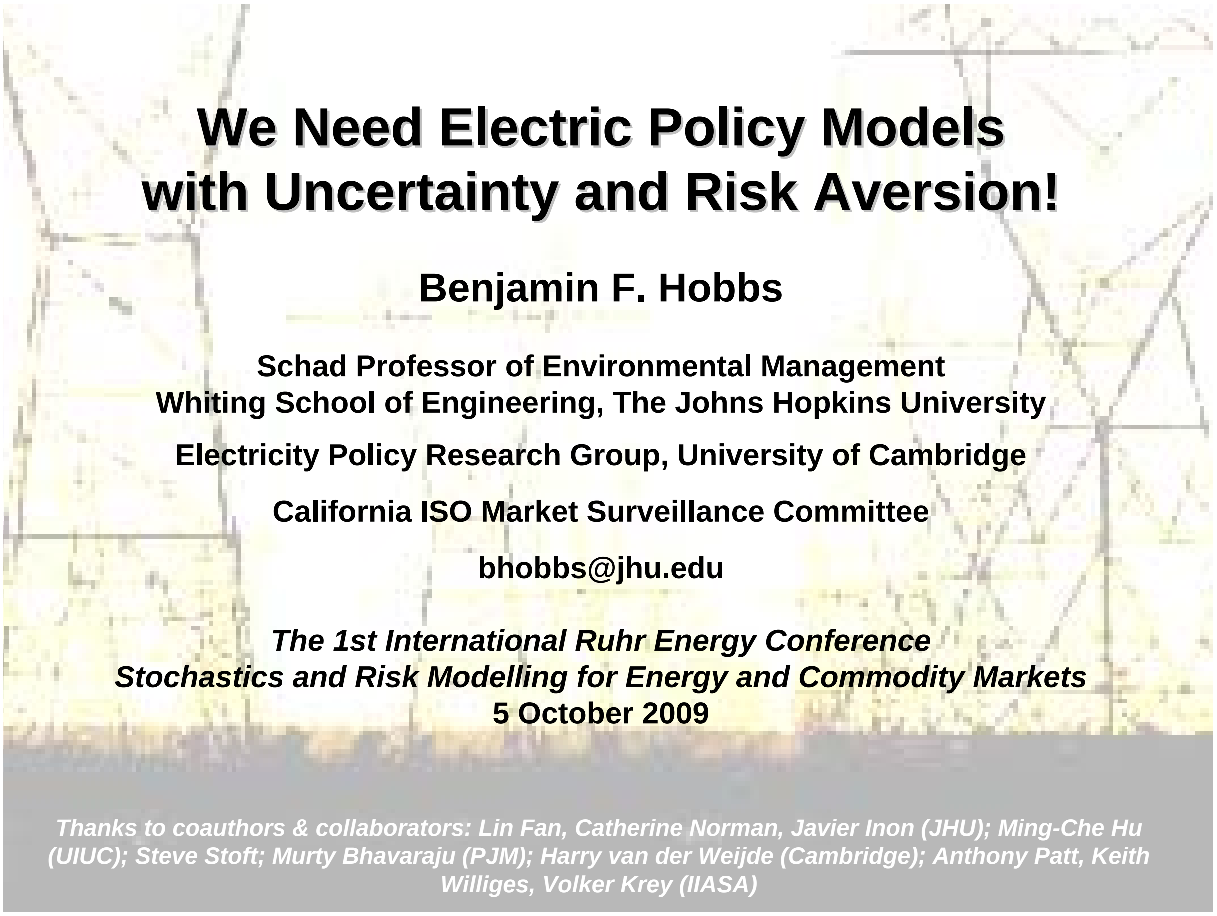

We Need Electric Policy Models with Uncertainty and Risk Aversion!

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The 1st International Ruhr Energy Conference
Stochastics and Risk Modelling for Energy and Commodity Markets
5 October 2009

Thanks to coauthors & collaborators: Lin Fan, Catherine Norman, Javier Inon (JHU); Ming-Che Hu (UIUC); Steve Stoft; Murty Bhavaraju (PJM); Harry van der Weijde (Cambridge); Anthony Patt, Keith Williges, Volker Krey (IIASA)

"Prediction is very difficult,
... especially about the future."
--Neils Bohr on Prediction

"There is no reason anyone would want a computer in their home."
--Ken Olsen, Digital Equipment Corporation, 1977

All quotes from:
http://www.blogcatalog.com/blog/joy-in-the-rain/70f370e405178aa7b352a4cf2384fd7e &
http://www1.secam.ex.ac.uk/famous-forecasting-quotes.dhtml

JHU Cambridge EPRG

Overview: Do Uncertainty & Risk Aversion Matter?

1. **Which uncertainties matter most in US power markets?**
   - *Stochastic MARKAL*
2. **Risk averse agent modeling for power market design**
   - *What parameters for the PJM Capacity market?*
3. **Including risk aversion in equilibrium models**
   - *How does risk aversion and regulatory uncertainty affect generation investment choices?*
4. **Infrastructure design under uncertainty**
   - *What transmission investments should be made now, given renewables & other uncertainties?*

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I think there is a world market for maybe five computers."
-- Thomas Watson, IBM, 1943

"Those who have knowledge, don't predict. Those who predict, don't have knowledge. "
--Lao Tzu, 6th Century BC Chinese Poet

Uncertain Driver: *Demand*

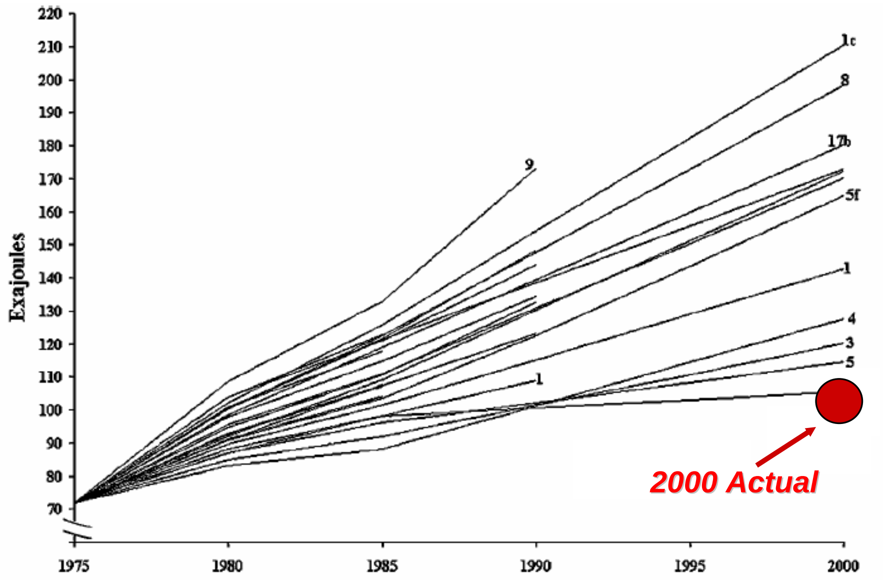
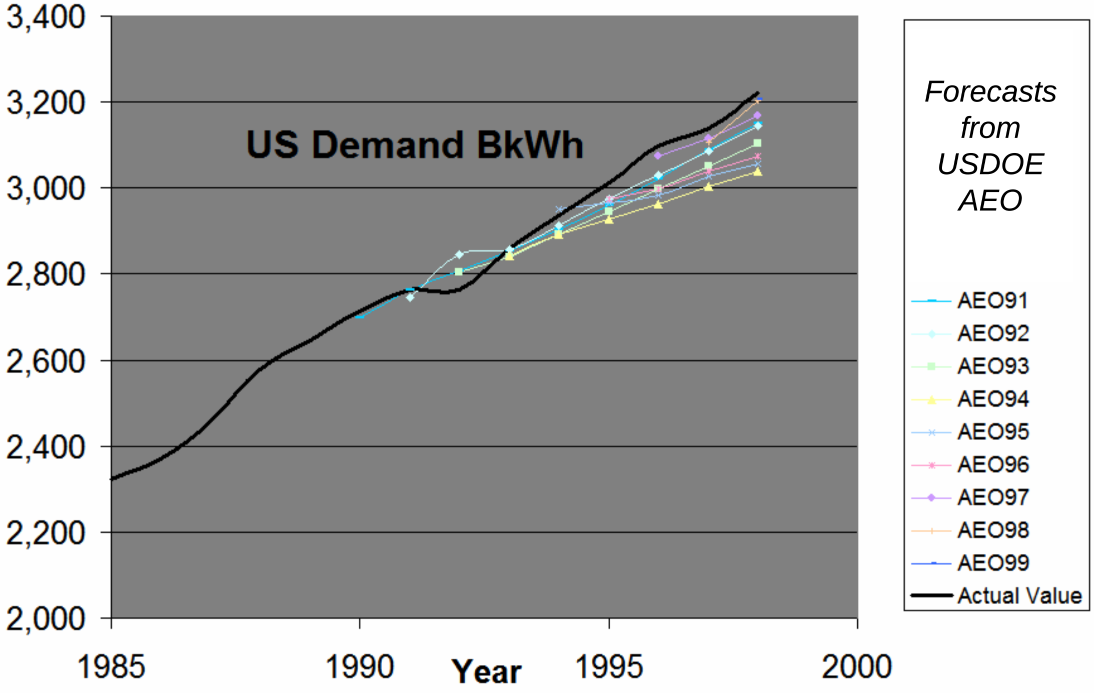
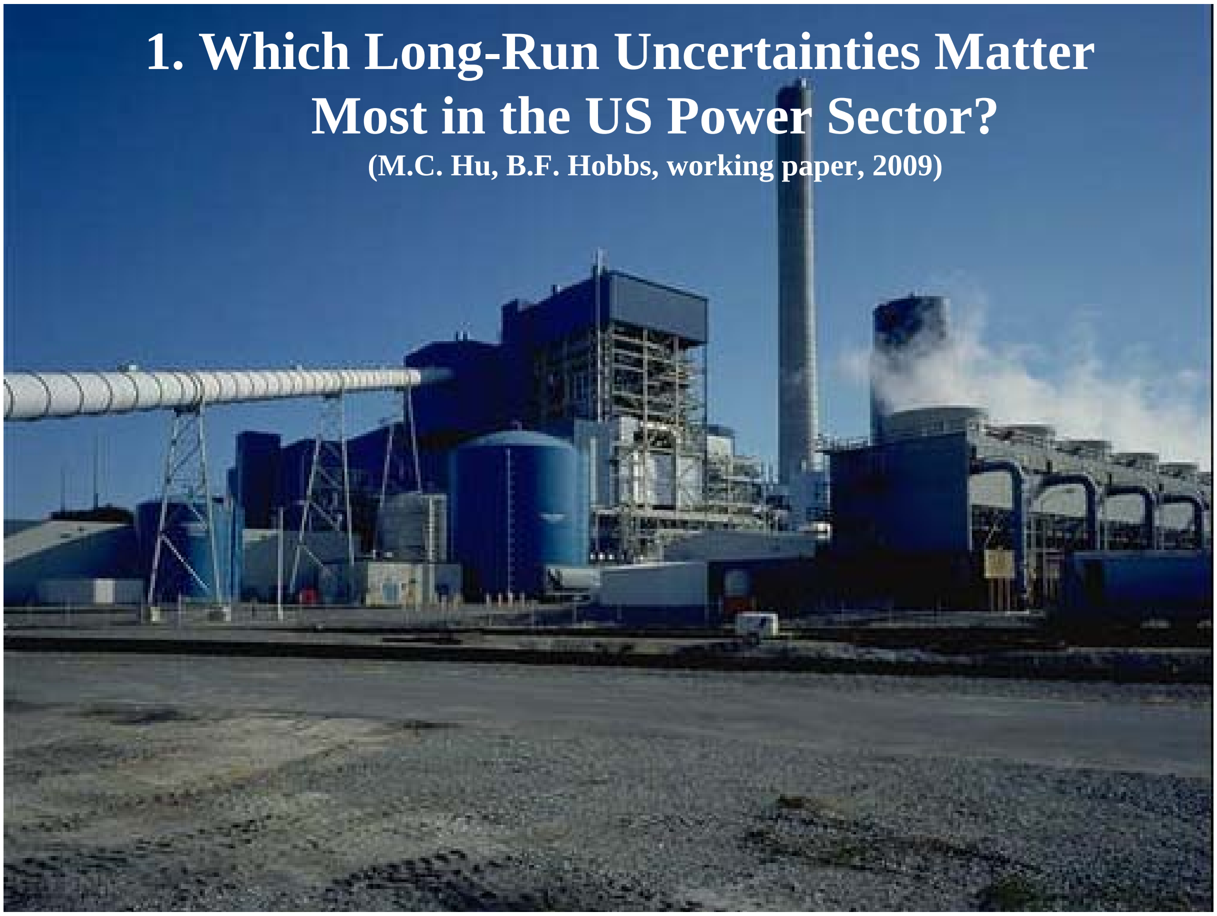


Figure 1 Projections of total U.S. primary energy use from the 1970s. The figure is redrawn from a Department of Energy report (3) and simplified from a summary of dozens of forecasts.

