Integrating uncertainty into public energy R&D decisions

Valentina Bosetti

Bocconi University, FEEM, CMCC

IEB, 19 January 2017

Background

- Huge transformations in the energy system are implied by a 2°C target (Kriegler et al., 2013; Tavoni et al., 2013; Calvin et al., 2012; Clarke et al., 2009).
- Technology availability plays a major role on feasibility and costs of mitigation targets (Krey and Clarke, 2011; Kriegler et al., 2016).
- Recent events, including the Paris Agreement, Mission Innovation, the Breakthrough Energy Coalition, and the Sustainable Development goals, imply that public investment in innovation will maintain a central role
- Need for:
  - improving currently known energy technologies;
  - creating new technologies altogether.

What is the role of future R&D investments in clean energy technologies under the challenge of a 2°C (1.5°) target?

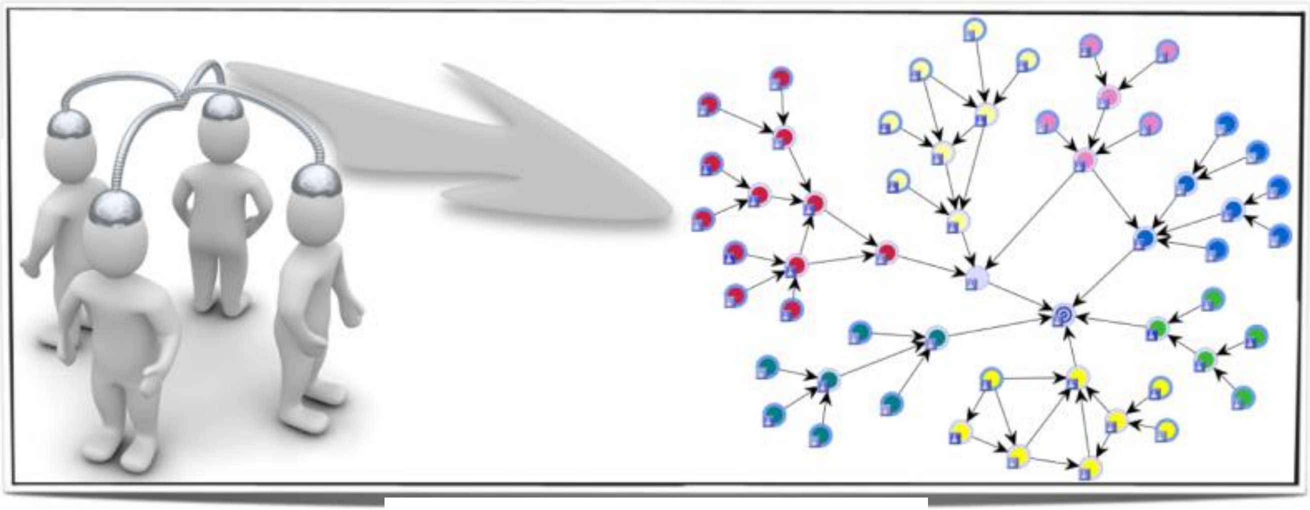
Roadmap of Presentation

1. Future energy cost uncertainties
2. Robust Portfolio Decision Analysis to investigate the Energy R&D Portfolio problem

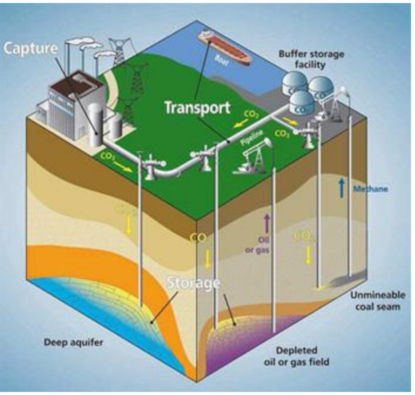
Future energy cost uncertainties

Bosetti, V. , L.D. Anadon, L.D., E. Baker, E. Verdolini, L. Aleluia Reis (2016) "The Future of Energy Technologies: An Overview of Expert Elicitations". GGKP Research Committee on Technology and Innovation Working Paper 01.

