

E[u(C)] > E[u(D)]   E[u(C)] = E[u(D)]   E[u(C)] < E[u(D)]

There is no dominance between C & D.

In the literature as "admissibility", "knightian decision making", "objective rationality", "unambiguous preferences".

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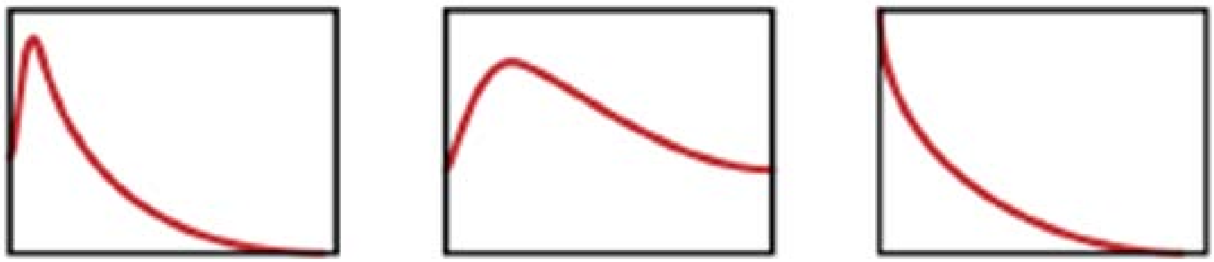

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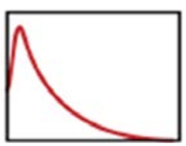
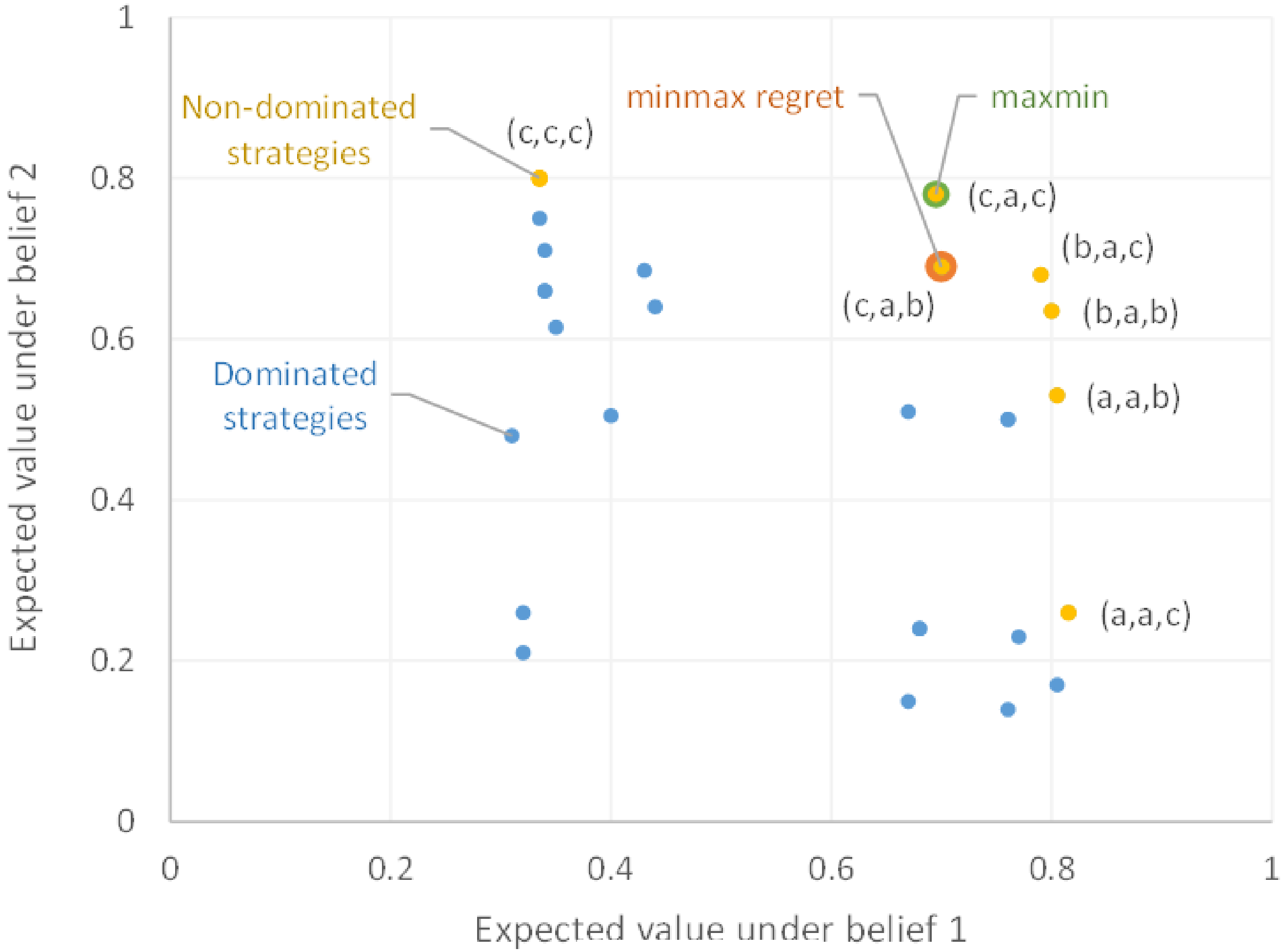
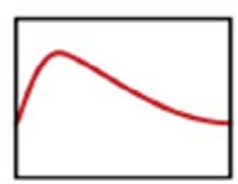
Belief Dominance