Source: P.P. Craig, A. Gadgil, and J.G. Koomey, "What Can History Teach Us? A Retrospective Examination of Long-Term Energy Forecasts for the United States," *Annual Review of Energy and the Environment*, 27: 83-118

Past Biases May Not Persist!





1. Which Long-Run Uncertainties Matter Most in the US Power Sector?

(M.C. Hu, B.F. Hobbs, working paper, 2009)

Background

- Uncertainty + irreversible commitments

  ⇒ *Risk of regret*
- E.g.,
  - *Stranded costs* (wrong fuels, too much capacity, restrictions on use of new capacity)
  - *High recourse costs* (pollution control retrofits, construction of short lead-time facilities)
- Problem: Define “robust” strategies
  - Perform well under wide range of scenarios
  - Diverse portfolios; flexible resources
- Question: What uncertainties are most important in policy analysis models?

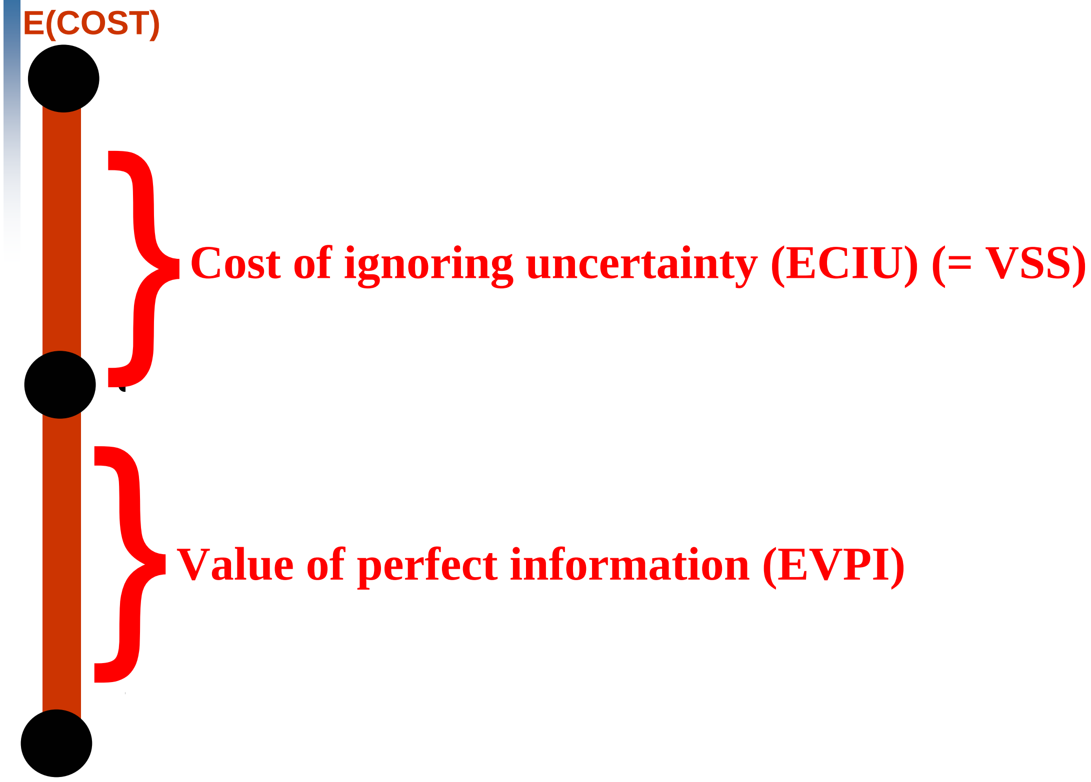
Method

- Simulate energy market response in two stages:
  - Stage 1: “Here and now” decisions:
    - *1995-2010 Investments made to MIN E(Cost) over scenarios (⇔ competitive market, zero elasticity)*
  - State 2: “Wait and see” decisions:
    - *2015-2030 investments made after scenario realized*
    - *One set of decision variables for each scenario*
- MARKAL
  - MARKet ALlocation: LP/least cost representation of energy economy
  - Multiyear solution (5 yr time steps)
  - Probability weighted scenarios for “wait and see” decisions
  - Stochastic version modified so that that commitments to new 2015 capacity made in 2010

    ⇒Possibility of regret
- Caveat: Unreviewed EPA data base

  ⇒ Results merely indicative

Uncertainty Analysis



Scenario Assumptions

Emission Caps [Kt/yr]

Case	Emission	1995	2000	2005	2010	2015-2035
Existing Caps	NO_x	7200	4750	4000	3500	3600
	SO_2	11600	10630	10540	9900	8950
CAIR-Like Caps	NO_x	7200	4750	4000	1510	1510
	SO_2	11600	10630	10540	2250	2250
Possible CO_2 Cap		-	-	-	560000	560000

Demand Scenarios

Code	Description
CC	Commercial Chillers, Air Conditioners
CE	Commercial Computer & Office Equipment
CH	Commercial Heating
CK	Commercial Cooking Ranges
CL	Commercial Lighting
CME	Miscellaneous Commercial Appliances - Electricity
CR	Commercial Refrigeration
CV	Commercial Ventilation
CW	Commercial Water Heaters
RC	Residential Space Cooling
RF	Residential Freezers
RH	Residential Space Heating
RL	Residential Lighting
RME	Miscellaneous Household Appliances, Electric
RR	Residential Refrigeration
RW	Residential Water Heating
TR2	Passenger Servies Intercity Rail-Electricity

MARKAL Power Demand Categories Considered

Demand [% relative to base case]

Scenario	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**
Low	95	93.125	89.375	89.375	89.375	89.375
Base (Medium)	100	100	100	100	100	100
High	105	106.875	110.625	110.625	110.625	110.625

Gas Scenario Assumptions

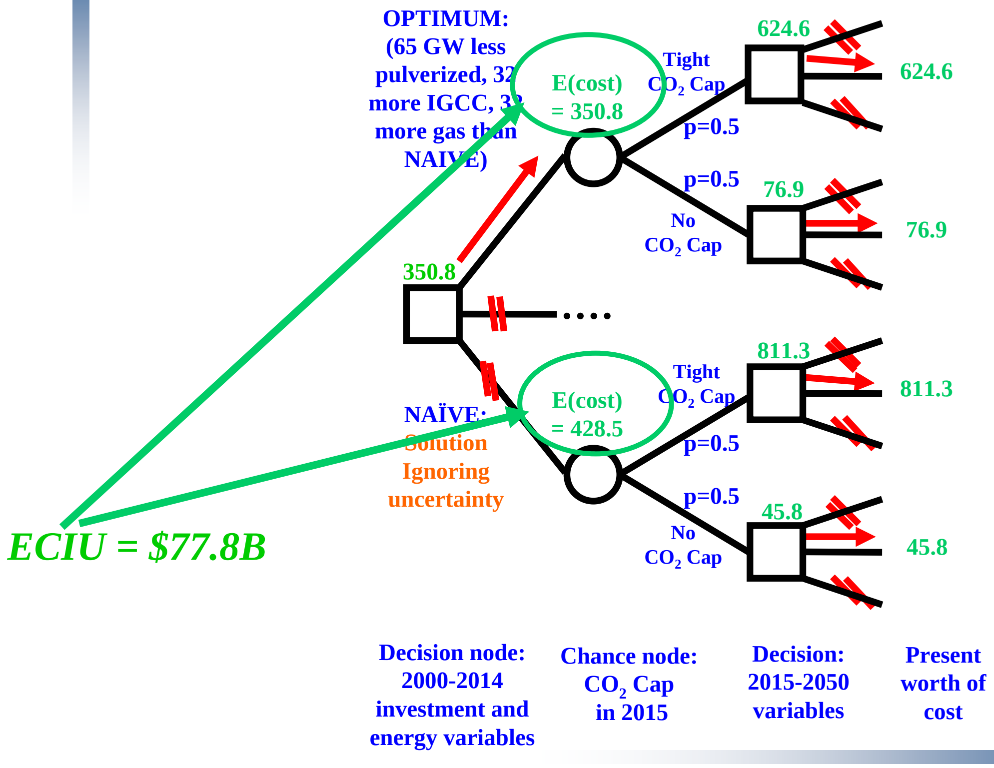
MARKAL Gas supply categories

Code	Description
IMPNGA1	Imported Natural Gas- Step1
IMPNGA2	Imported Natural Gas- Step2
IMPNGA3	Imported Natural Gas- Step3
IMPNGAZ	Imported Natural Gas--For Debugging
MINNGA1	Domestic Dry Natural Gas- Step 1
MINNGA2	Domestic Dry Natural Gas- Step 2
MINNGA3	Domestic Dry Natural Gas- Step 3

Gas prices [% relative to base case]

2005	2010	2015	2020	2025	2030	2035
Low	70	60	60	60	60	60
Base (Medium)	100	100	100	100	100	100
High	130	140	140	140	140	140

Comparisons of Uncertainties: Cost of Ignoring Carbon Policy Uncertainty



OPTIMUM: (65 GW less pulverized, 32 more IGCC, 3 more gas than NAIVE)

NAÏVE: Solution Ignoring uncertainty

ECIU = $77.8B

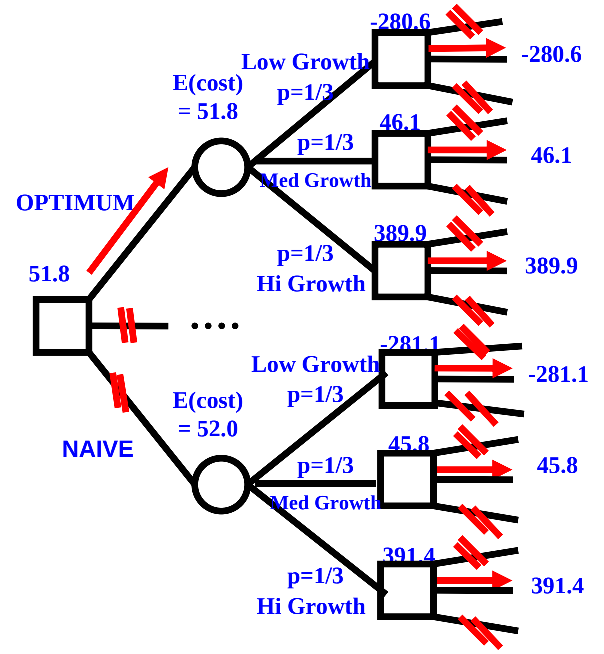
Decision node: 2000-2014 investment and energy variables

Chance node: CO$_2$ Cap in 2015

Decision: 2015-2050 variables

Present worth of cost

Cost of Ignoring Demand Uncertainty



OPTIMUM

51.8

E(cost)
= 51.8

Low Growth
p=1/3

-280.6

-280.6

p=1/3
Med Growth

46.1

46.1

p=1/3
Hi Growth

389.9

389.9

....

