JOHNS HOPKINS
ENVIRONMENT, ENERGY, SUSTAINABILITY & HEALTH INSTITUTE

Modeling Electricity Markets & Policy with Optimization: Why It's Important (and Fun!)

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Outline

I. Why is power fun?
Ubiquitous uncertainty

II. Why is power *modeling* fun?

III. Fun with simple models
Who should limit their CO_2 emissions: generators or consumers?

IV. Fun with complex models
Dealing with uncertainty:
Where & when to build transmission?

V. Conclusions

I. Why is the Power Sector Fun?

http://cdn.themetapicture.com/media/funny-cat-static-electricity.jpg

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I. Why is the Power Sector Fun?

- *Unique physics*
- *Economy's lynchpin*
- *Environmental impacts*
  … and potential
- *Ongoing restructuring*
- *Dumb grids*
- *Surprises*

www.fuelyourwriting.com/start-the-story-where-do-we-begin-01-25-10/

Why Power? Surprises

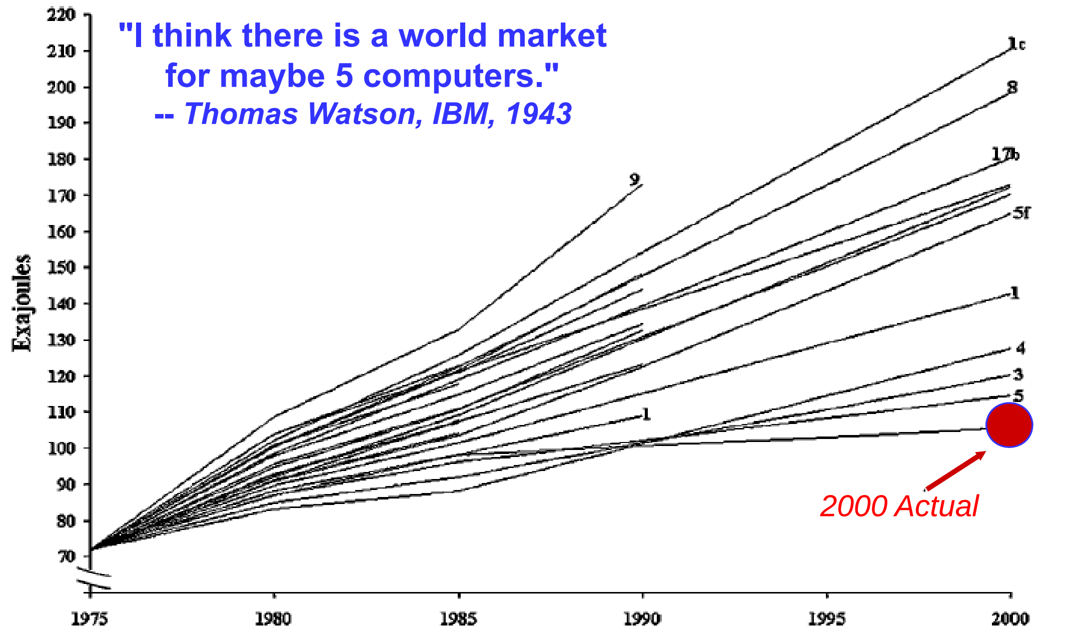

Figure 1 Projections of total U.S. primary energy use from the 1970s. The figure is redrawn from a Department of Energy report (3) and simplified from a summary of dozens of forecasts.