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







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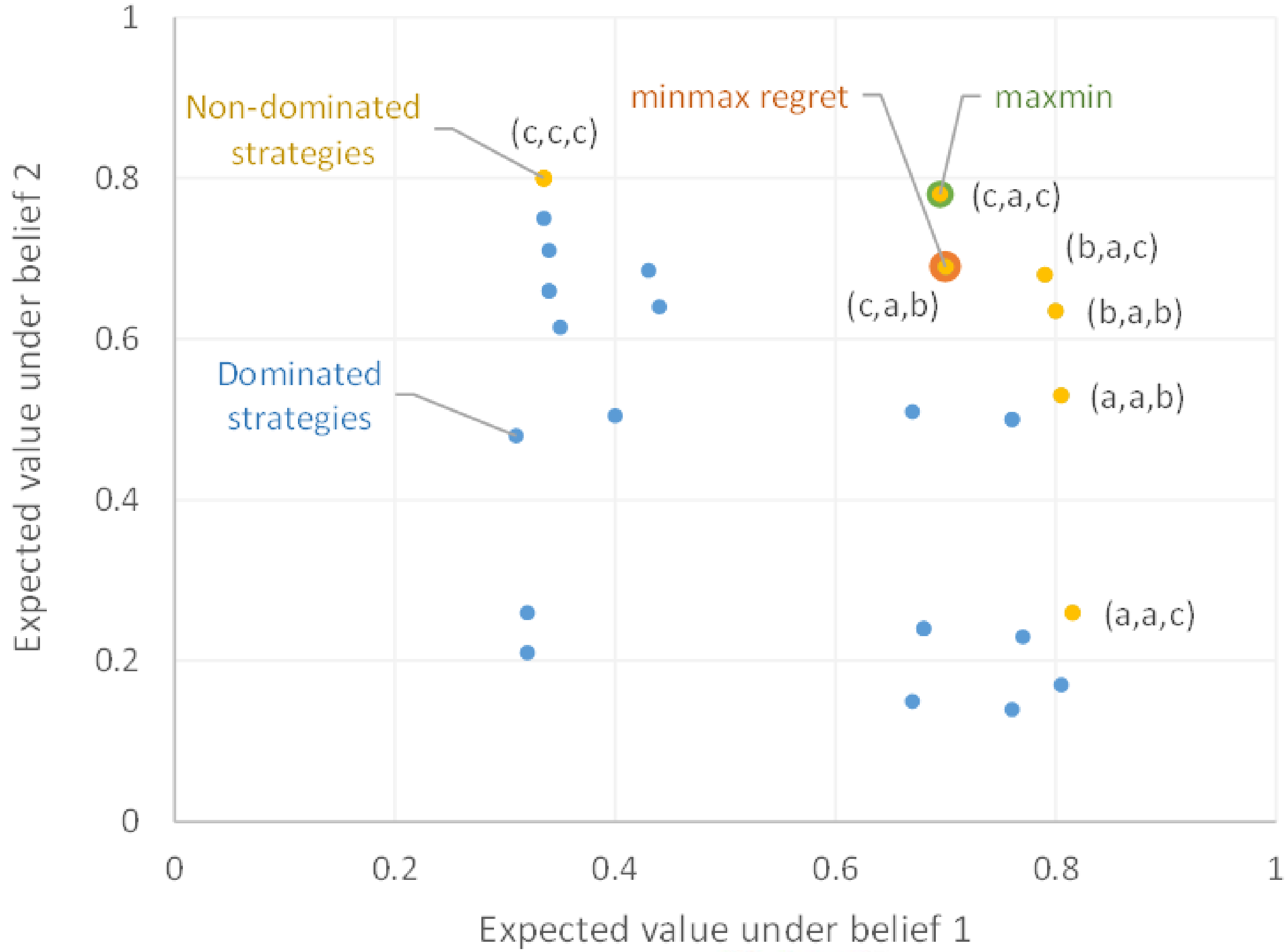


Eckholm & Baker 2019

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

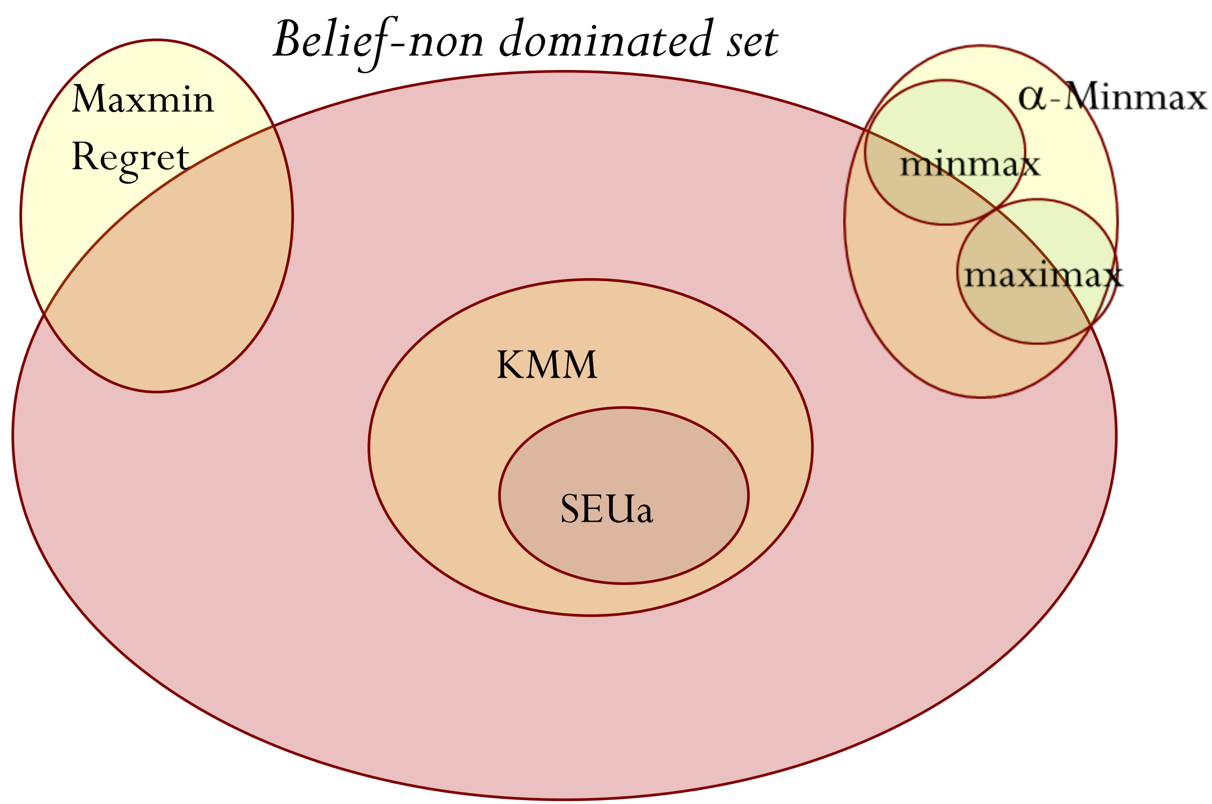
$$\int U(\mathbf{x};z)f(z)\,dz \geq \int U(\mathbf{x};z)g(z) \;\; \forall \mathrm{U} \in \mathrm{V}_S$$

- *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 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

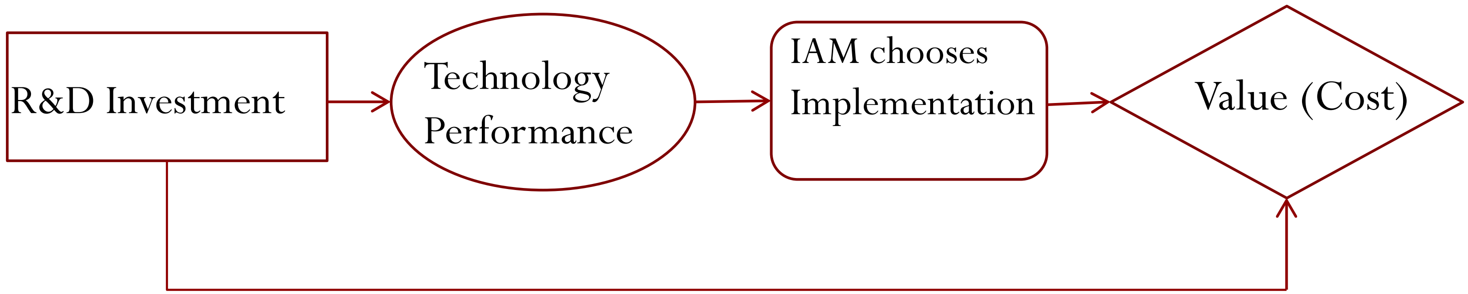
a	b	c	d	e	f
1	0	0	1	1	0
1	0	1	1	1	0
1	0	0	1	1	0
0	0	1	1	0	1
0	0	0	1	0	1
0	0	1	1	0	1