Expert Elicitation on energy technologies



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



Expert Elicitations

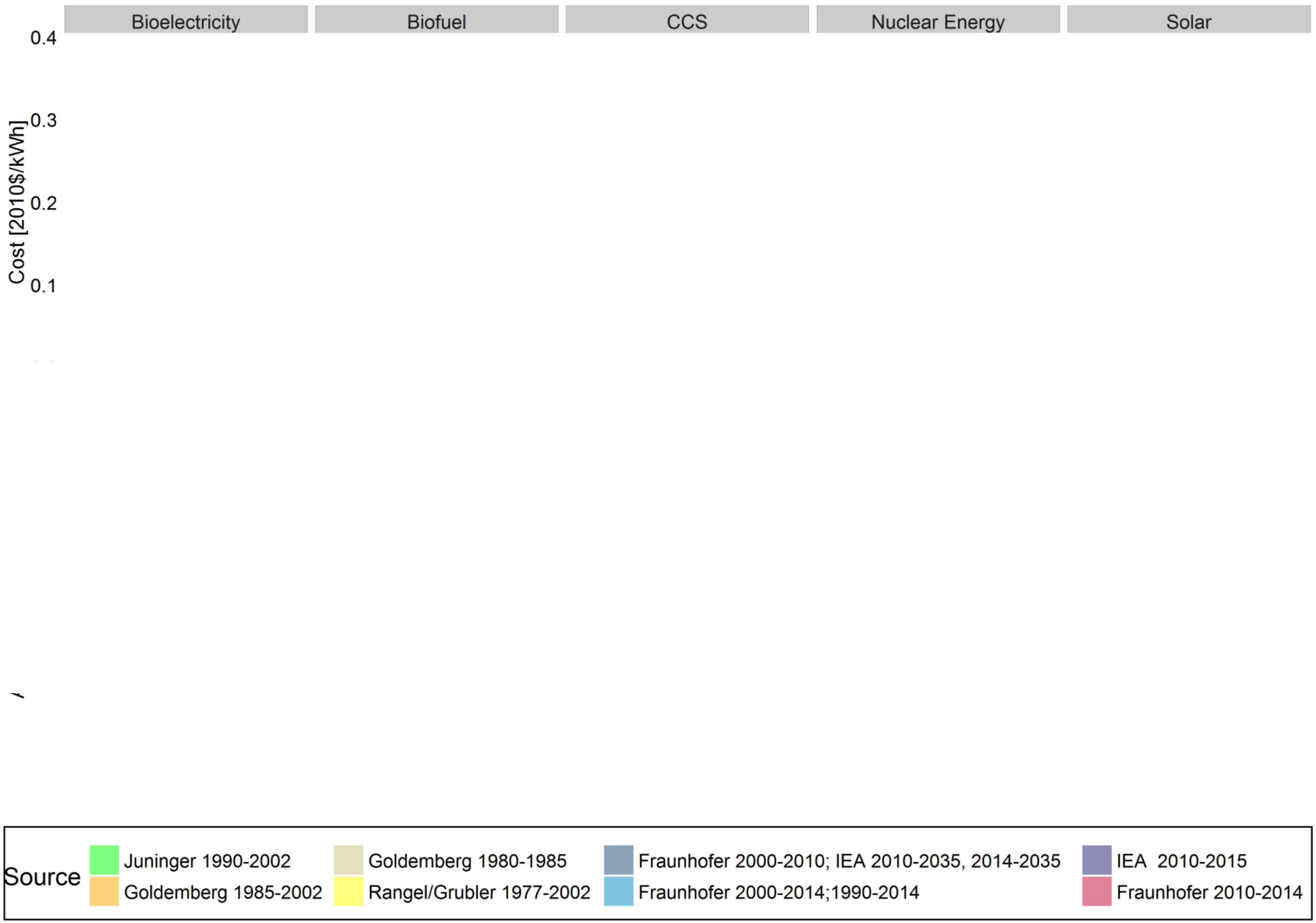
- Expert elicitations are structured processes for eliciting subjective probability distributions from scientists, engineers, and other analysts who are knowledgeable about particular metrics of interest.
- Over the past 8 years, various research groups have carried out expert elicitations to collect experts’ views on the future cost and performance of a range of energy technologies and how they might be affected by R&D.
- This source of data complements econometric studies looking at the past evolution of technology costs.
- Several challenges and potential biases.
- Still in some cases it is the only source of information and might be better than modellers’ best guesses.

Expert Elicitations on Future energy technologies

Research Group	Publication
Bioelectricity	
UMass	Baker et al. (2008a)
Harvard*	Anadón et al. (2011); Anadón, et al. (2014a)
FEEM*	Fiorese et al. (2014)
Biofuel	
UMass	Baker and Keisler (2011)
Harvard*	Anadón et al. (2011); Anadón, et al. (2014a)
FEEM*	Fiorese et al. (2013)
Solar	
UMass	Baker et al 2009a*
Harvard*	Anadón et al. (2011); Anadón, et al. (2014a)
FEEM*	Bosetti et al. (2012) *
NearZero	Inman (2012)
CMU*	Curtright et al. (2008)
Nuclear	
UMass	Baker et al (2008b)
Harvard* and FEEM*	Anadón et al. (2012)
CMU*	Abdulla et al (2013) - GEN III only

Research Group	Publication
CCS	
UMass	Baker et al. (2009b)
Harvard*	Chan et al. (2011)
Duke	Chung et al (2011)
UMass	Jenni et al (2013)
FEEM	Ricci et al. (2014)
CMU	Rao et al. (2006)
NRC	NRC (2007)
Vehicles	
UMass	Baker et al. (2010)
FEEM	Catenacci et al. (2013)
Harvard	Anadón et al. (2011); Anadón, et al. (2014a)
Other	
Harvard - **Utility scale storage**	Anadón et al. (2011); Anadón, et al. (2014a)
NRC – **IGCC**	NRC (2007)
Stanford - **Natural Gas**	Bistline (2013)
GHG MI – **Wind**	Gillenwater (2013)
UCL - **Low Carbon Energy**	Usher and Strachan (2013)

2030 Costs Conditional on RD scenarios



Lessons Learnt

- The elicited costs differ substantially across studies within the same technology categories (design of survey)
- Some of the 2030 costs provided by experts are higher than the average 2010 values (nuclear)
- Median costs, along with a large part of the future cost distribution, are lower than the 2010 cost for the different RD&D scenarios
- Relationship between past experience and experts' beliefs
- **RD&D impacts median cost and the full distribution of costs**
- **Technologies differ in their response to RD&D**, with solar, for example, showing the most consistent response to increased RD&D
- **Expert forecasts show decreasing returns to scale in RD&D**