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

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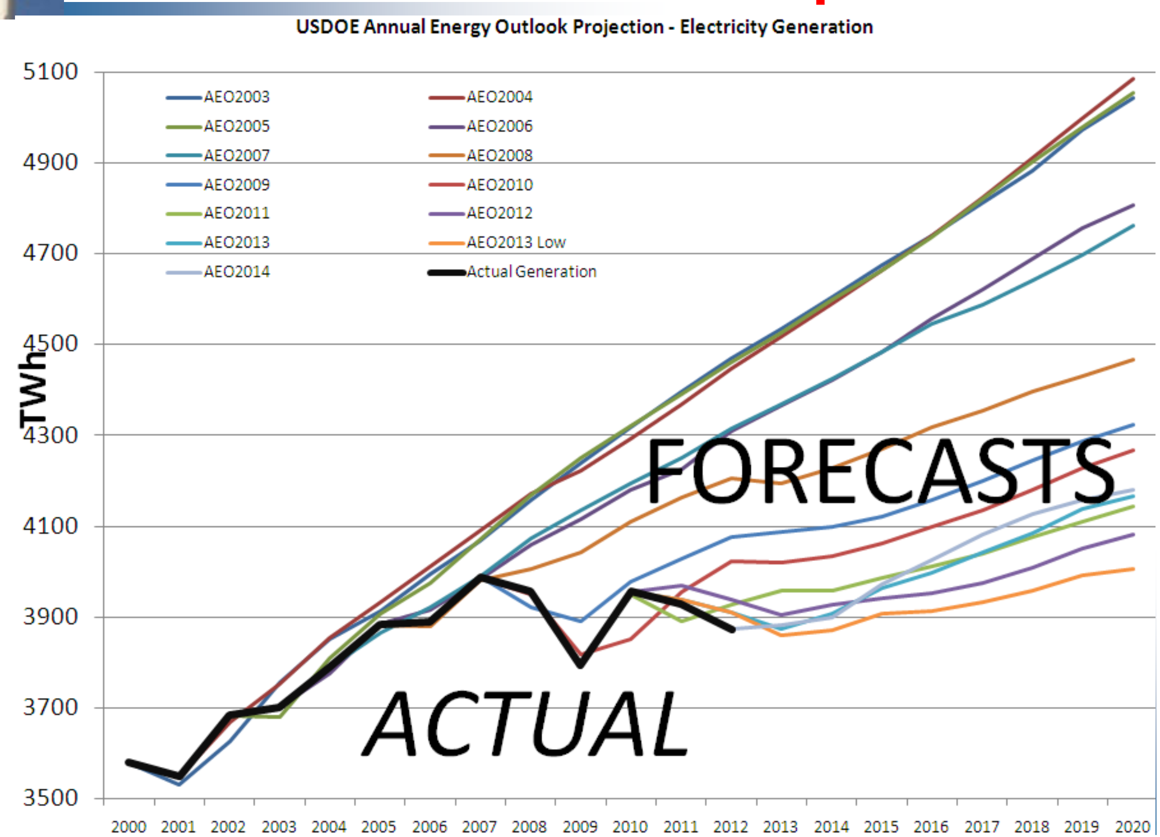
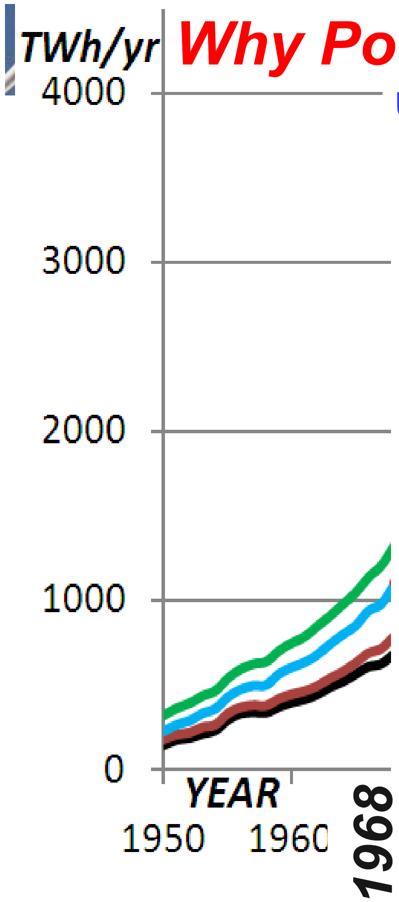
….& More Demand Surprises