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

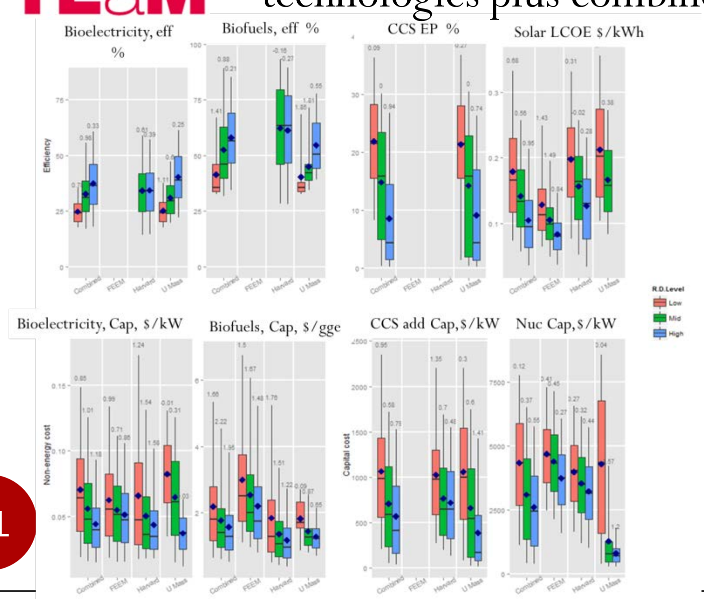
Public energy technology R&D portfolios: Deep parameter uncertainty

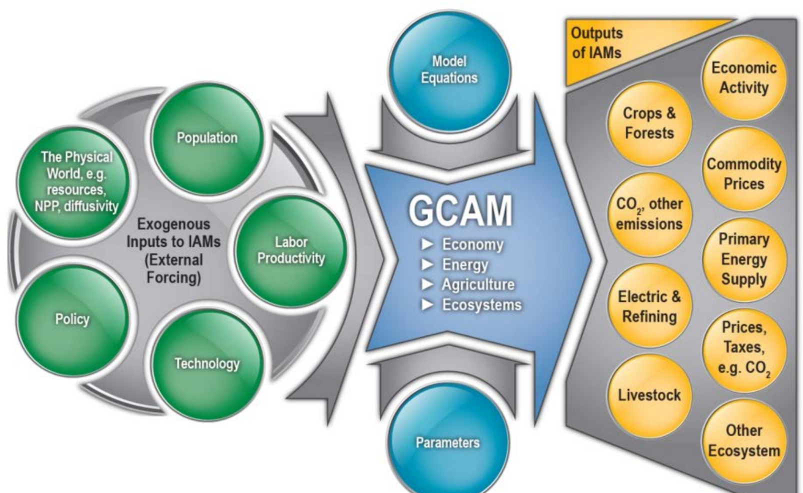
Proof of concept: Energy Technology R&D Portfolio in Response to Climate Change.

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



3 sets of elicitations on 5 technologies plus combined





Results: non-dominated portfolios

Portfolio	Technologies					R&D	Objectives ENPV(Cost in billions of $2005)		
	Solar	Nuc	BF	BE	CCS	($millions)	Harvard	FEEM	UMass
1	Low	Mid	Mid	High	Low	47	22671	25442	15142
2	Low	Mid	Mid	High	Mid	59	21806	24434	15213
3	Mid	Mid	Mid	High	Mid	61	21659	24379	15528
4	Low	Mid	High	High	Mid	75	21654	24188	15720
5	Mid	Mid	High	High	Mid	78	21513	24163	16162
6	Mid	High	Mid	High	Mid	220	21741	24548	15509
7	Low	High	High	High	Mid	234	21770	24327	15509
8	Mid	High	High	High	Mid	237	21588	24345	15813
9	High	Mid	Low	High	High	239	21325	22747	20003
10	High	High	Low	High	High	398	21581	22901	19324

10 out of 243 total are non-dominated

Portfolios	Robustness Concepts			
	SEUa	α-Maxmin	Minmax Regret	KMM (equal weights)
1	Umass	$\alpha = 0$ (Maximax)		
2	Equal weight	$\alpha = 0.1 \ldots 0.6$		Above 32.4
3				
4		$\alpha = 0.7$		6.3- 32.4
5			Minmax Regret	6.0 - 6.2
6				
7				
8				
9	FEEM, Harvard	$\alpha = 0.9, 1$ (Maxmin)		below 4.7
10		$\alpha = 0.8$		4.7 - 6.0

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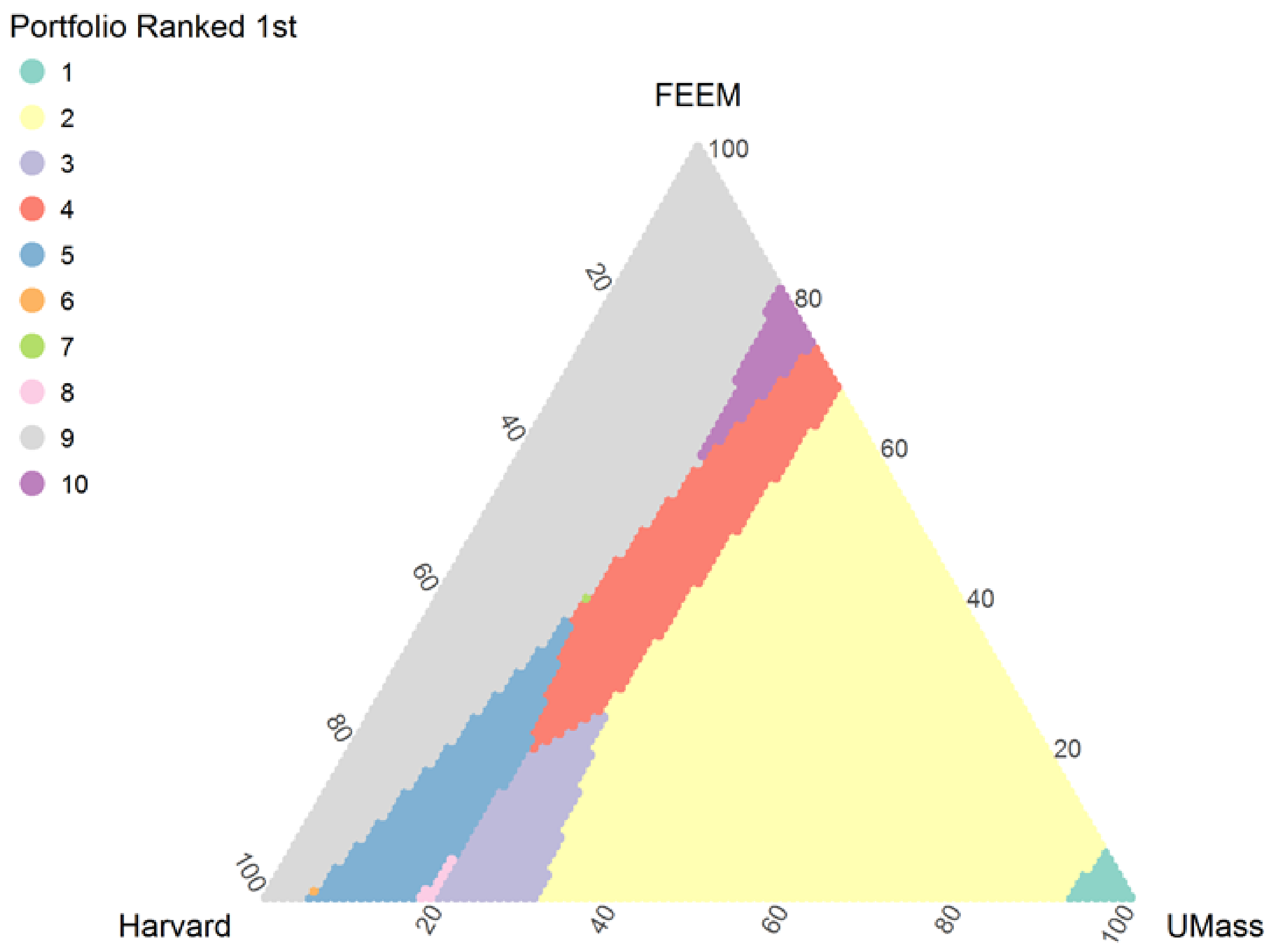
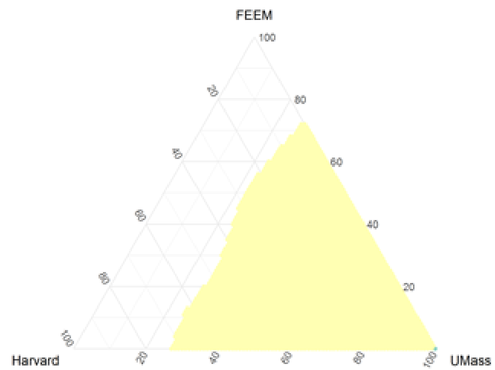
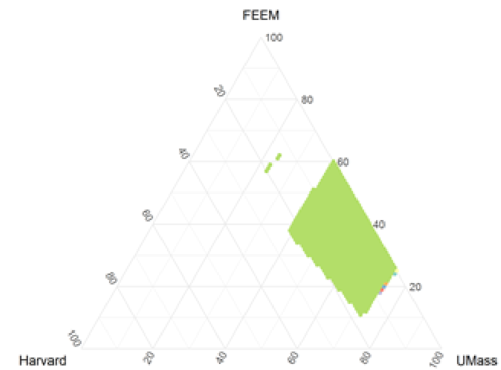
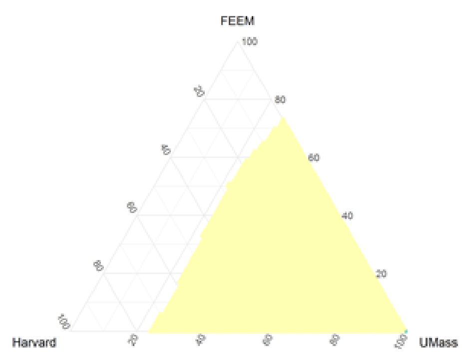
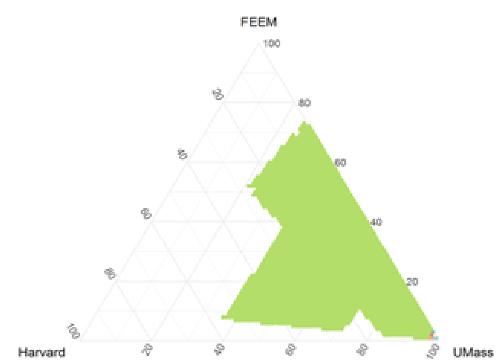
10		$\alpha = 0.8$		4.7 - 6.0