Use of EE Data

- Basis for assessment of technology-specific potential for learning, bottlenecks or regulatory issues (e.g. Near Zero and the Breakthrough Energy Coalition)
- <u>However</u>, impact of RD&D on technological change is only one part of designing portfolios. Additional critical information:
  - Technological substitutes (e.g. nuclear and carbon capture and storage) or complementarities (e.g., solar and storage);
  - Interactions with climate policies and other government objectives
- For these reasons, it makes sense to use this information together with IAMs

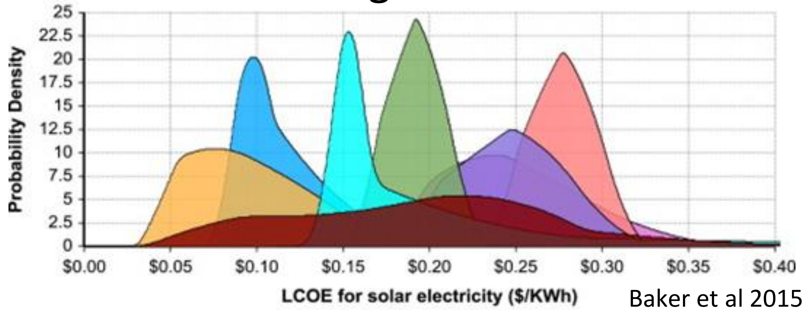
Robust Portfolio Decision Analysis to investigate the Energy R&D Portfolio problem

Baker, Bosetti, Salo, (2016) Finding common ground when experts disagree: Belief dominance over portfolios of alternatives, FEEM Working Paper/Nota di Lavoro 46.2016

Deep Uncertainty

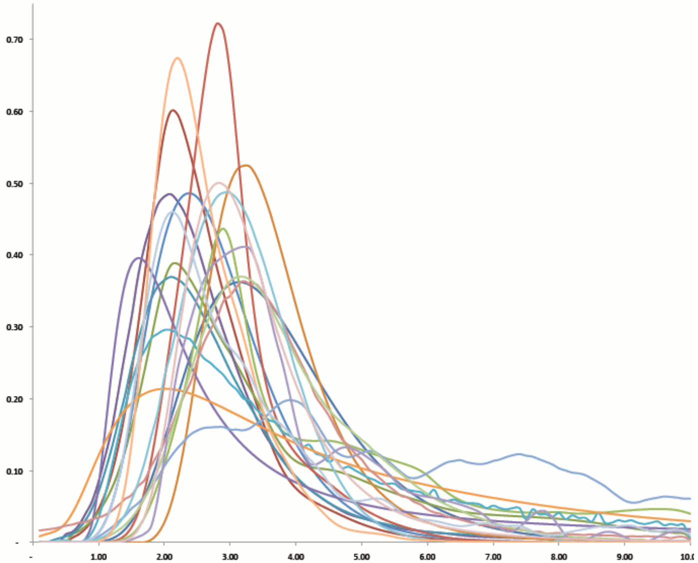
- Conflicting experts or models

Technical change



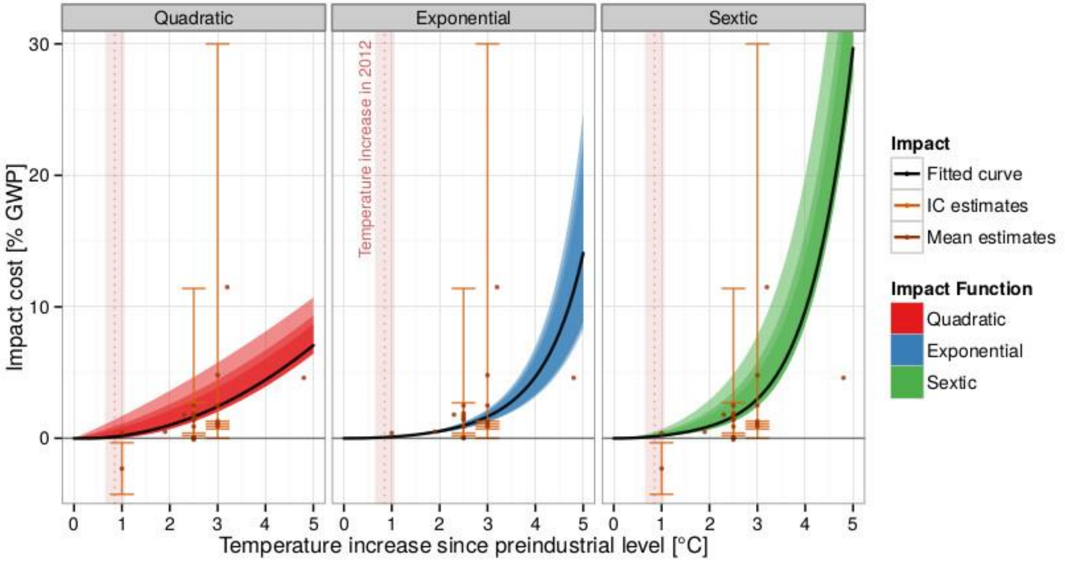
Baker et al 2015

Climate Sensitivity



(Meinshausen et al. 2009)