NAIVE

E(cost)
= 52.0

Low Growth
p=1/3

-281.1

-281.1

p=1/3
Med Growth

45.8

45.8

p=1/3
Hi Growth

391.4

391.4

Decision node: 2000-2014 investment and energy variables

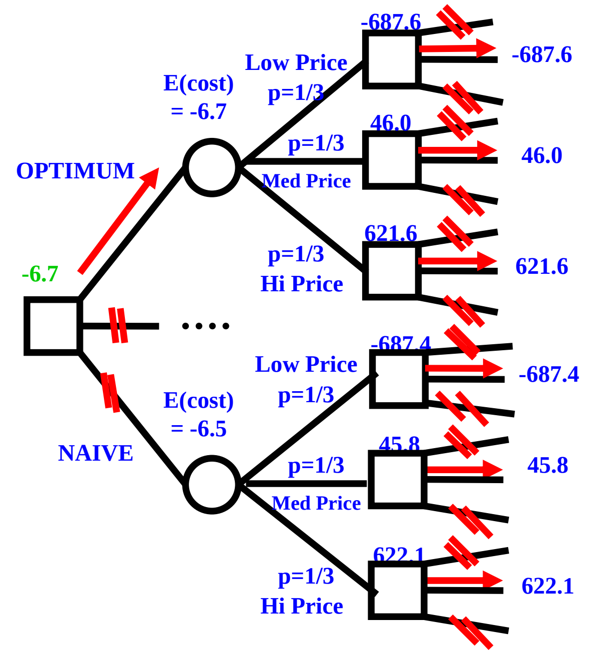
Chance node: CO_2 Cap in 2015

Decision: 2015-2050 variables

Present worth of cost

ECIU = $0.2B

Cost of Ignoring Natural Gas Price Uncertainty



OPTIMUM

-6.7

E(cost)
= -6.7

Low Price
p=1/3

-687.6

-687.6

p=1/3
Med Price

46.0

46.0

p=1/3
Hi Price

621.6

621.6

....

NAIVE

E(cost)
= -6.5

Low Price
p=1/3

-687.4

-687.4

p=1/3
Med Price

45.8

45.8

p=1/3
Hi Price

622.1

622.1

Decision node: 2000-2014 investment and energy variables

Chance node: CO_2 Cap in 2015

Decision: 2015-2050 variables

Present worth of cost

ECIU = $0.2B

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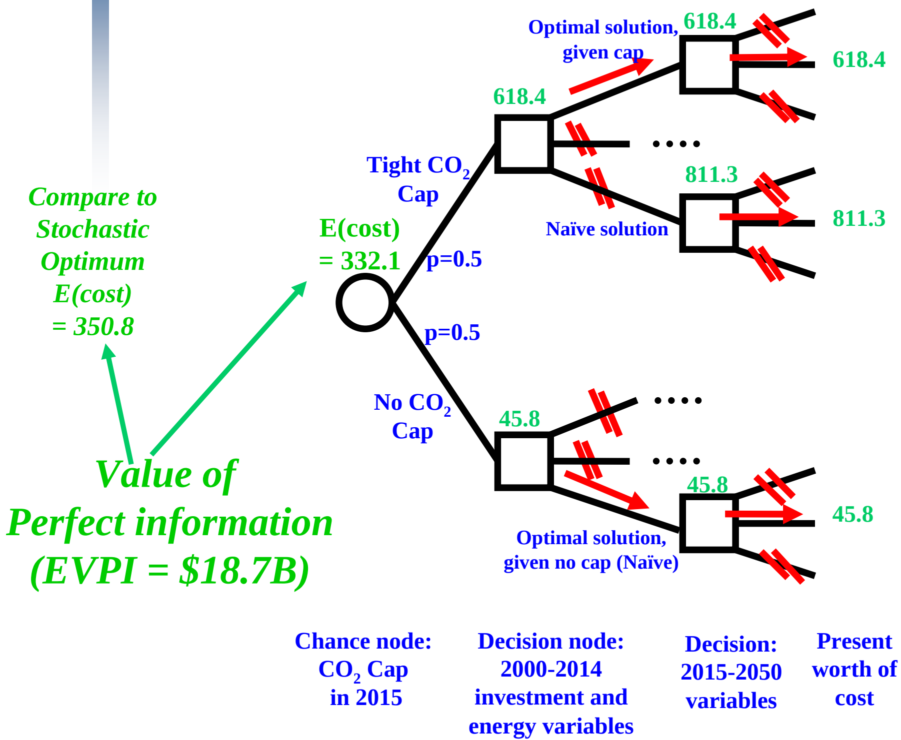
EVPI under CO_2 policy uncertainty



Optimal solution, given cap

618.4

618.4

618.4

....

811.3

811.3

Naïve solution

Tight CO_2 Cap

E(cost) = 332.1

p=0.5

p=0.5

No CO_2 Cap

45.8

....

....

45.8

45.8

Optimal solution, given no cap (Naïve)

Compare to Stochastic Optimum E(cost) = 350.8

Value of Perfect information (EVPI = $18.7B)

Chance node: CO_2 Cap in 2015

Decision node: 2000-2014 investment and energy variables

Decision: 2015-2050 variables

Present worth of cost

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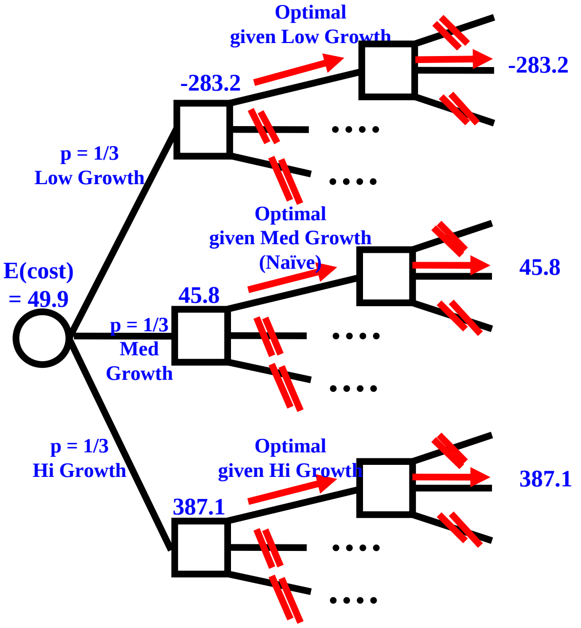
EVPI: Demand growth uncertainty



Optimal given Low Growth

-283.2

-283.2

....

....

p = 1/3 Low Growth

Optimal given Med Growth (Naïve)

45.8

45.8

E(cost) = 49.9

p = 1/3 Med Growth

....

....

p = 1/3 Hi Growth

Optimal given Hi Growth

387.1

387.1

....

....

EVPI = $1.9B

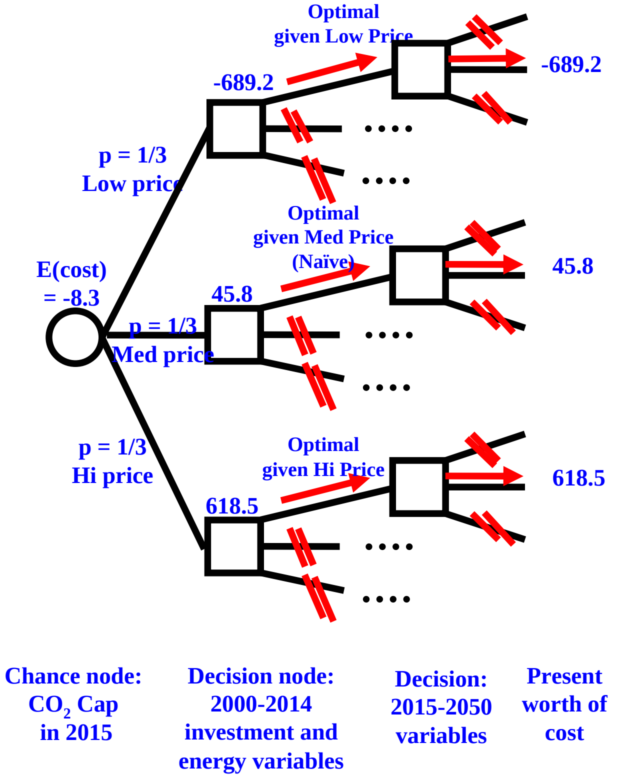
Chance node: CO_2 Cap in 2015

Decision node: 2000-2014 investment and energy variables

Decision: 2015-2050 variables

Present worth of cost

EVPI: Natural gas price uncertainty



Optimal
given Low Price

-689.2

-689.2

p = 1/3
Low price

Optimal
given Med Price
(Naïve)

E(cost)
= -8.3

45.8

45.8

p = 1/3
Med price

p = 1/3
Hi price

Optimal
given Hi Price

618.5

618.5

Chance node:
CO$_2$ Cap
in 2015

Decision node:
2000-2014
investment and
energy variables

Decision:
2015-2050
variables

Present
worth of
cost

EVPI = $1.6B

Upshot

- **High variance doesn't mean an uncertainty is decision-relevant**
  - *A decision may dominate other decisions for all scenarios*
- **Long-term uncertainty can affect decisions today *if*:**
  - *Investments are one-of-a kind that will shape system for decades*
  - *Uncertainty affects relative performance of different alternatives*
  - *Irreversibilities*

    ⇒high possibility of regret
- **Long-term uncertainty less important *if*:**
  - *Decisions are about increments of capacity to meet growing demand*

    ⇒ long-term uncertainties may only affect timing of later additions

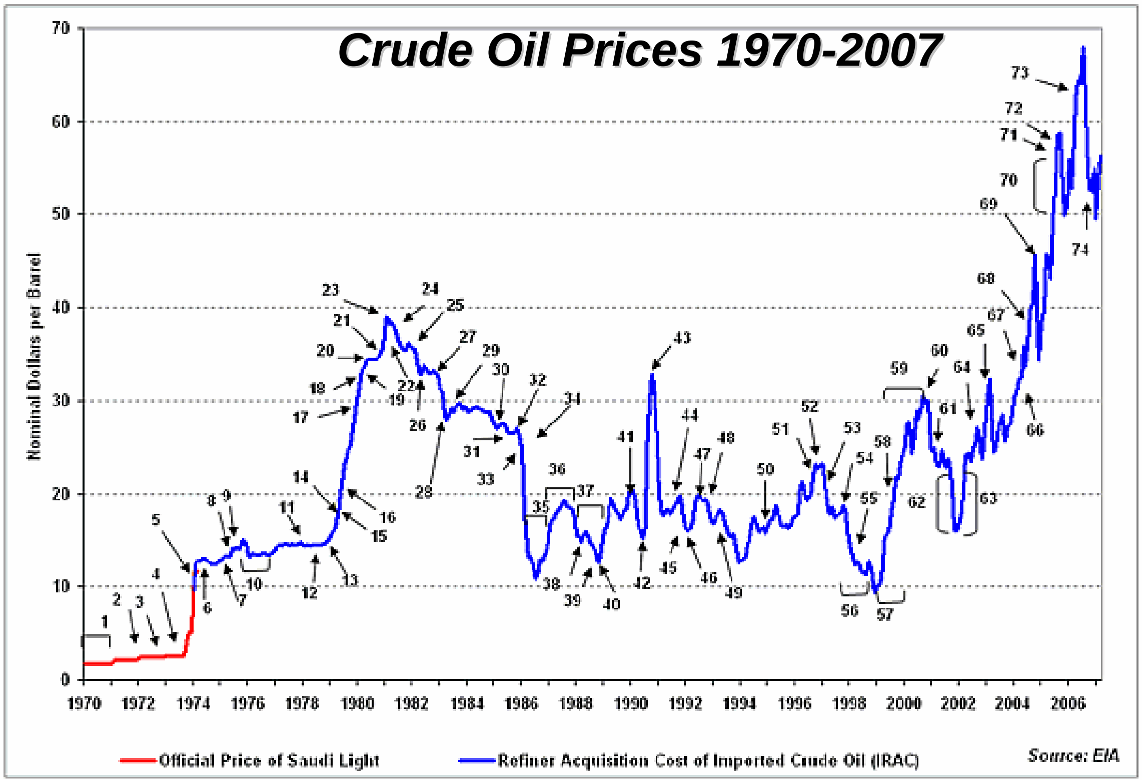
“No one will need more than 637 kb of memory for a personal computer. 640K ought to be enough for anybody.”