Which Portfolio is ranked first for each weighting



Robustness: In the top 2 or top 3

	Portfolio 2	Portfolio 7
Portfolio is Ranked 1st or 2^{nd}		
Portfolio is Ranked 1^{st}, 2^{nd} or 3^{rd}		

Results: core and exterior projects

Portfolio	Technologies					R&D	Objectives ENPV(Cost in billions of $2005)		
	Solar	Nuc	BF	BE	CCS	($millions)	Harvard	FEEM	UMass
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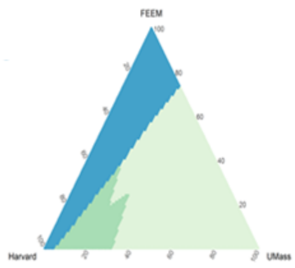
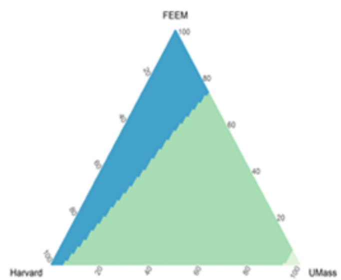
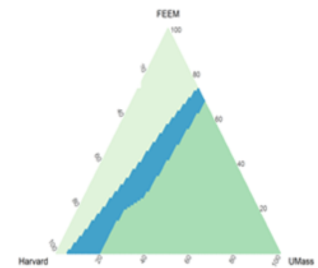
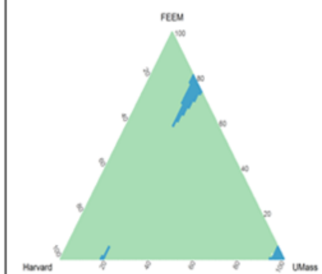
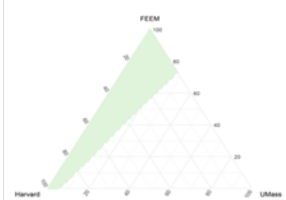
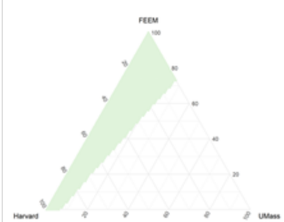
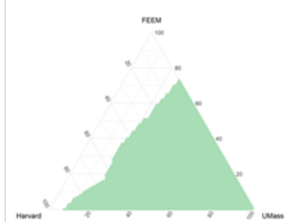
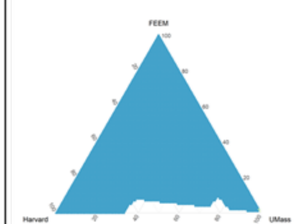
10	High	High	Low	High	High	398	21581	22901	19324

BE high is in core; Nuc low is in exterior

Individual investments on simplex

Solar	CCS	BE	BF	Nuclear
				

Investment Level
- Low
- Mid
- High

	Biofuel L	Biofuel M	Biofuel H
Alternative is in a portfolio is Ranked 1st or 2nd			
Alternative is in a portfolio is Ranked 1st , 2nd or 3rd			

Public energy technology R&D portfolios: Deep model uncertainty

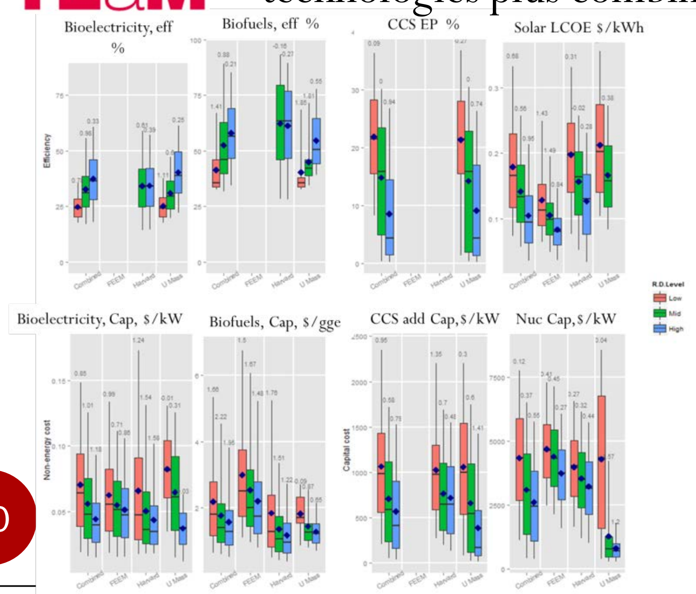
From: *Low carbon energy R&D portfolios that are robust to model uncertainty by* Frankyn Kanyako, Erin Baker, & David Anthoff, 2021