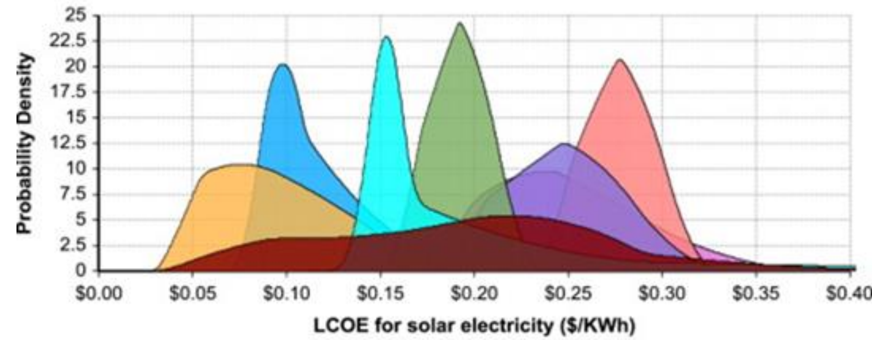
Climate damages

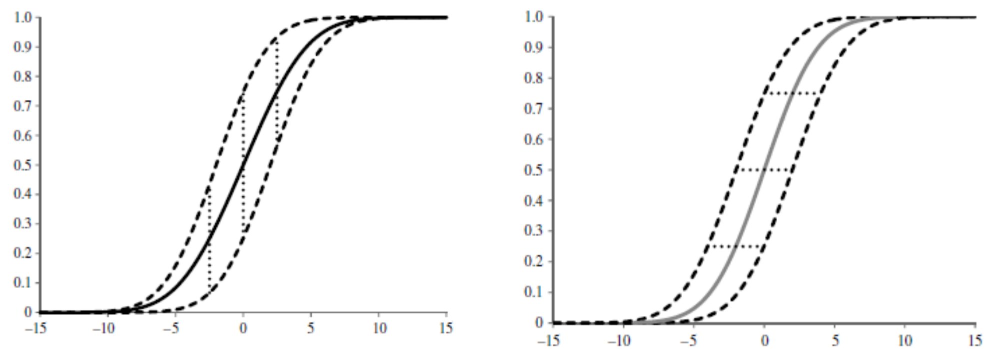


(Drouet et al 2015)

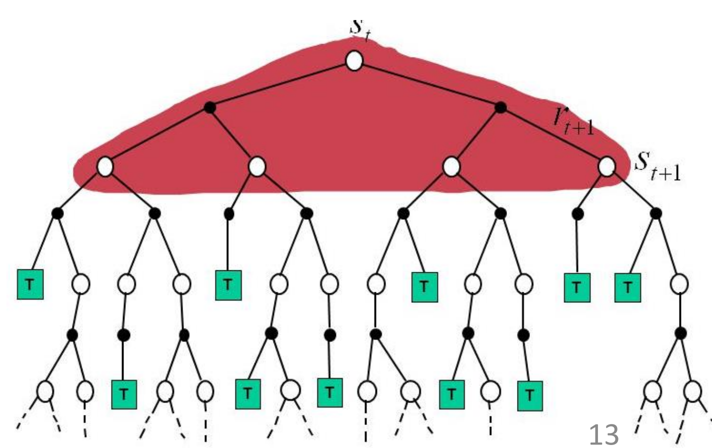
Deep Uncertainty - Approaches

- Aggregate beliefs (Clemen & Winkler; Cooke; Lichtendahl et al.)
- Expected Utility (von Neuman-Morgenstern, Savage)
- Dynamic Decision making under uncertainty and learning : (Kolstad, Baker, Lemoine, Pyndyck)
- Criticism:
    - “lacking external consistency”
    - Mathematically resolve disagreement resulting in a single best recommendation