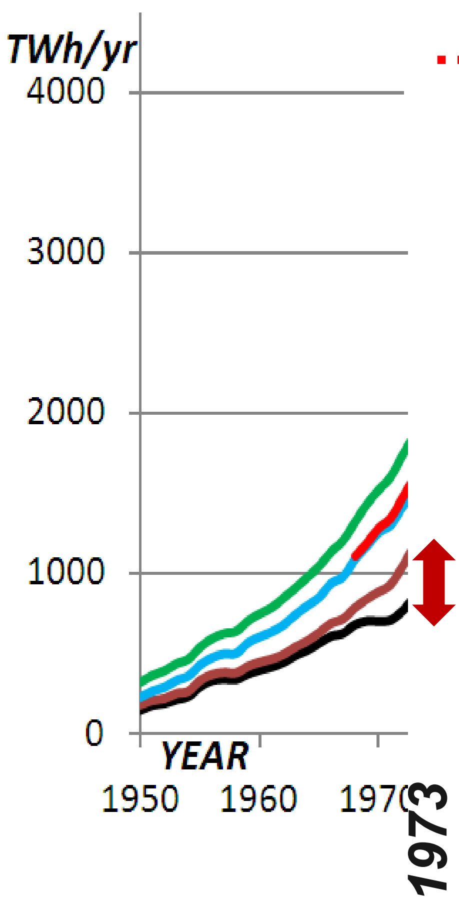
Why Power? Surprising Twists..

US Electric Production (source: USEIA AEO)