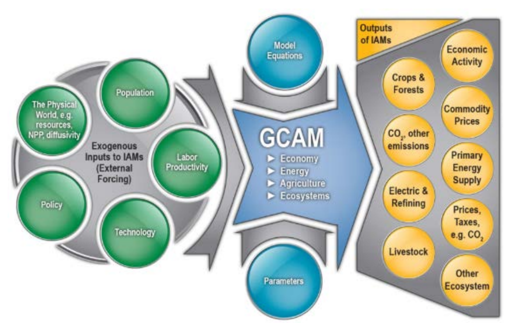
Proof of concept: Energy Technology R&D Portfolio in Response to Climate Change under model uncertainty

Given a climate goal (no policy; $50/tC; $125/tC):

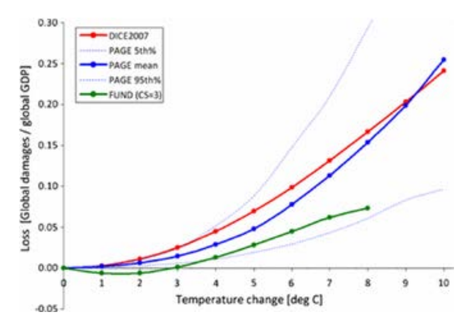
R&D Investment → Technology Performance → GCAM chooses Implementation → Damage Models → Value

3 sets of elicitations on 5 technologies plus combined





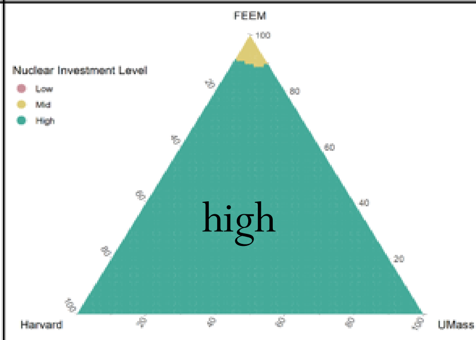
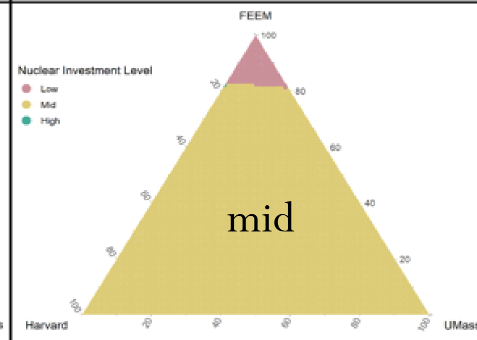
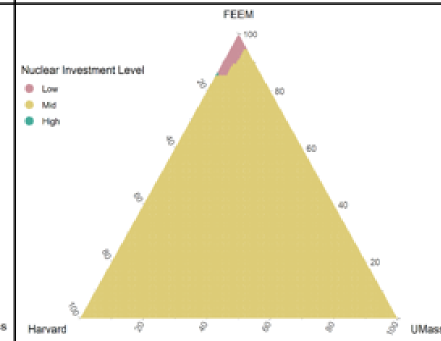
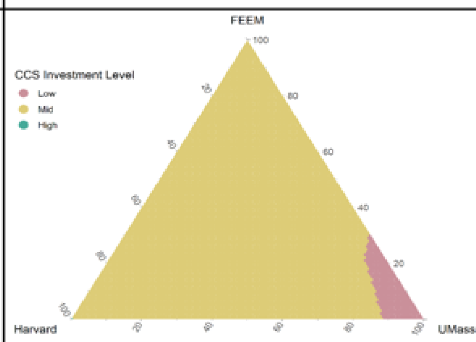
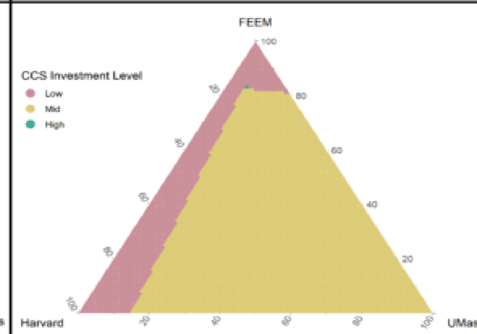
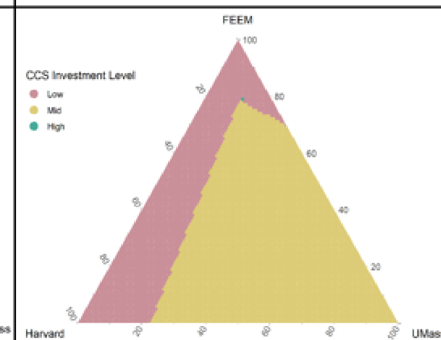
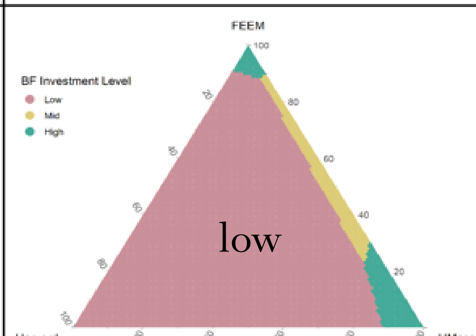
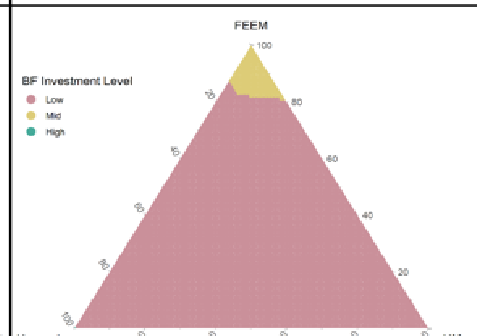
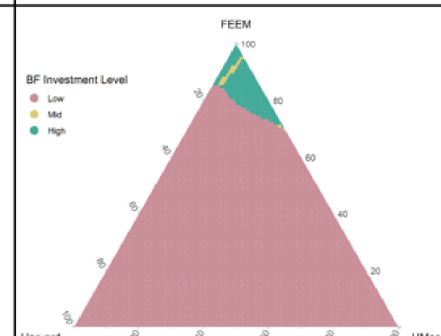
DICE; PAGE; FUND