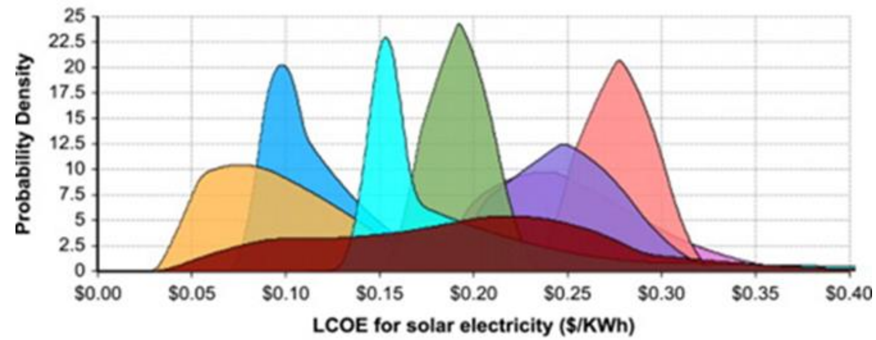


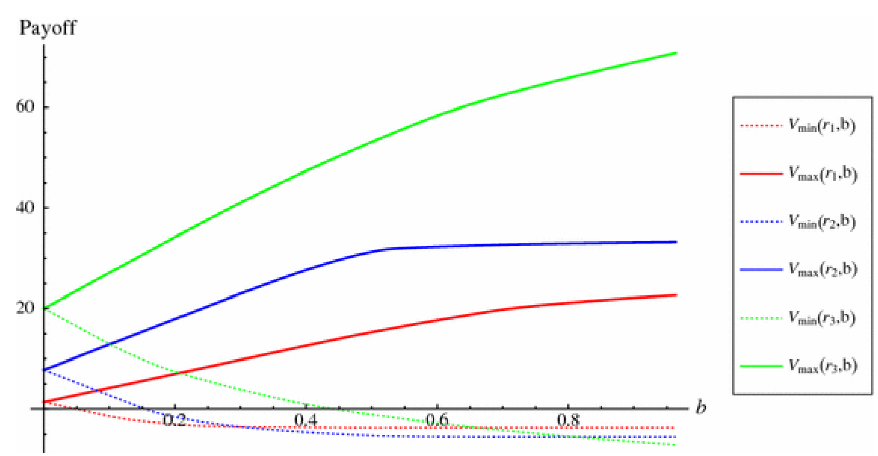
Lichtendalh et al 2013



Deep Uncertainty - Approaches

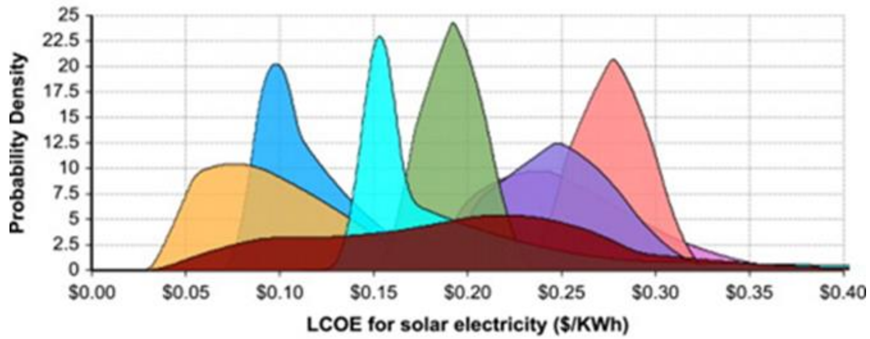
- Retain individual beliefs
- Synthesize them in the context of a decision
- Ambiguity Aversion, robust optimization
- Criticism:
  - Beliefs are not portable
  - “Lacking internal consistency”
  - Mathematically resolve disagreement resulting in a single best recommendation



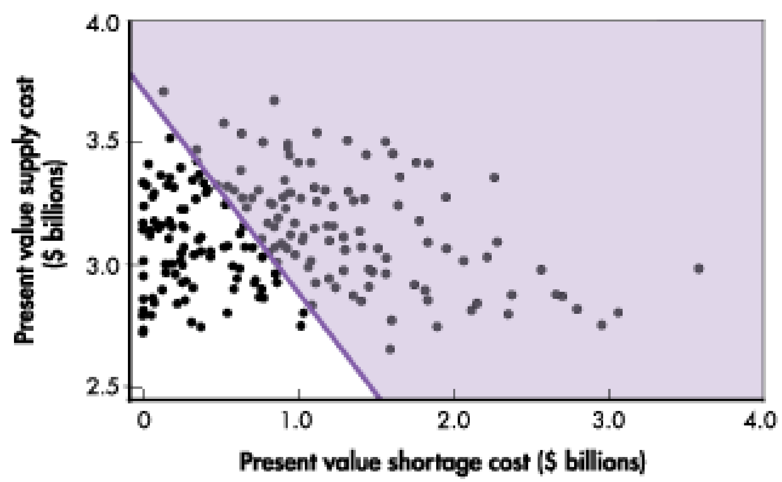


Athanassoglou and Bosetti 2015

Deep Uncertainty - Approaches



- Retain individual beliefs
- Synthesize them 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" 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.

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, …}

- 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.

RPDA: theoretical framework

- Belief dominance
- From non-dominated portfolios to robust individual alternatives

Belief Dominance: Terminology

- Alternatives (R&D portfolios), **x**
- Uncertain outcomes (R&D effectiveness), z
- Preferences, U(**x**,z) (e.g. total cost of abatement)
- Expected utility $V(\mathbf{x}, f) \equiv \int U(\mathbf{x}, z) f(z, \mathbf{x})\, dz$

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

Belief Dominance

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

$$V(\mathbf{x}, f) \geq V(\mathbf{x}', f) \;\; \forall f \in \Phi$$

and the inequality is strict for at least one *f*.

*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

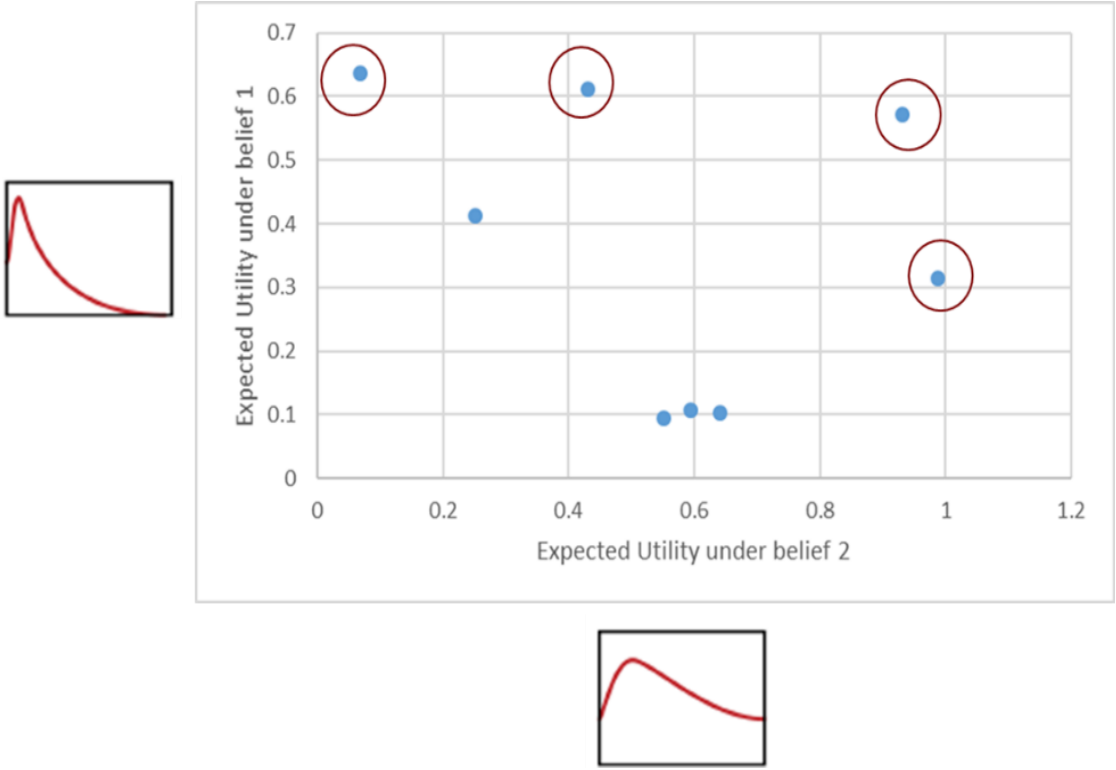
$$\int U(\mathbf{x};z)f(z)dz \geq \int U(\mathbf{x};z)g(z) \;\; \forall \mathrm{U} \in \mathrm{V}_S$$