--Bill Gates, Microsoft, in 1981

"It is far better to foresee even without certainty than not to foresee at all. "

--Henri Poincare in The Foundations of Science, page 129.

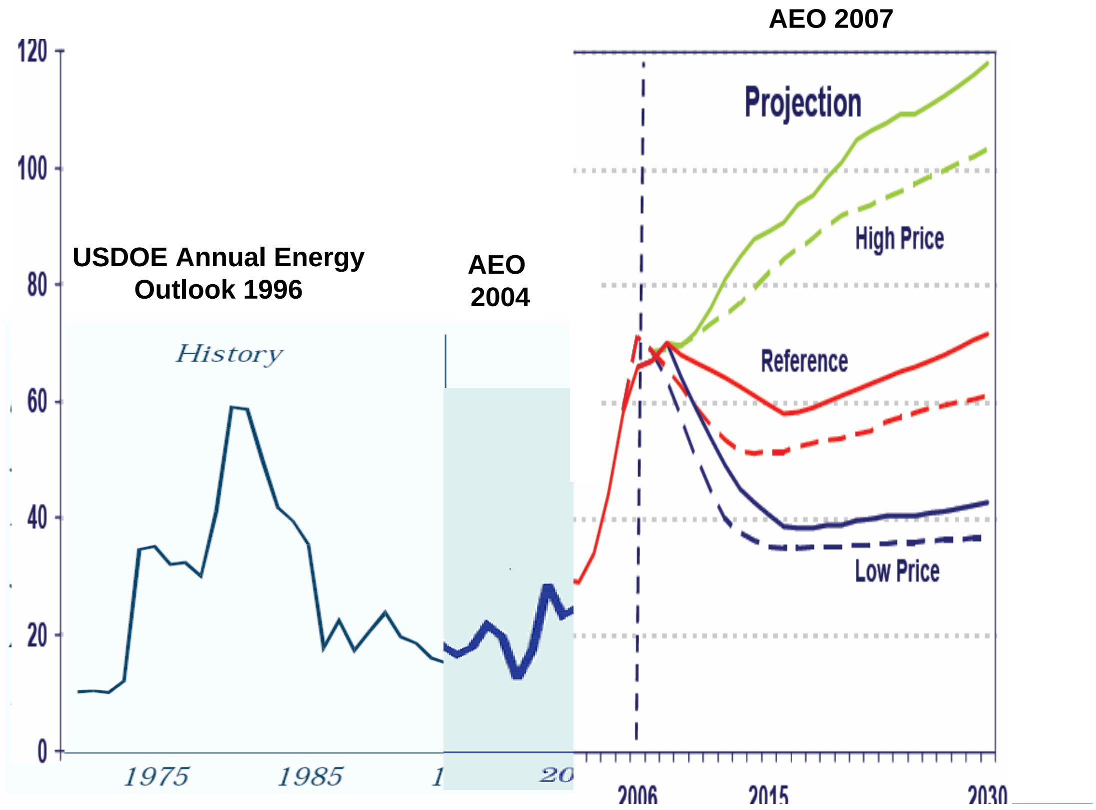
Uncertain Driver: Fuel Prices



Source: EIA

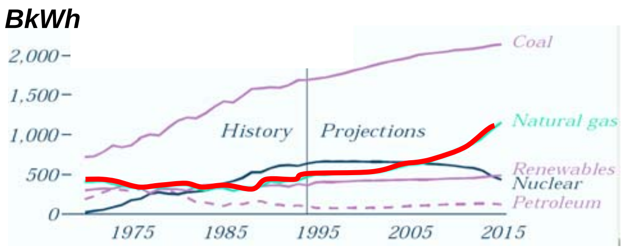
http://www.eia.doe.gov/emeu/cabs/AOMC/Overview.html

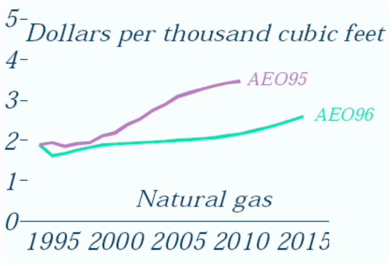
Uncertain Driver: Fuel Prices
EIA Lower 48 Crude Oil Price Forecasts



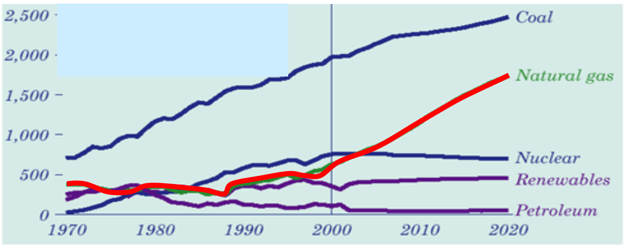
Volatile Forecasts from Uncertain Drivers: The Case of Gas Prices

1996 AEO

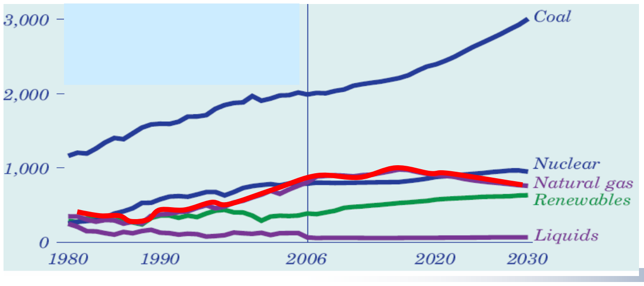


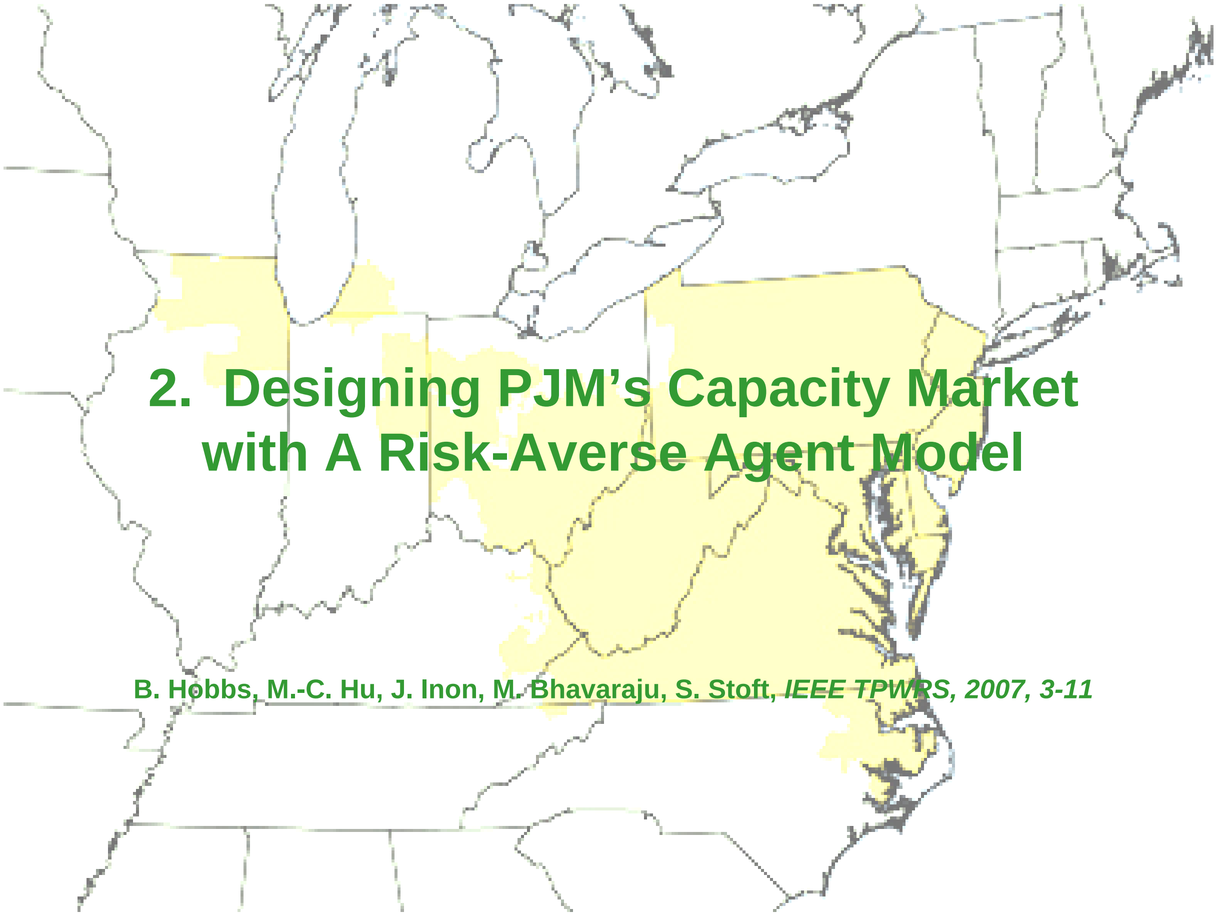


2000 AEO



2008 AEO





2. Designing PJM's Capacity Market with A Risk-Averse Agent Model

B. Hobbs, M.-C. Hu, J. Inon, M. Bhavaraju, S. Stoft, *IEEE TPWRS, 2007, 3-11*

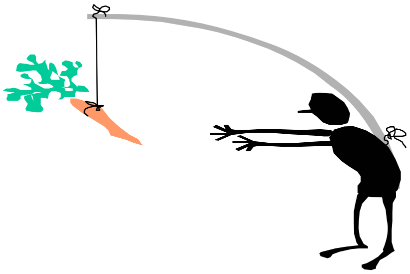
JHU
Cambridge
EPRG

Why Capacity Markets?

- **Demand-Side market failures can lead to wrong prices and capacity shortages**
  - ***E.g., Retail price rigidities and price caps***
    - **⇒Prices don't reflect consumer "Willingness to Pay" for reliability**
    - **⇒ Missing money: energy market revenues don't support investment**
- **Cost of overcapacity << Cost of undercapacity ⇒ Capacity markets = insurance**

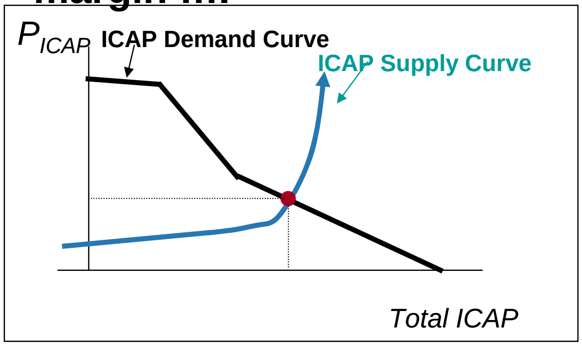
How Can Market Designers Respond?