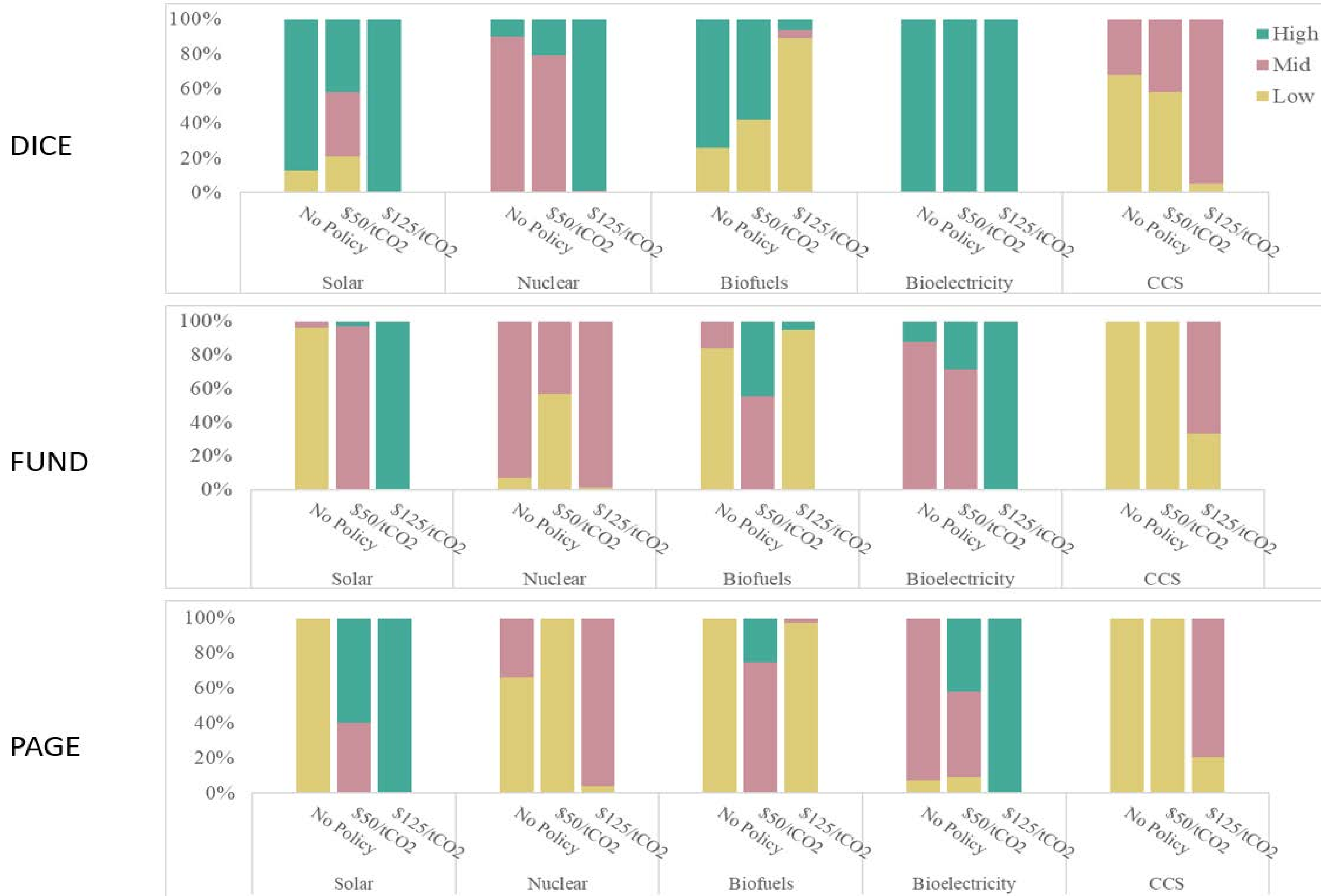
Results: Solar and Bio-electricity are robust (under \$125/tCO_2)

Portfolio	Technologies					Total R&D (In million USD \$2019)
	Solar	Nuclear	Biofuels	Bio-elec	CCS	
1	High	Low	Low	High	Low	80.75
2	High	Low	Mid	High	Low	83.66
3	High	Low	Low	High	Mid	95.88
4	High	Mid	Low	High	Low	97.42
5	High	Mid	Mid	High	Low	100.33
6	High	Low	High	High	Low	105.02
7	High	Mid	Low	High	Mid	112.55
8	High	Mid	Mid	High	Mid	115.47
9	High	Mid	High	High	Low	121.69
10	High	Mid	High	High	Mid	136.82
11	High	High	Low	High	Low	301.69
12	High	Mid	Low	High	High	306.56
13	High	High	Low	High	Mid	316.82
14	High	High	Mid	High	Mid	319.73
15	High	High	High	High	Low	325.96
16	High	High	Low	High	High	510.82

Models are most important for nuclear

	DICE	PAGE	FUND
Nuclear			
CCS			
Biofuels			

Role of policies



Some portfolios are in non-dominated set for all 3 policies

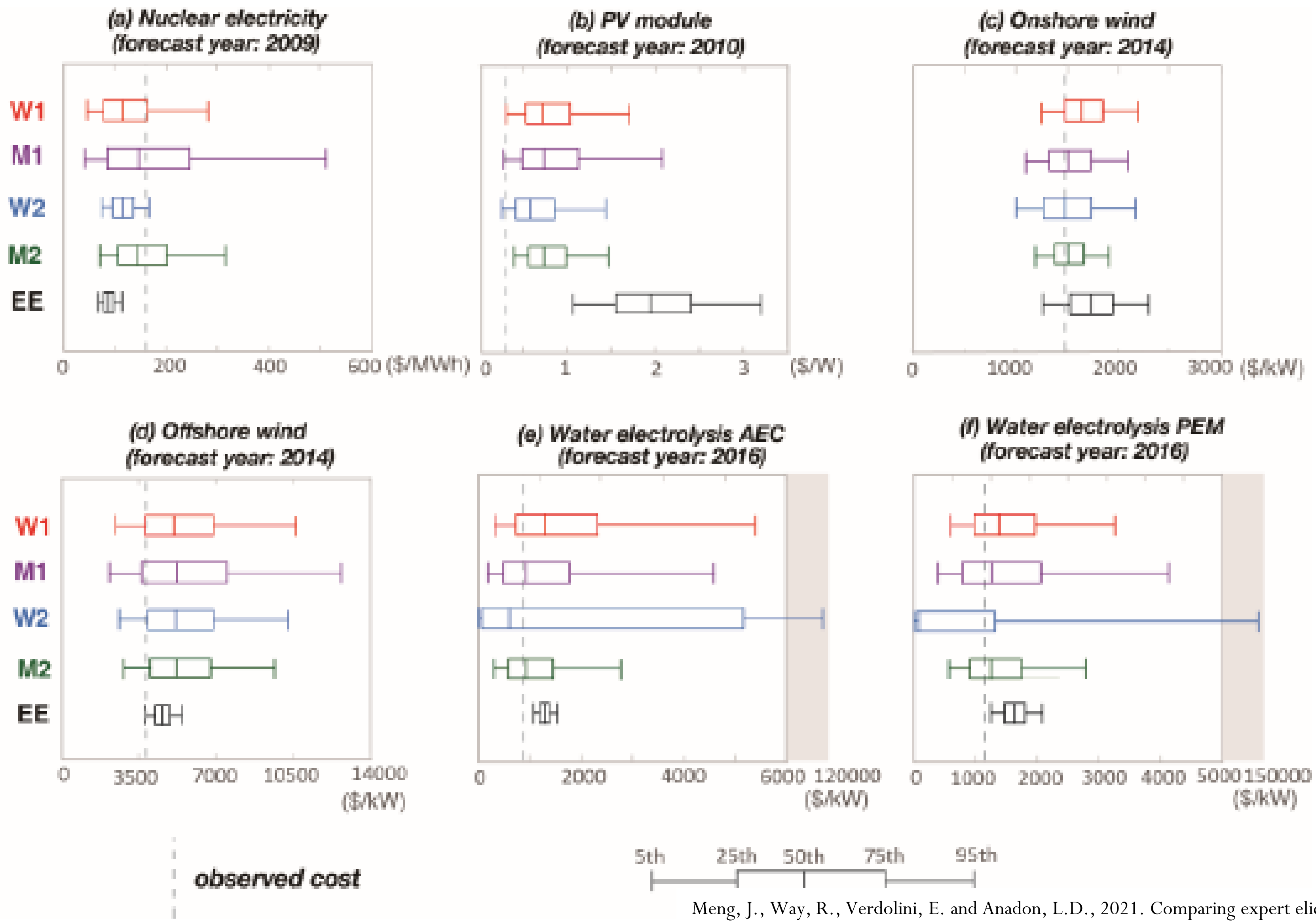
Portfolio	Technologies					Total R&D (In million USD $2019)
	Solar	Nuclear	Biofuels	Bio-elec	CCS	
1	High	Low	Low	High	Low	80.75
2	High	Low	Mid	High	Low	83.66
3	High	Low	Low	High	Mid	95.88
4	High	Mid	Low	High	Low	97.42
5	High	Mid	Mid	High	Low	100.33
6	High	Low	High	High	Low	105.02
7	High	Mid	Low	High	Mid	112.55
8	High	Mid	Mid	High	Mid	115.47
9	High	Mid	High	High	Low	121.69
10	High	Mid	High	High	Mid	136.82
11	High	High	Low	High	Low	301.69
12	High	Mid	Low	High	High	306.56
13	High	High	Low	High	Mid	316.82
14	High	High	Mid	High	Mid	319.73
15	High	High	High	High	Low	325.96
16	High	High	Low	High	High	510.82