Early:
Old King Coal
… + Hydro
& Gas Steam

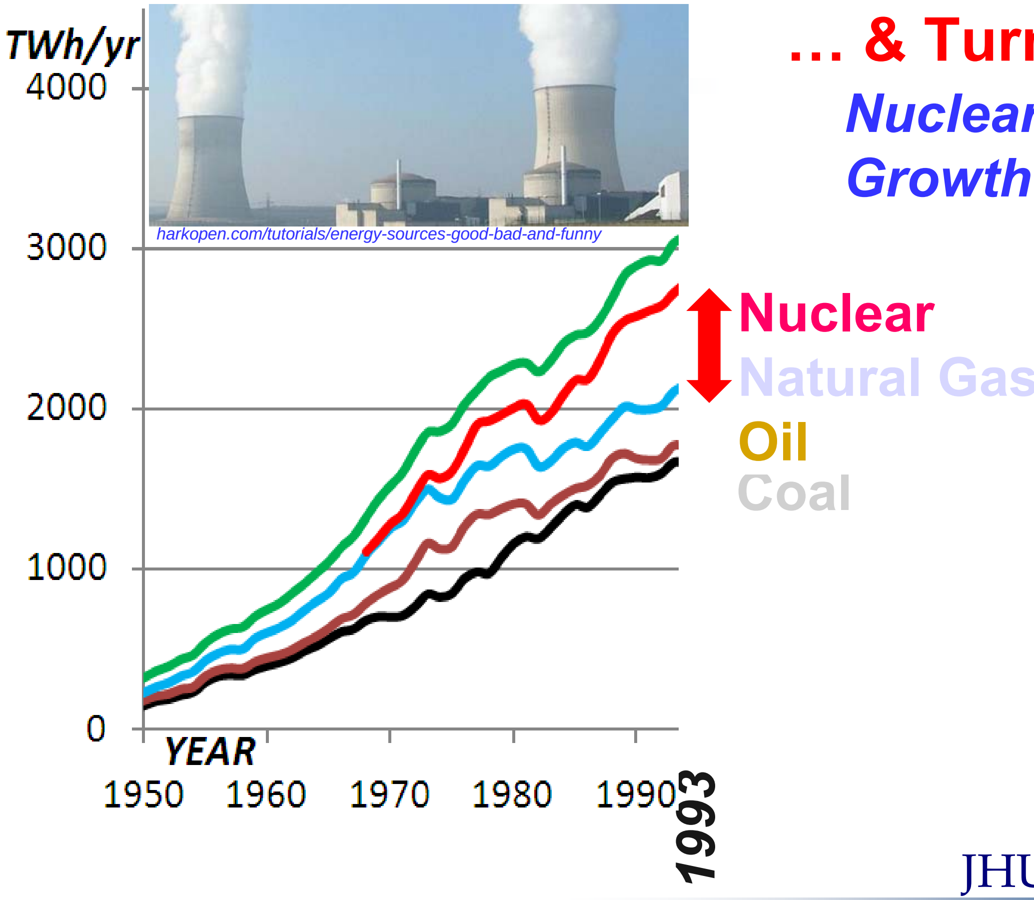
… and Turns



1960's:
Rise of Oil

bakersfieldinternational.com/products.html

… & Turns *Nuclear Growth*



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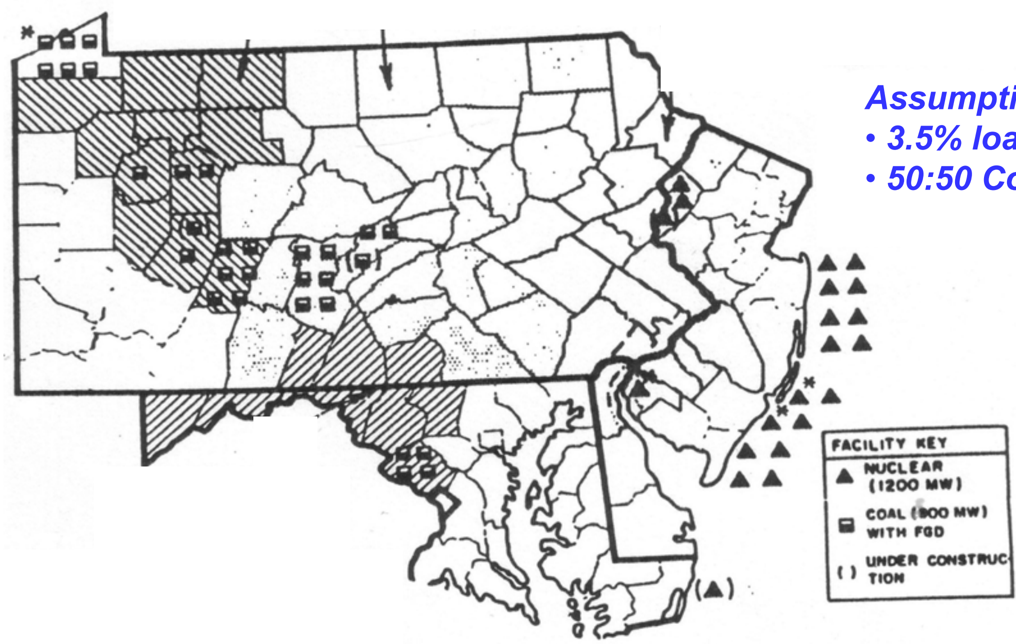
Mea Culpa – a 1979 Forecast

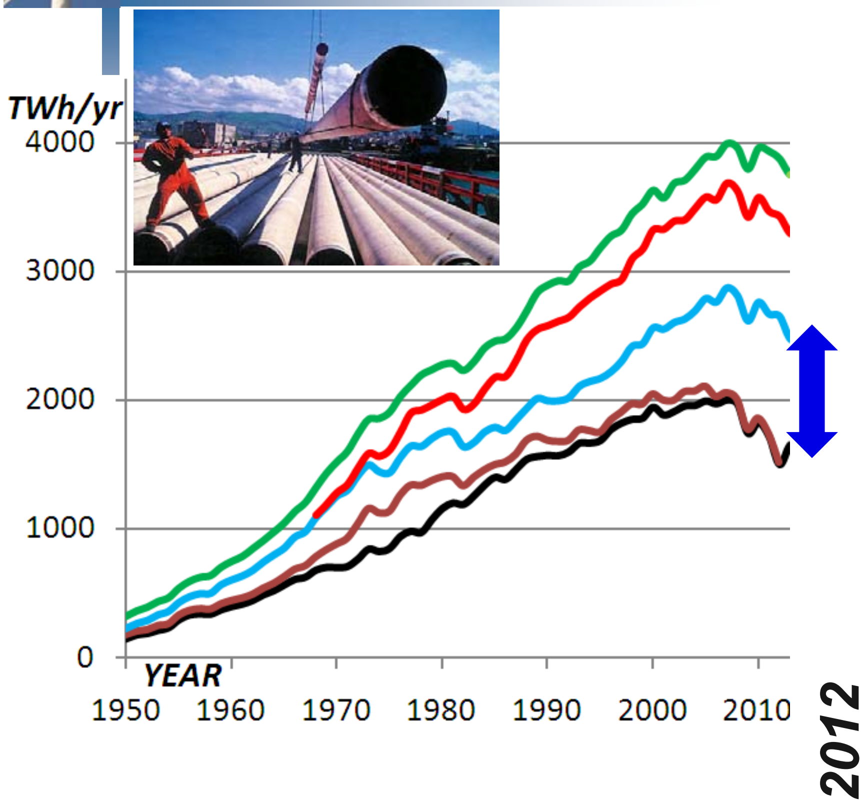
MidAtlantic1985-2000 Power Plant Siting Scenario