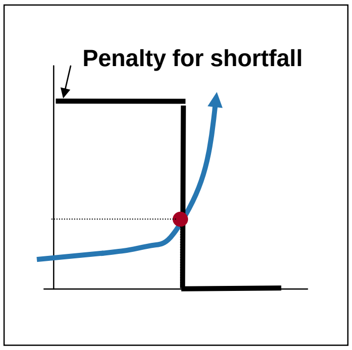
1. **Demand-side reform**
   - Correct the market failure
2. **Capacity markets ("top down"):**
   - Tradable "Installed Capacity" (ICAP) rights or auctions, or
   - Capacity payments
3. **Mandatory contracts ("bottom up")**



ICAP Variant: Demand Curves for Capacity

- **Administrative payment from ISO depends on reserve margin ….**





…. instead of fixed requirements, with penalty for falling short ("vertical demand")

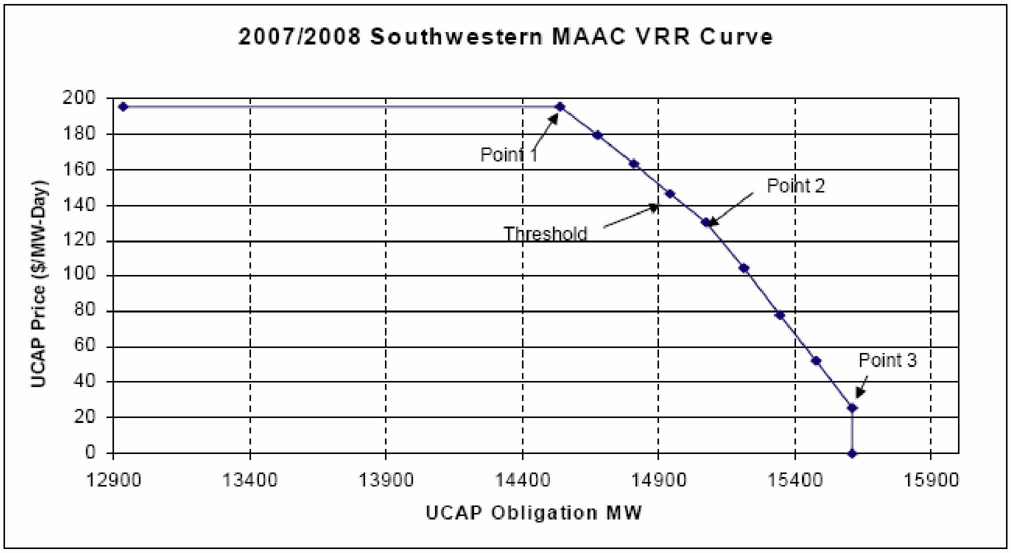
Overview of PJM “Reliability Pricing Model”

1. **Previous PJM system: ICAP**
   - A vertical demand curve
   - One market covering all of PJM
   - Short-term (annual, monthly, daily markets)

2. **Why replace ICAP?**
   - Prices too volatile: “bipolar”
     - *Discouraged risk-averse investors*
   - Didn’t reflect locational value: capacity in wrong places
   - Failed to provide a sufficient forward signal

3. **RPM proposal**
   - Stakeholder process, JHU analysis 2004-2005
   - August 31, 2005: initial filing
   - Settlement talks, Fall 2006, JHU reanalysis
   - FERC approved settlement, Dec. 2006
   - Implemented: June 1, 2007

Example of a Local RPM Curve



Overview of Dynamic Analysis: Questions

1. **How do different RPM curves affect….**
   - *Stability of capacity market?*
   - *Costs to consumers?*
   - *Ability to meet reserve requirement, reliability criterion?*

2. **How robust are these conclusions to different assumptions about….**
   - *Generator behavior?*
   - *Demand curve parameters?*

PJM Dynamic Analysis: Basic Assumptions

- **Capacity additions are a dynamic process. Investment depends on:**
  1. *Forecast revenue streams*
     - Based on capacity and energy prices from recent auctions

     More forecast net revenue

     ⇨ more investment
  2. *Revenue stream variability*
     - Variations due to forecast changes and weather

     Highly variable energy and capacity prices

     ⇨less investment (due to risk aversion)
  3. *Risk attitudes*:
     - No hedges (incomplete market)
     - Risk aversion
     - Short-sightedness
- **Random shocks (weather, economic fluctuations) cause variation in returns**
  - Result: boom/bust cycles in investment

Dynamic Model Overview

1. **The model assesses profitability of CTs needed to meet the reliability requirement**
   - **“Representative Agent” approach**
2. **Simple & transparent model simulates dynamic process of investment:**
   - **annual construction of turbine capacity,**
   - **revenues from energy, ancillary services, & capacity markets,**
   - **market stability in face of random demand shocks,**
   - **consumer costs**
3. **Allows exploration of assumptions**

Simulation Overview: Auction in Year *y*-4 for Capacity Installed by Year *y*: Repeated for 100 years

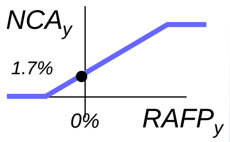
Actual and Estimated Profits: ***Blue = Known at Auction in Year y-4; Brown = Estimated***

Year y-7:	Year y-6:	Year y-5:	Year y-4:	Year y-3:	Year y-2:	Year y-1:	Year y:
Profit = P_{ICAP} + E/AS Gross Margin – Fixed Cost	P_{ICAP} + E/AS GM – FC	P_{ICAP} + E/AS GM – FC	P_{ICAP} + E/AS GM – FC	P_{ICAP} + E/AS GM – FC	P_{ICAP} + E/AS GM – FC	P_{ICAP} + E/AS GM – FC	P_{ICAP} + E/AS GM – FC

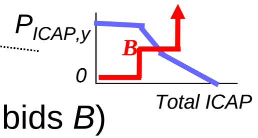
Weights for profits in each year

Exponential risk averse U( ) penalizing variable profits

Risk-Adjusted Forecast Profit (***$RAFP_y$***)
(Increases if profits higher, decreases if profits more variable)



Maximum New Capacity Additions NCA_y



Capacity Price from Demand Curve
(Assume existing capacity bids 0, and NCA_y bids B)

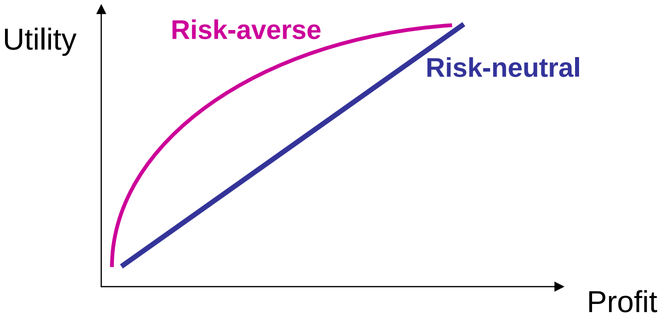
Utility Function

Agent makes decisions to maximize E(U)

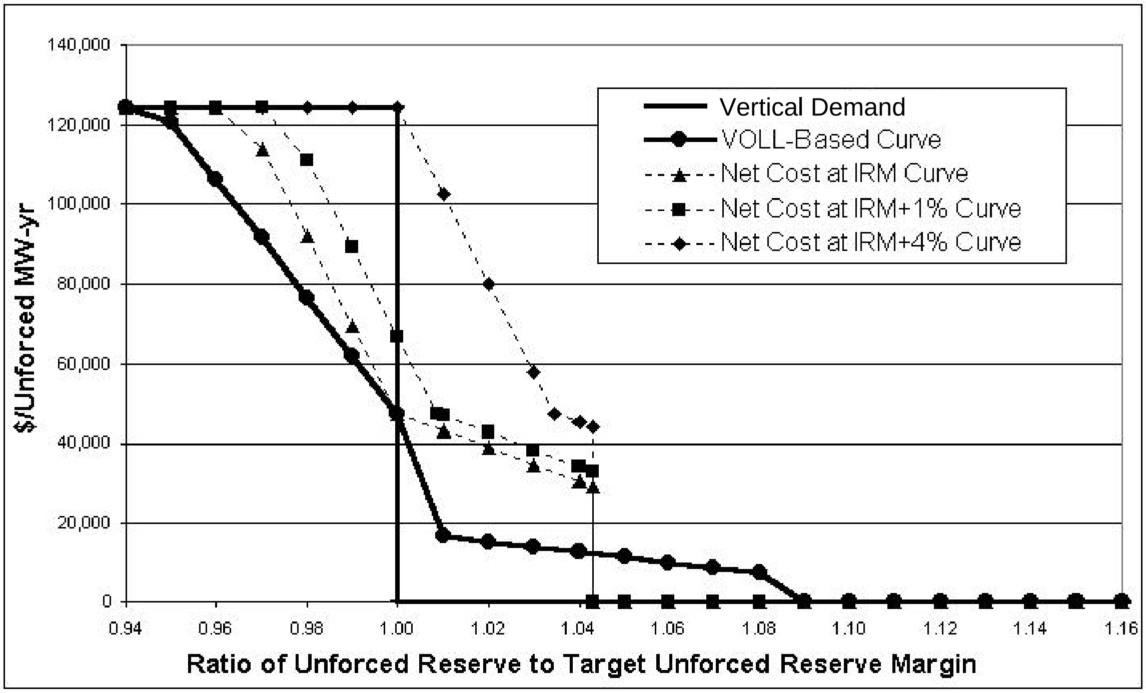
- Constant relative risk aversion

$$U(\pi) = a - b \cdot e^{-r\pi} \quad b > 0, r > 0$$

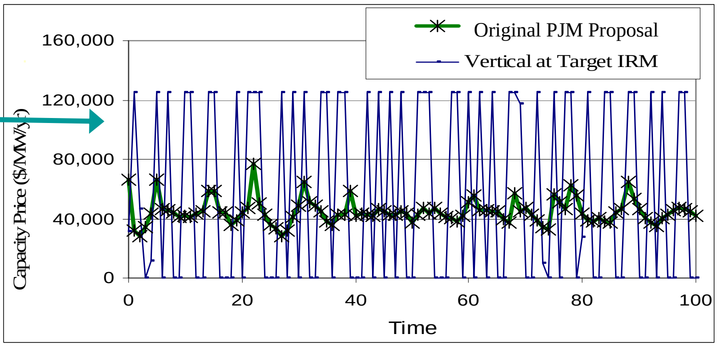
- Risk neutral: Max E(Profit)



Initial PJM Analysis: Five Curves Considered

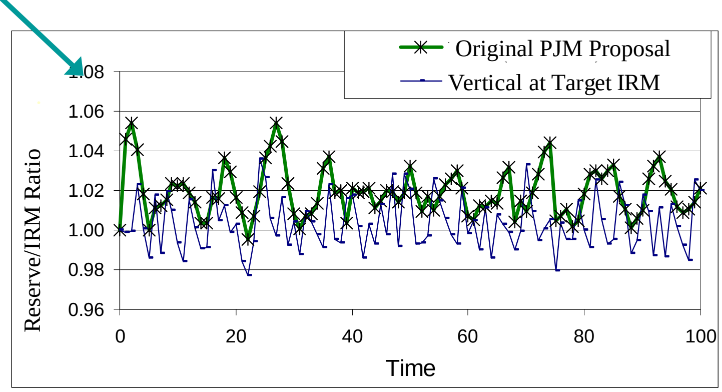


PJM Results: Summary



1. **Sloped curve stabilizes capacity payments**

2. **More stable payments even out investment, forecast reserves**



3. **More stable revenues lowers capital costs. Consumer costs (capacity, scarcity) fall:**
   - *$127/peak kW/yr for vertical*
   - *$71/peak kW/yr for sloped curve*

   (values depend on assumptions)