- *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 belief-dominates it.



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 $\mathbf{x} \equiv (x_1, \ldots, x_N)$
- Let ND = {non-dominated portfolios}

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

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

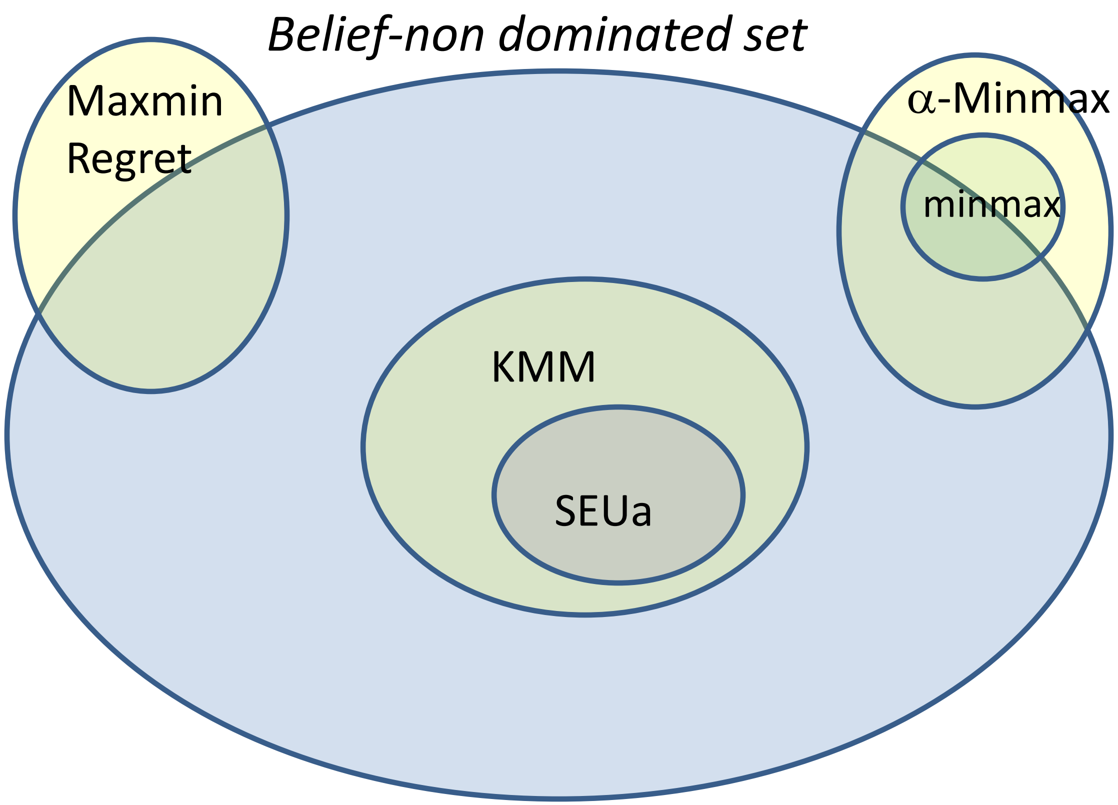
$$bord \equiv \{i \mid i \notin core \text{ and } i \notin ext\}$$

Individual Projects:	a	b	c	d	e	f
Portfolios						
1	1	0	0	1	1	0
2	1	0	1	1	1	0
3	1	0	0	1	1	0
4	0	0	1	1	0	1
5	0	0	0	1	0	1
6	0	0	1	1	0	1