Conclusions

- Deep uncertainty is important in climate change, technology policy, and other issues.
- Analysis under deep uncertainty
  - Tradeoffs between flexibility, external consistency, internal consistency
  - 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.

Backup slides

Parameter Uncertainty: Data-based vs elicitation-based forecasts



Meng, J., Way, R., Verdolini, E. and Anadon, L.D., 2021. Comparing expert elicitation and model-based probabilistic technology cost forecasts for the energy transition. Proceedings of the National Academy of Sciences, 118(27).

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 .

Models are most important for nuclear

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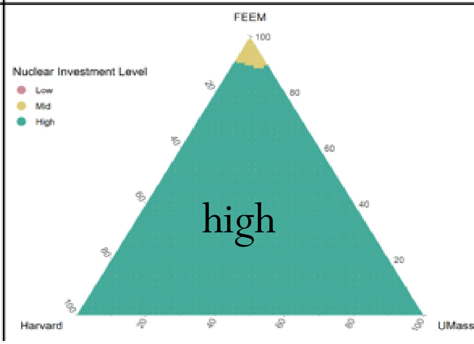
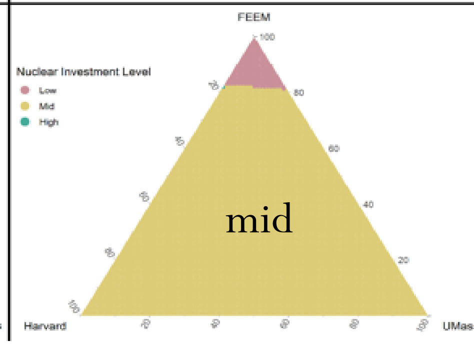
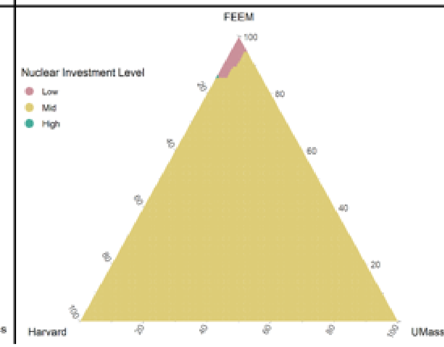
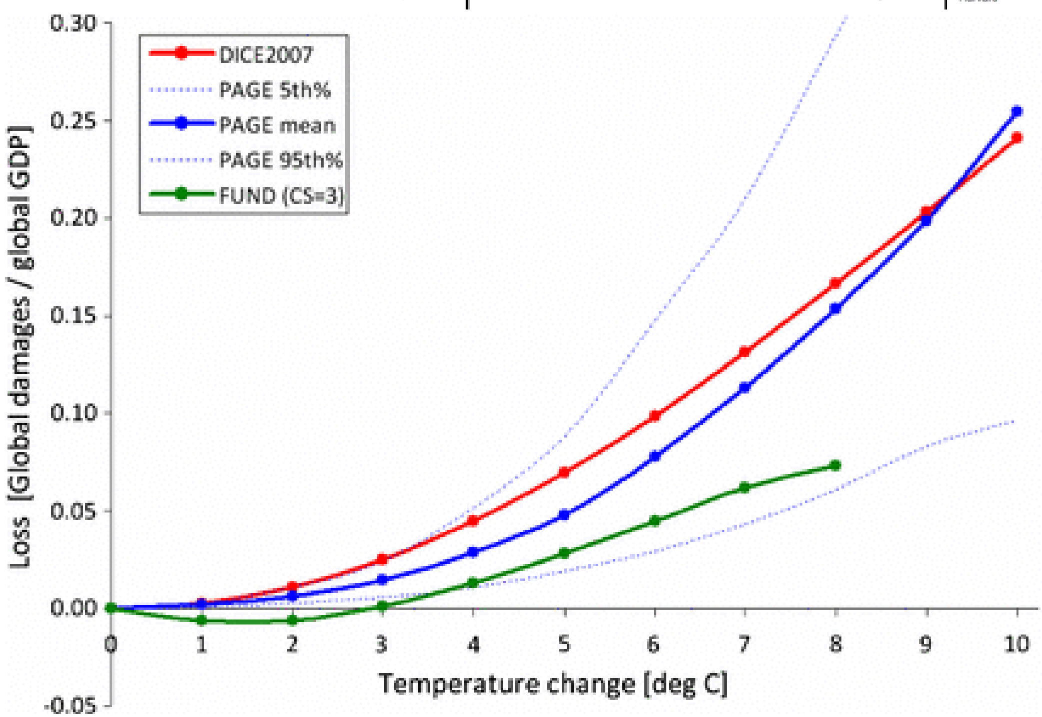
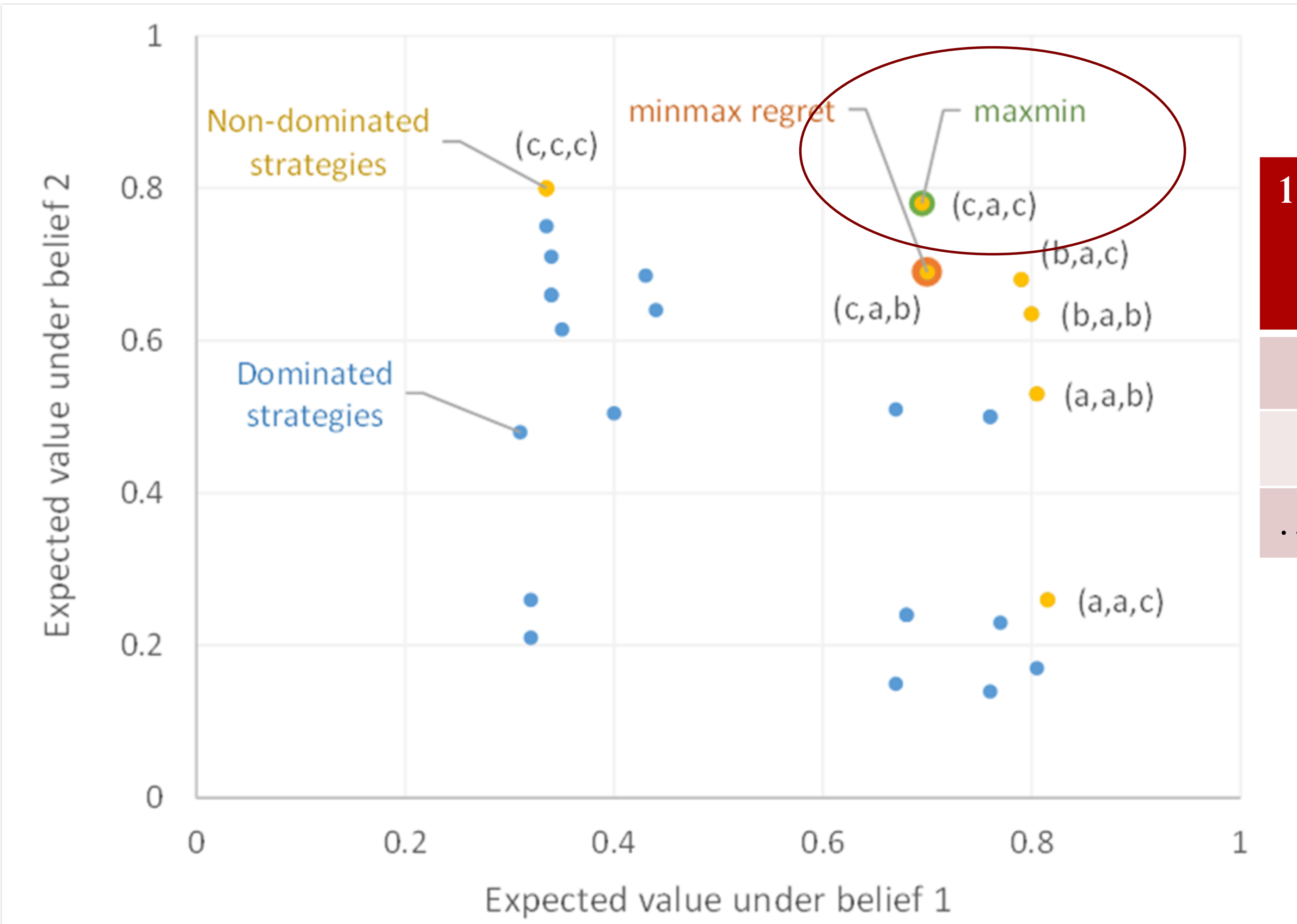
Nuclear			