4. **Results robust**

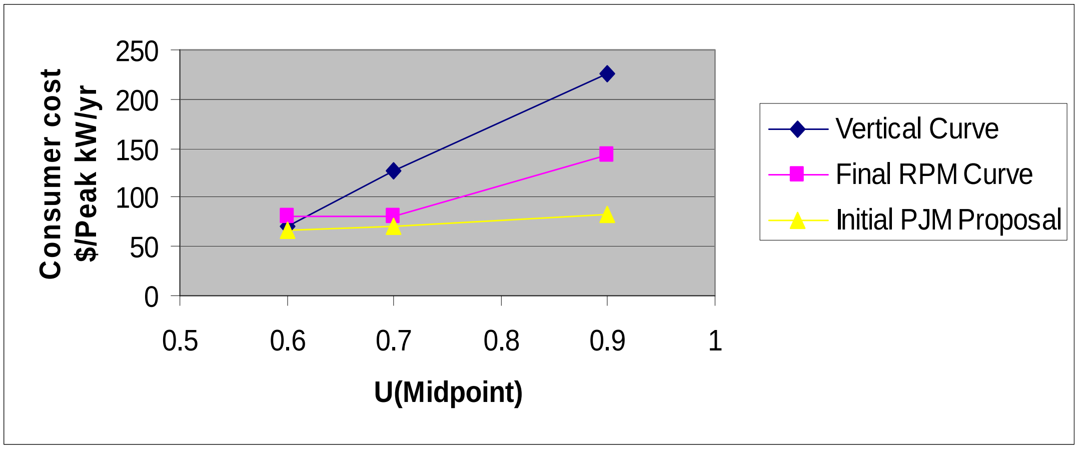
Sample Results: Average

(Risk aversion parameter = 0.7; Results depend on specific assumptions)

Curve	% Years meet or Exceed IRM	Average % Reserve over IRM	Generation Profit $/kW-yr {ROE}	Scarcity Rev. $/kW-yr	E&AS Revenue $/kW-yr	ICAP Payment $/kW-yr	Scarcity + ICAP Payment by Consumers (Peak Ld Basis)
1. Initial PJM Proposal	**98**	**1.79**	**11{17%}**	**21**	**10**	**42**	**71**
2. Final RPM Proposal	**98**	**2.17**	**13{17%}**	**19**	**2**	**52**	**81**
3. Vertical Demand	**39**	**-0.49**	**64{35%}**	**45**	**10**	**69**	**127**

⇒Alternate (sloped) curves have better adequacy … and lower consumer cost

Sensitivity Analyses



- *Sloped demand almost always preferred to vertical*
- *More risk aversion ⇒ sloped curve more advantageous*

PJM Conclusions: Advantages of Sloped Demand

- Compared to vertical demand, lower risk to generators. Result:
  - *Lower required return to capital*
  - *More investment in generation*
  - *Dampened capacity cycles*
  - *Lower consumer cost*
- More advantageous if generators more risk averse
  - *Risk neutrality ⇒ sloped demand unnecessary*

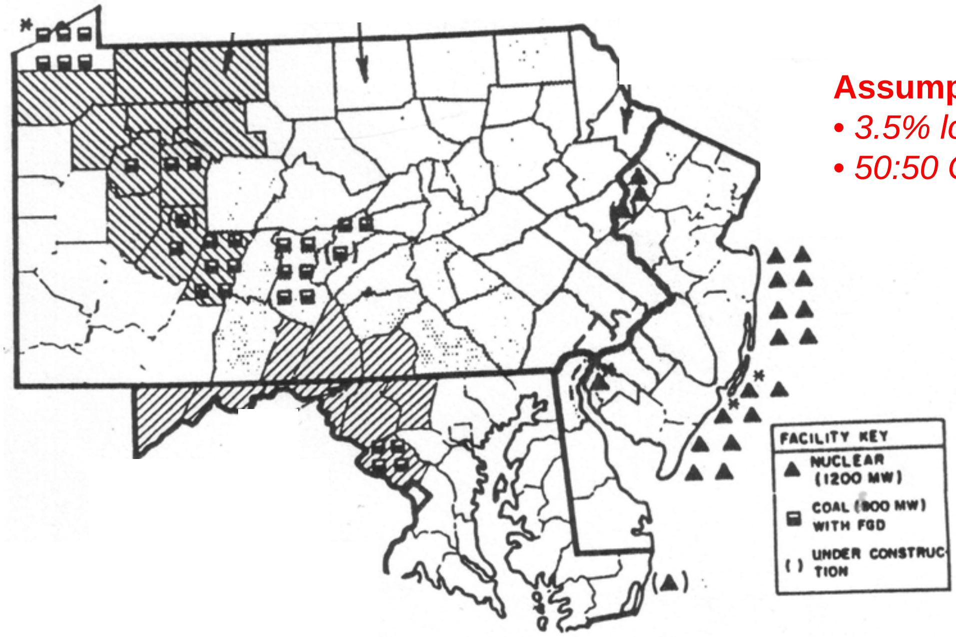
“Heavier-than-air flying machines are impossible.”
--Lord Kelvin, ca. 1895, UK mathematician, physicist

**"This is the first age that's ever paid much attention to the future, …
which is a little ironic since we may not have one. "**
--Arthur C. Clarke

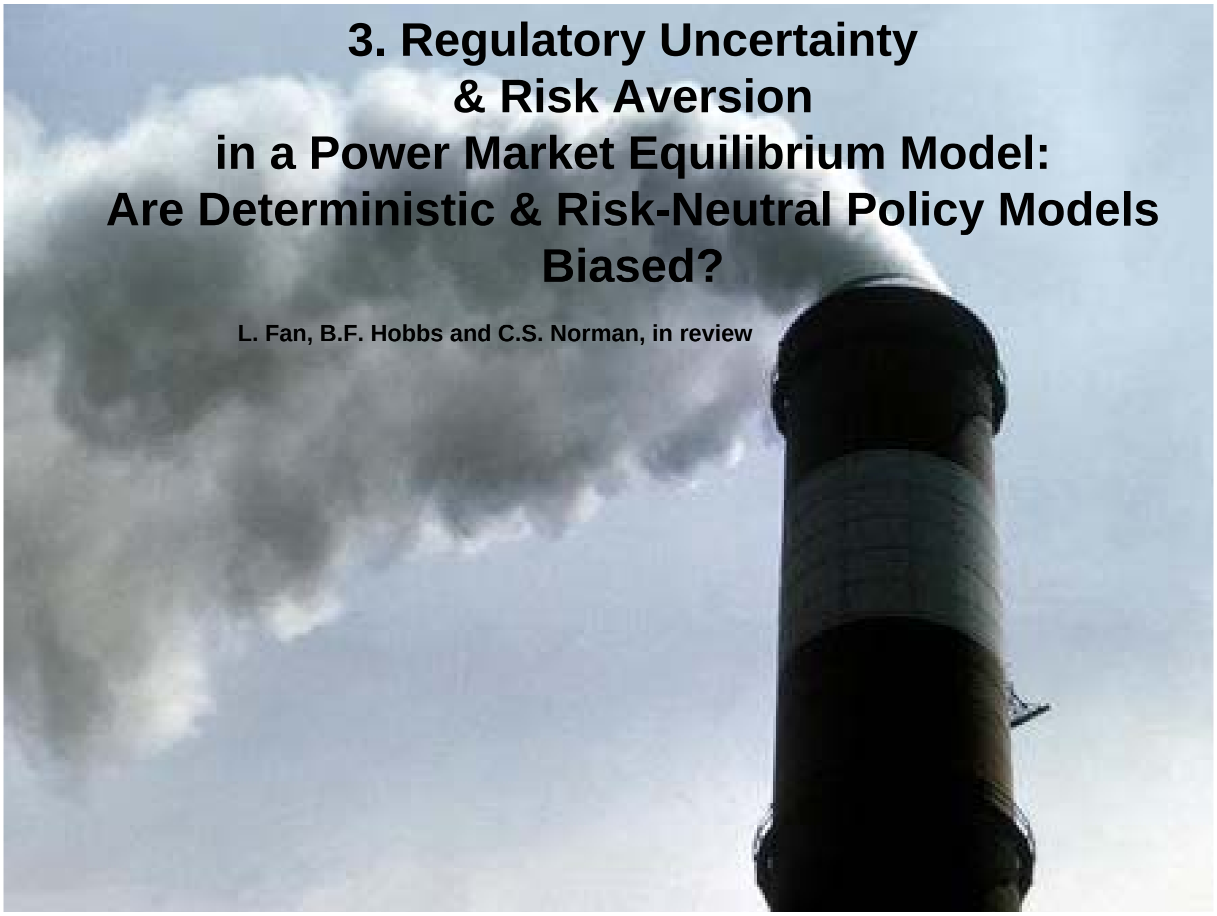
Uncertain Driver: Regulation & Technology

Example: 1985-2000 Power Plant Siting Scenario

1978 National Coal Utilization Assessment ***(Hobbs & Meier, Water Resources Bulletin, 1979)***



Assumptions:
- *3.5% load growth*
- *50:50 Coal:Nuclear*



3. Regulatory Uncertainty & Risk Aversion in a Power Market Equilibrium Model: Are Deterministic & Risk-Neutral Policy Models Biased?

L. Fan, B.F. Hobbs and C.S. Norman, in review

Motivation

- **Future GHG regulation timing & form are unknown**
- **Agents risk averse when investing**
- **Investments today will affect costs of carbon policy for decades**
  - **Consequences of poor modeling of decisions will also persist!**
- **Energy policy strongly linked to models, but they simplify risk:**
  - **Deterministic models, or**
  - **Stochastic with risk-neutral agents**
- ***Are resulting equilibria & policy conclusions biased?***

Previous Energy Work

- *Evaluation of generation optionality under uncertain (exogenous) price processes*
  - Investment
    - e.g., Fleten (2002)
  - Operations
    - e.g., Tseng (2004), Liu (2008)
- *Some stochastic equilibrium models*
  - Bottom-up modeling of investment under risk neutrality
    - e.g., Stochastic Markal (Loulou, 2000; Hu and Hobbs, 2009), MCP (Gabriel, 2008)
  - Equilibrium operations and financial hedging under risk aversion
    - e.g., Willems (2007)
  - Short-run equilibrium among risk-averse (CVar-constrained) generators
    - e.g., Ventosa et al. (2008); Shanbhag et al. (2008)

Under uncertain carbon regulations

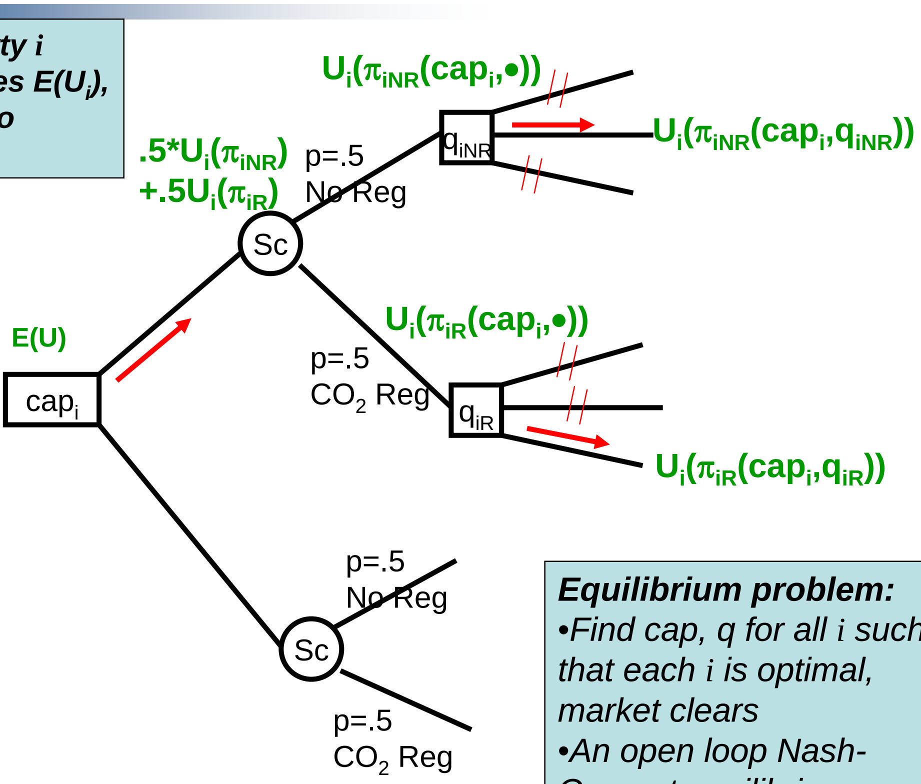
- How will investment decisions differ if we model risk averse generators under alternative regulatory scenarios?
- How do these results change with alternate policy instruments?
    - Tax vs. cap and trade?
    - Auction vs. grandfathering vs. contingent allocation of allowances?