exterior core

Belief non-dominance encompasses robustness concepts

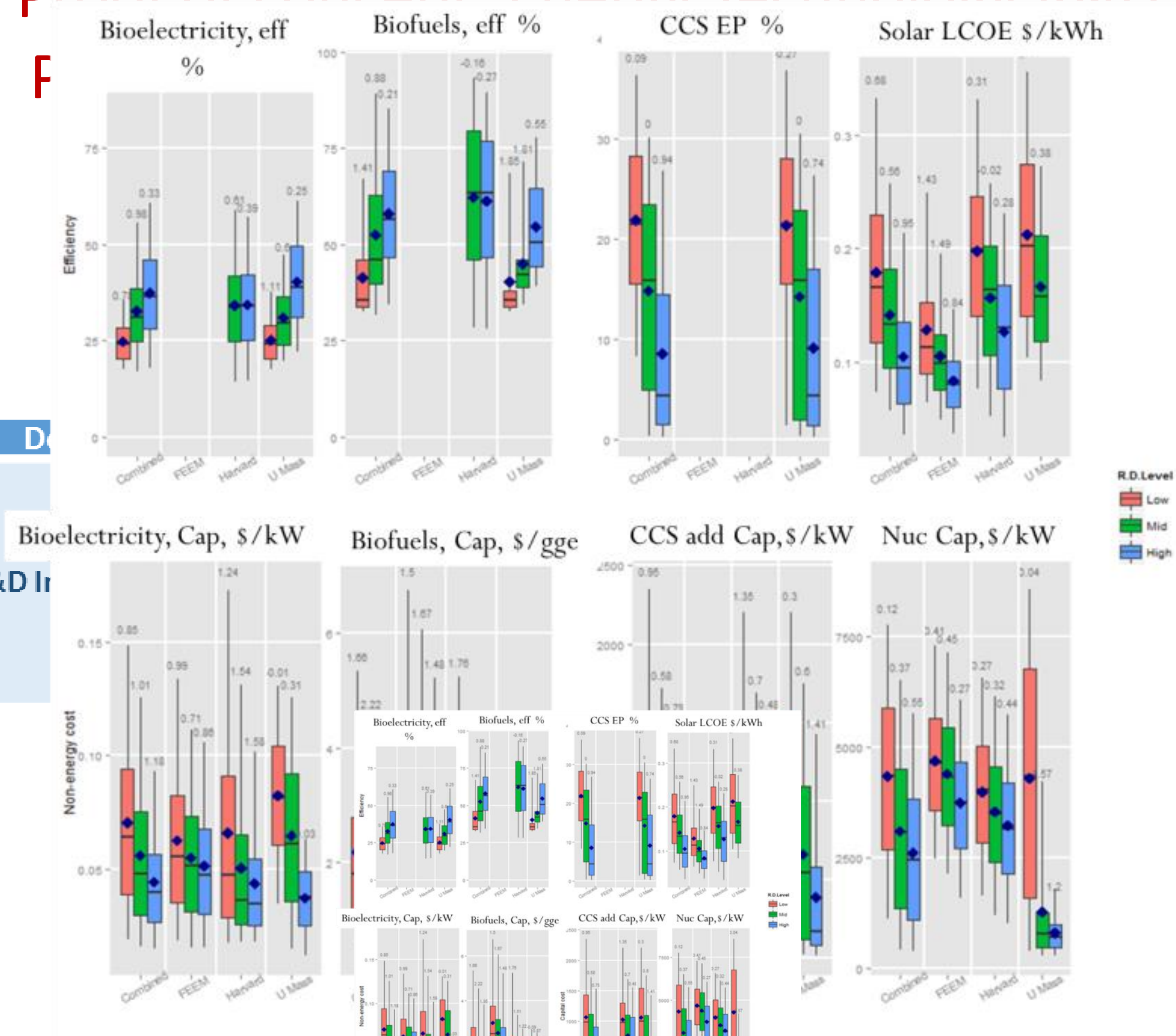
Theorem: If there is at least one optimal solution x* to robustness concept C, then at least one optimal solution to robustness concept C is in the belief-non-dominated set.



Proof of concept: Public energy technology R&D portfolios

Proof of concept: Energy Technology R&D

F



D

R&D I

The computational model

The discrete version of the objective function in the previous equation, given a specific (discrete) probability disctribution, f_τ, is:

$$H\left(x;\tau\right) \equiv \sum_{l=1}^{1000} f_\tau\left(\mathbf{z}_l;\mathbf{x}\right)\left\{C\left(\mathbf{z}_l\right)+\kappa B\left(\mathbf{x}\right)\right\}$$

A vector **x** is defined by level of investment in 5 technologies: solar, nuclear, CCS, bio-elec, bio-fuel.

Level of investments can be low, mid, high.

z_l are the realizations of technology values

We say that a portfolio **x** *belief dominates* **x'** if $H(\boldsymbol{x};\tau) \geq H(\boldsymbol{x}';\tau)$ for all τ, with a strict inequality for at least one of the beliefs. A portfolio **x** is non-dominated if there is no portfolio that dominates it and it is strictly better than at least one portfolio.

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

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

BE high is in core; Nuc low is in exterior

Other Robustness Concepts

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

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

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

core = {BE high; CCS mid}

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

Future work – When Models Disagree

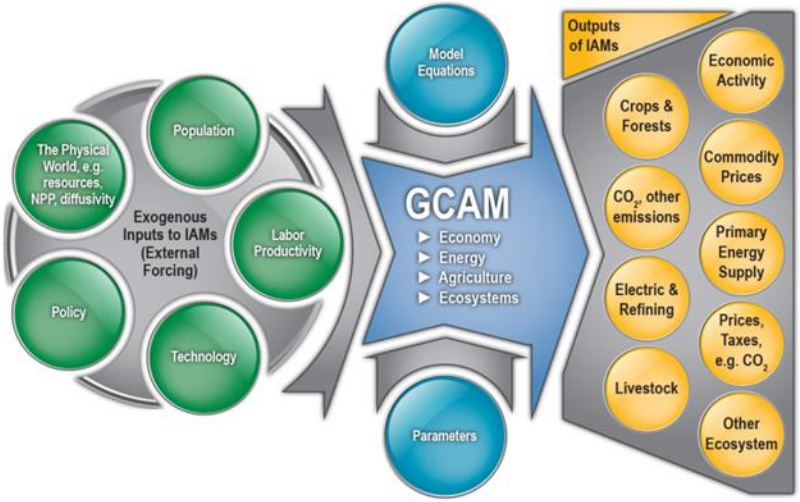
- Model uncertainty and parametric uncertainty

$$\mathrm{H}(\mathbf{x};\tau,m)=\min_{\mathbf{x}}\int U(\mathbf{x},\mathbf{z},m)f_{\tau}(\mathbf{z},\mathbf{x})\,d\mathbf{z}$$

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

A World Induced Technical Change Hybrid Model

IIASA
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.