Deep Uncertainty and Dynamic Consistency

From: Ekholm, Tommi; Erin Baker, *Multiple Beliefs, Dominance, and Dynamic Consistency*, **Management Science**

What is dynamic inconsistency?



Strategy:

1st	2nd, signal 1	2nd, signal 2
c	a	c
c	a	b
…		

Dynamic inconsistency: Theoretical results

Definitions

1. *Fallacious Inconsistency*:
   Second-stage action of an "optimal" strategy is sub-optimal in the second stage
2. *Fallible Inconsistency*:
   Second-stage action that wasn't "optimal" in the first stage is optimal in the second stage

Theoretical results

- The two definitions are equivalent for complete orders
  - Non-EU are subject to both
  - SEU avoids both
- Belief Dominance:

$$\boxed{ND_1 \Rightarrow ND_2}$$

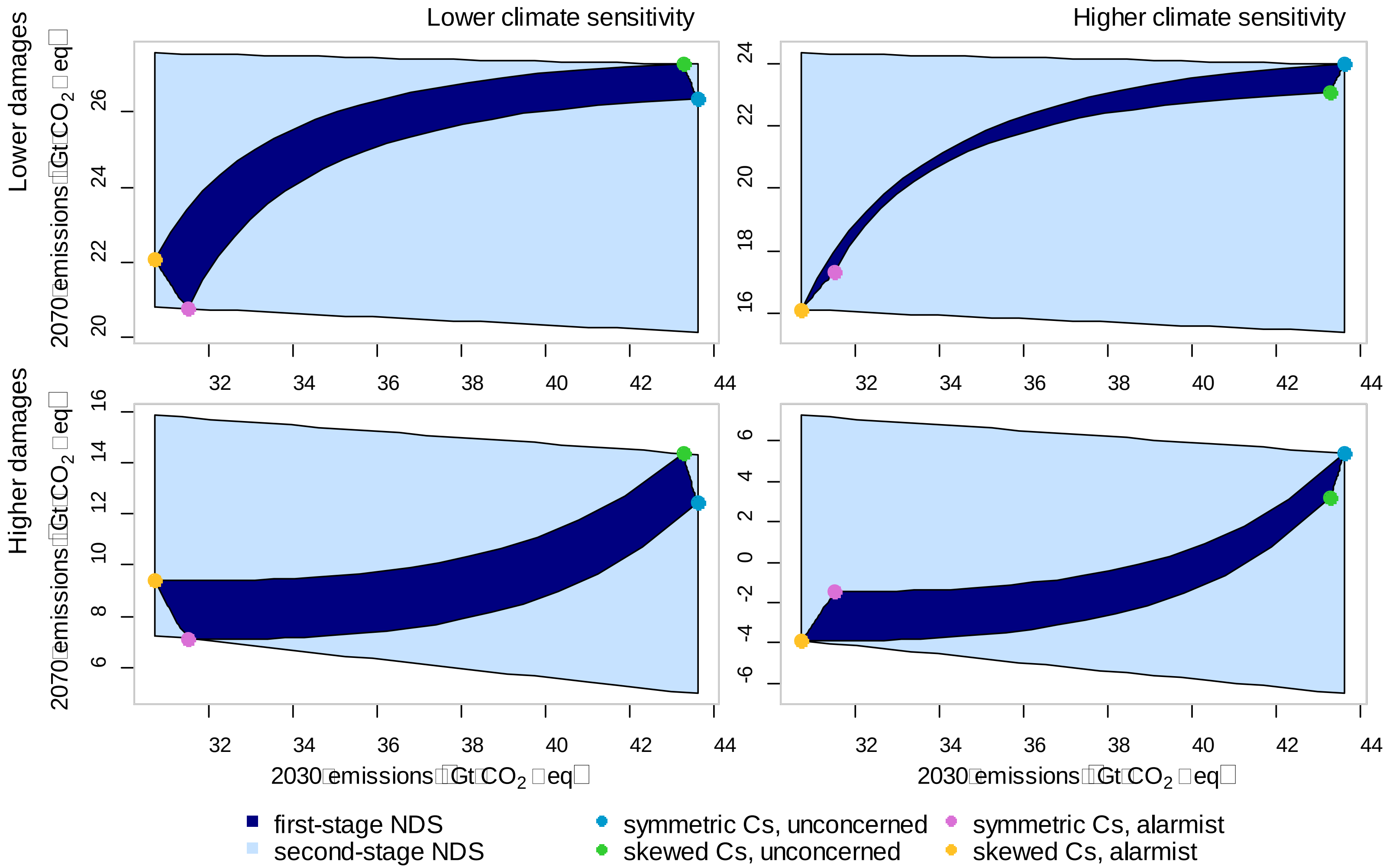
avoids Fallacious Inconsistency;

but

$$\boxed{ND_1 \not\Leftarrow ND_2}$$

is subject to Fallible Inconsistency

Example: Non-dominated mitigation strategies



Decision making under conflicting beliefs induces a tradeoff between flexibility and consistency

	Flexibility for decision makers	Weak Consistency	Strong Consistency
Belief Dominance	Y	Y	N
Subjective Expected Utility	N	Y	Y
Non-expected utility	N	N	N