Competitive Model Formulation

- Two firms face a capacity expansion problem, with different technologies (one coal-fired and one gas-turbine)
  - *Variation:* 3rd technology (solar thermal)
- Scenarios:
  - *With regulation*
    - Cap-and-Trade
      - Auctioned allowances
      - Freely allocated allowances
    - Carbon Tax
  - *Without regulation*
- Two stage problem:
  - 1st stage: investment under uncertainty
  - 2nd stage:
    - regulation scenario revealed
    - plants are operated
    - profits realized

Model Formulation (Cont.)

Each party i maximizes E(U_i), subject to prices:



Equilibrium problem:

•Find cap, q for all i such that each i is optimal, market clears

•An open loop Nash-Cournot equilibrium

Model Formulation (Cont.)

- **Stochastic Equilibrium problem**
  - **Consists of KKTs for each market party’s optimization problem**
  - **Plus market clearing conditions**
- **KKTs for Operators’ utility maximization problem:**

$$\pi_{ik} = \sum_j HR_j \cdot q_{ijk} \cdot (p_{ij} - MC_{ik}) - CC_k \cdot cap_k - Z_i \cdot p^e_{reg} \cdot t_{reg,k}$$

$$U_{ik} = 1 - e^{-r\pi_{ik}}$$

$$\boxed{\begin{array}{lll} Risk\ \ Neutral: Max \quad \pi_k = \sum_i PR_i \cdot \pi_{ik} & & \\ Risk\ \ Averse: Max \quad U_k = \sum_i PR_i \cdot U_{ik} & & \\ s.t. \quad q_{ijk} - cap_k \le 0 \qquad \forall\ i, j, k & & (\mu_{ijk}) \\ \sum_j E_k \cdot HR_j \cdot q_{reg,jk} - t_{reg,k} - Allowance_k \le 0 & & (\lambda_{reg,k}) \end{array}}$$

- i: scenario indicator (reg, nreg);
- j: time period indicator;
- k: fuel/firm indicator;
- HR_j: hours in the time period;
- MC_{ik}: marginal cost;
- CC_k: capacity cost;
- Z_i: scenario indicator: Z_i=1 for regulation, Z_i=0 otherwise;
- E_k: emission rate;
- $Allowance_k$: free allowance allocated;
- q_{ijk}: generation variable;
- p_{ij}: electricity price variable;
- p^e: emission price variable;
- cap_k: capacity to be built;
- $t_{reg,k}$: net emission permit purchase.

Model Formulation (Cont.)

– **KKTs for Consumers’ problem:**

$$Max \quad CS_i = \sum_j HR_j \cdot [(P_{0ij} \cdot d_{ij} - \frac{1}{2}\frac{P_{0ij}}{Q_{0ij}} \cdot d_{ij}{}^2) - p_{ij} \cdot d_{ij}]$$

$$s.t. \quad d_{ij} \ge 0 \qquad \forall\ i, j$$

– **Market Clearing condition:**

$$\sum_k q_{ijk} = d_{ij} \qquad \forall\ i, j \qquad\qquad (p_{ij})$$

$$\sum_k t_{reg,k} = E^{cap} \qquad\qquad (p^e_{reg})$$

- **P_0, Q_0: inverse demand parameters;**
- **d: demand;**
- **E^{cap}: total emission cap.**

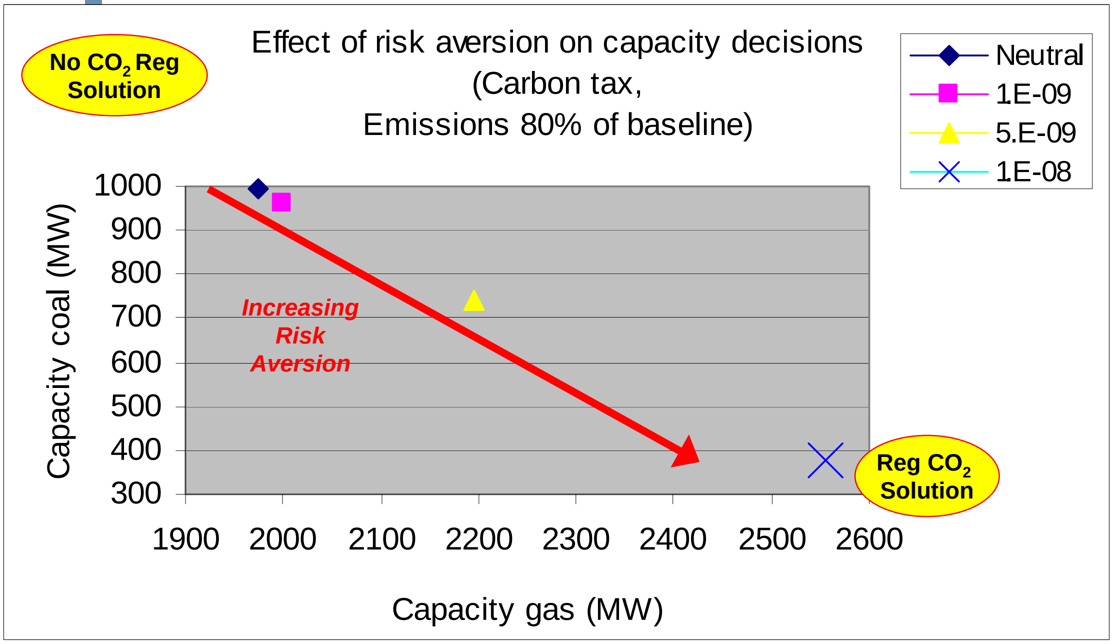
– **Can also include allowance allocation rules**

- ***auctioned***
- ***free depending on sales***
- ***free depending on investment***

Solutions

- Solve as a Nonlinear MCP (Mixed Complementarity Problem)
  - No analytical solution
  - Allows flexibility in the constraints
  - Commonly used in this policy setting
- PATH solver in GAMS
  - Successive linear approximation

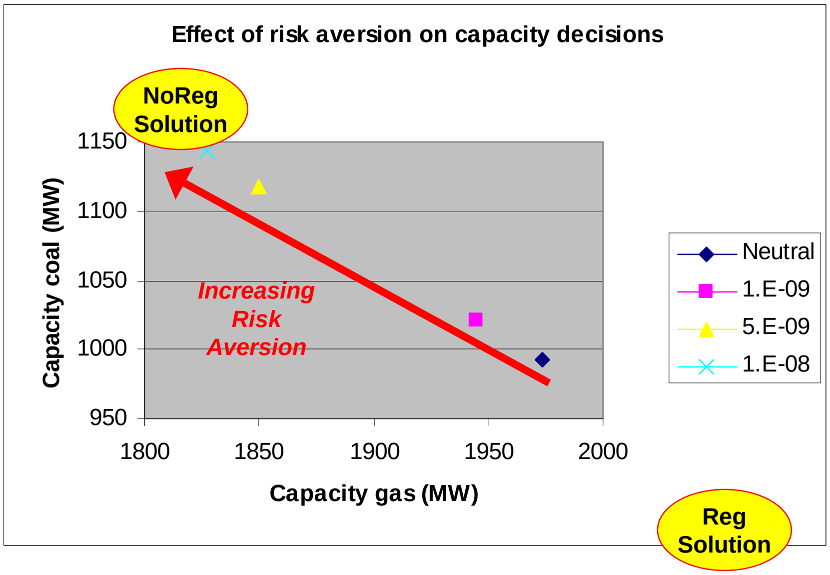
Carbon tax / 100% Auction



Gas capacity↑, coal ↓ with more risk-aversion

Risk aversion pushes solution towards least profitable scenario solution

With free allocation of allowances: A reversal



Risk aversion moves owners *towards* the regulation solution in the auction / tax cases; *away* from it in the free allocation cases

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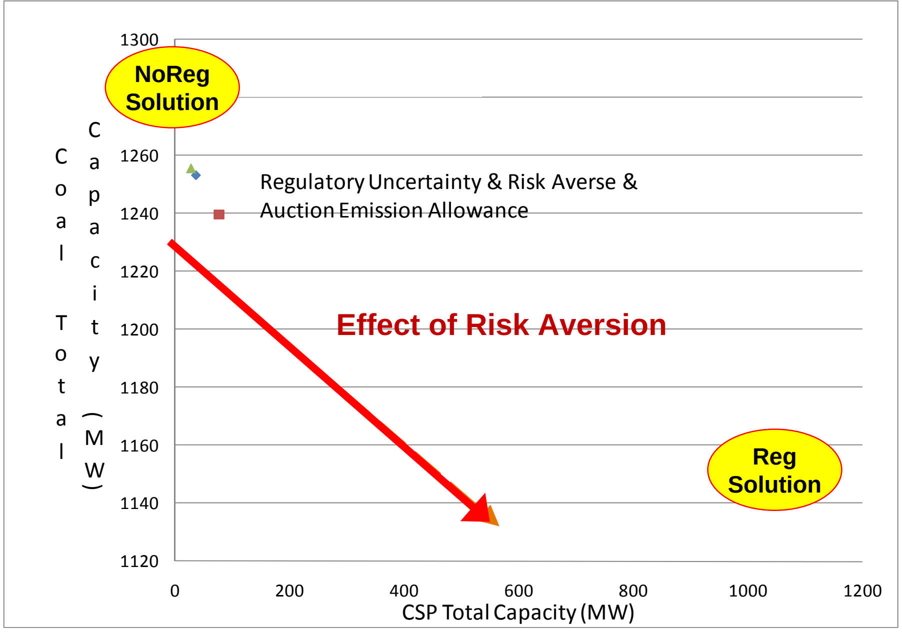
More Complex Model Formulation

(Fan, Patt, Williges, & Krey, Working Paper, IIASA, 2009)

- Existing fossil fuel sector, with a new entrant “Concentrating Solar Power”
  - Coal-fired steam (*existing*)
  - Gas-fired turbines (*existing*)
  - CSP (*new entrant*)
- Scenarios (2×6×2=24):
  - *Carbon regulatory uncertainty*
    - No-regulation
    - Cap-and-Trade
  - *CSP cost uncertainty*
    - assumptions vary across capacity growth rates (5% or 10%),
    - learning rates (5%, 10% or 15%)
  - *Fossil fuel price uncertainty*
    - high fuel price scenario
    - low fuel price scenario

Capacity Effects of Risk Aversion with CSP (Auction Allowances)



CSP capacity ↑ and coal ↓ as risk-aversion increases

Risk aversion pushes solution towards least profitable scenario solution

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Comments

- **Risk aversion ⇒ profit under the least profitable scenario gets more weight**
  - **⇒ Investments sensitive to financial positions (e.g., allocation scheme for allowances)**
- **Risk-neutral owners make the same decisions, regardless of how emissions allowances distributed**
- **Effects on capacity as owners become more risk-averse:**
  - **If carbon taxed / allowances auctioned**
    - **gas capacity ↑**
    - **Coal ↓**
  - **If allowances are allocated for free, the <u>reverse</u> happens**

Comments (Cont.)

- Yes, risk aversion matters in simplified model
  - Are policy implications different? (E.g., welfare impacts of policy)
  - Will differences persist if there are many firms, more diverse set of technologies, and financial hedges?
- How might risk aversion be incorporated in large-scale policy models?
  - Defensible heuristics?
  - Estimating degree of risk aversion?

“Computers in the future may weigh no more than 1.5 tons.”