Way Forward

- Systematically improve, experiment with, and harmonize expert elicitations
- Use multiple models to approximate the value function (as in Gillingham, et al. 2015 NBER)
- Explore the role of strategic international interactions as well as public versus private
- Explore portfolios in a multicriteria settings

Comparison to Robustness Concepts

Let C = {Maxmin, MinMax Regret, a-maxmin, KMM, CEU, SEUa}

A solution is C-optimal, if it is optimal under robustness concept C

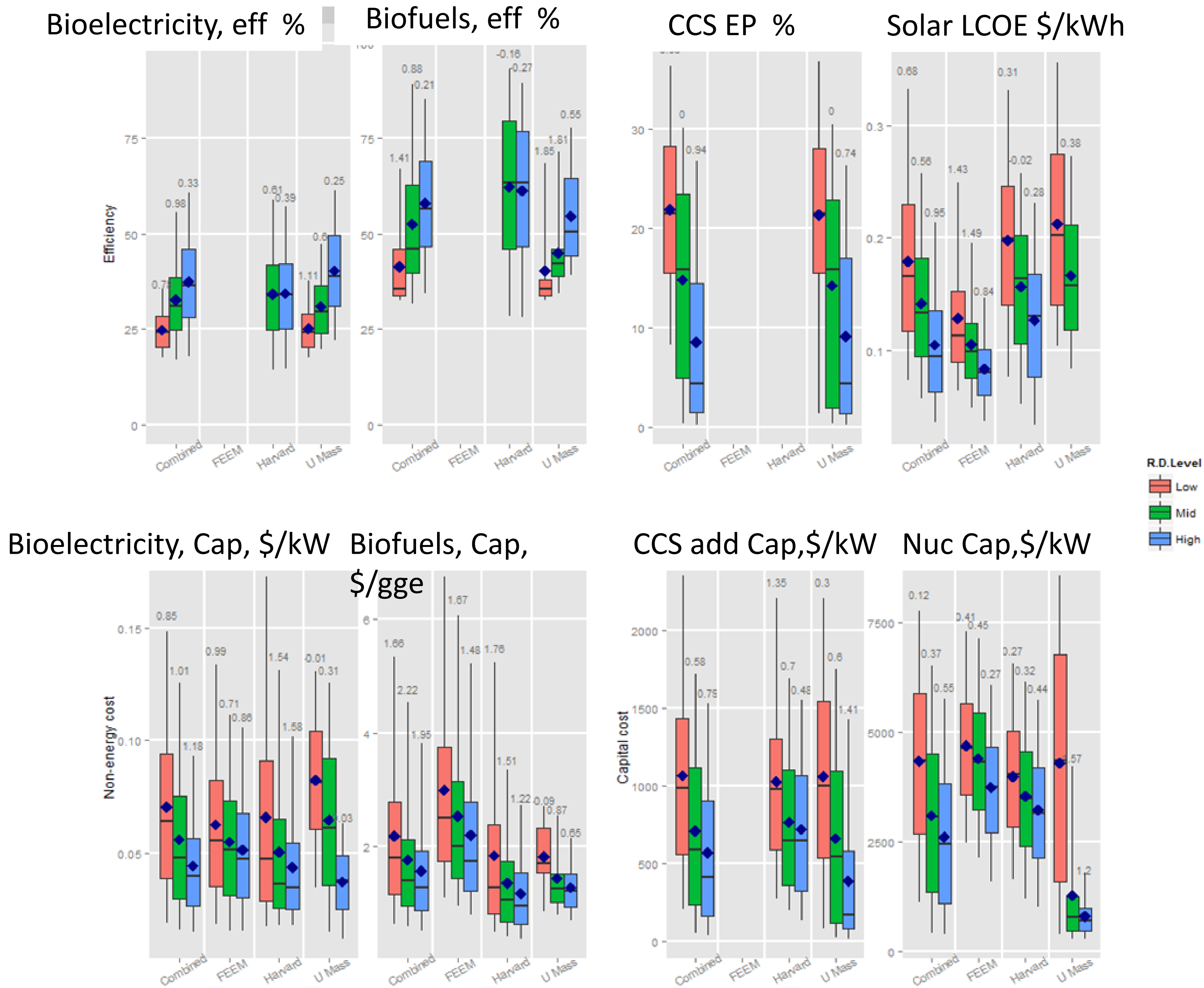
A solution x* is optimal under Maxmin if:

$$x^* = \max_{x \in X} \min_{f \in \Phi} \int U\left(x, z\right) f\left(z; x\right) dz$$

A solution x* is optimal under KMM if:

$$x^* = \max_{x \in X} \int_{\Phi} \psi\left(\int U\left(x; z\right) f\left(z; x\right) dz\right) d\pi$$

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