--Popular Mechanics, 1949

"Wall Street indices predicted nine out of the last five recessions ! "

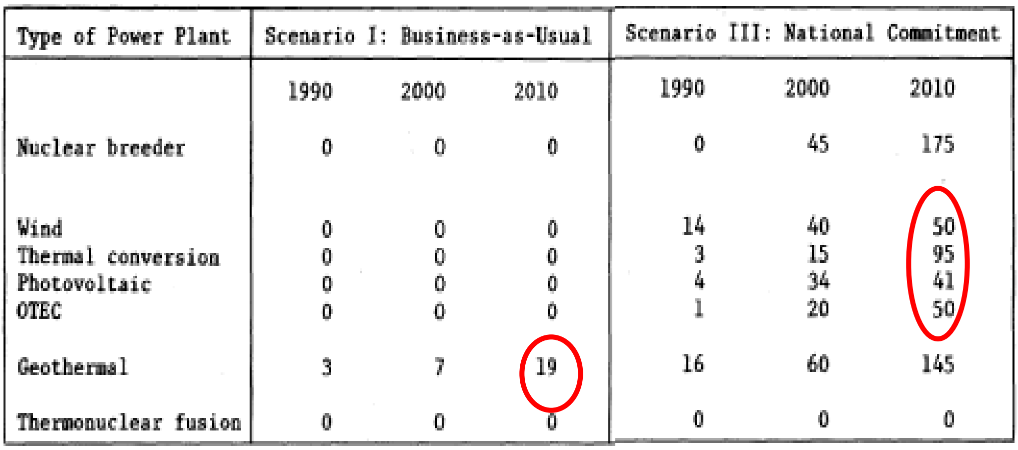
--Paul A. Samuelson in Newsweek, 19 Sep. 1966

"The herd instinct among forecasters makes sheep look like independent thinkers. "

--Edgar R. Fiedler, June 1977

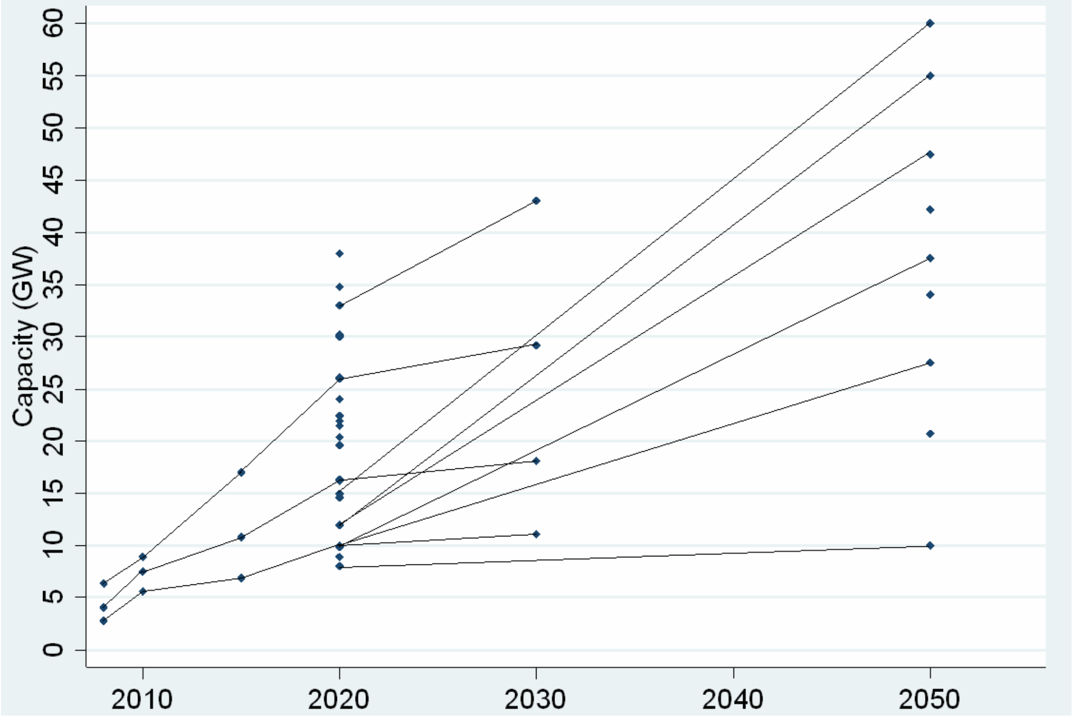
Uncertain Driver: Regulation & Technology

CONAES Report (1978)
Generation Capacity Projections (GW)



Type of Power Plant	Scenario I: Business-as-Usual			Scenario III: National Commitment		
	1990	2000	2010	1990	2000	2010
Nuclear breeder	0	0	0	0	45	175
Wind	0	0	0	14	40	50
Thermal conversion	0	0	0	3	15	95
Photovoltaic	0	0	0	4	34	41
OTEC	0	0	0	1	20	50
Geothermal	3	7	19	16	60	145
Thermonuclear fusion	0	0	0	0	0	0

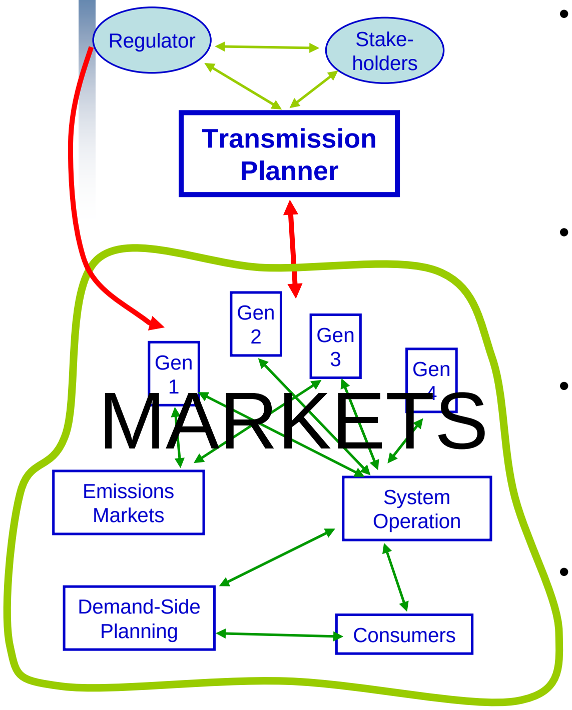
Future UK Wind Scenarios



4. Transmission Planning Under Hyper Uncertainty

(Hobbs, van der Weijde, in process)

Transmission Planning Considering Market Response



- *A "multilevel" (Stackelberg) game:*
  - *Upper level:* **planners (& regulator, stakeholders), who anticipate reactions of …**
  - *Lower level:* **market response of consumers, generators**
- *Account for responses:*
  - **Price effects on resource type and siting decisions**
  - **Effect of CO_2, renewable policies**
- *Possible methods:*
  - **Multilevel program/math program with equilibrium constraints, or**
  - **Simulate market response to finite number of transmission plans**
- *Some Literature*
  - **Sauma & Oren (2007); Roh, Shahidehpour, Wu (2009)**

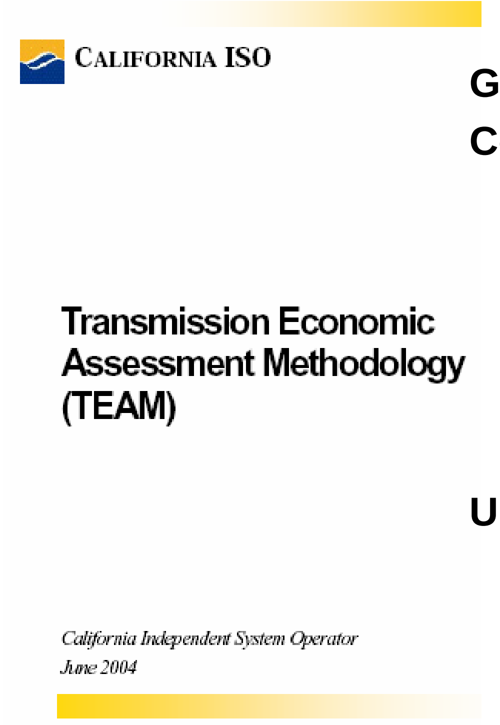
Hyperuncertainty

- Dramatic changes a-coming!
- Renewables
  - How much?
  - Where?
  - What type?
- Other generation
  - Centralized?
  - Distributed?
- Demand
  - New uses? (EVs)
  - Controllability?
- Electricity trade
- Policy

Do these uncertainties have implications for transmission investments *now*?

California's Approach: TEAM

(A. Awad et al., in X.-P. Zhang, ed., "Restructured Electric Power Systems - Analysis of Electricity Markets with Equilibrium Models", in press)



CALIFORNIA ISO

Transmission Economic Assessment Methodology (TEAM)

California Independent System Operator

June 2004

Goal: Estimate transmission benefits

Considers:

- *Savings in operation & construction costs*
- *Efficiency gains due to market power mitigation*
  - Improve supplier access to markets ⇒ lower bid markups
- *Transmission-DSM-Gen substitution*

Uncertainty:

~ *12 large remote renewable areas—which will be developed?*

- *Approach: invest in planning studies & approval for all*
  - creating options to build

Modeling Approaches

- **Presently:**
  - *Single stage decisions under uncertainty*
    - *E.g.,CAISO TEAM; Roh et al. (2009); Merrill et al. (2009)*
  - *Characterization of random flows*
    - *E.g., Bresceti (2004)*
- **Proposed approach:**
  - *Stochastic Two-Stage MPEC with 0-1variables (multiple scenarios), or*
  - *Decision tree analysis with discrete transmission options*
    - *Quantify ECUI, EVPI, option value*

“Radio has no future.”

--Lord Kelvin, ca. 1897

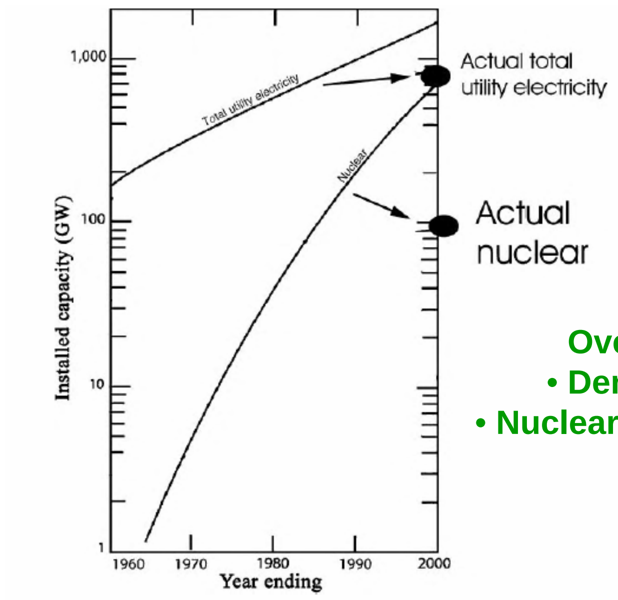
"There is not the slightest indication that nuclear energy will ever be obtainable. It would mean that the atom would have to be shattered at will."

--Albert Einstein, 1932

"An economist is an expert who will know tomorrow why the things he predicted yesterday didn't happen today. "

--Evan Esar

Uncertain Drivers: Technology



Log Scale

Overestimation:
- **Demand by 150%**
- **Nuclear capacity by 800%**

Figure 3 An Atomic Energy Commission forecast from 1962, designed to show demand for nuclear power plants. The curve of interest here shows electricity demand. The authors judgmentally assumed a growing nuclear market share. Actual electricity and nuclear electricity in 2000 is indicated (10).

Source: P.P. Craig, A. Gadgil, and J.G. Koomey, "What Can History Teach Us? A Retrospective Examination of Long-Term Energy Forecasts for the United States," *Annual Review of Energy and the Environment*, 27: 83-118

Conclusion: Uncertainty & Risk Aversion Matter!

1. **Which uncertainties matter most in US power markets?**
   - *CO_2 regulatory uncertainty!*
2. **Risk averse agent modeling for market design**
   - *Risk aversion ⇒ sloped demand curves for generation capacity are preferred*
3. **Including risk aversion in equilibrium models**
   - *Risk aversion shifts equilibrium towards "worst case" for owners*
4. **Transmission planning under uncertainty**
   - *Two-stage stochastic leader-follower game framework for insights on robust investments*