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



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

… & Turns



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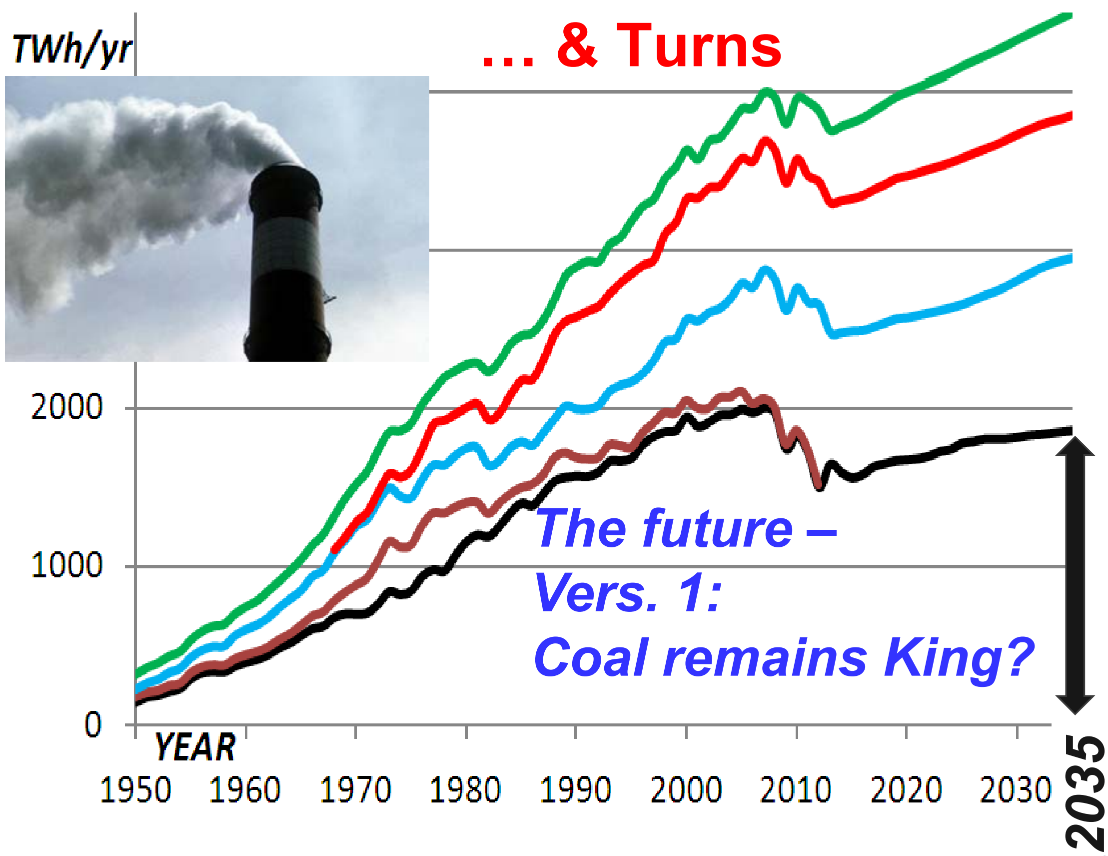
… & Turns



suckprofessor.com/words/cows-on-treadmills-make-electricity-with-jokes/

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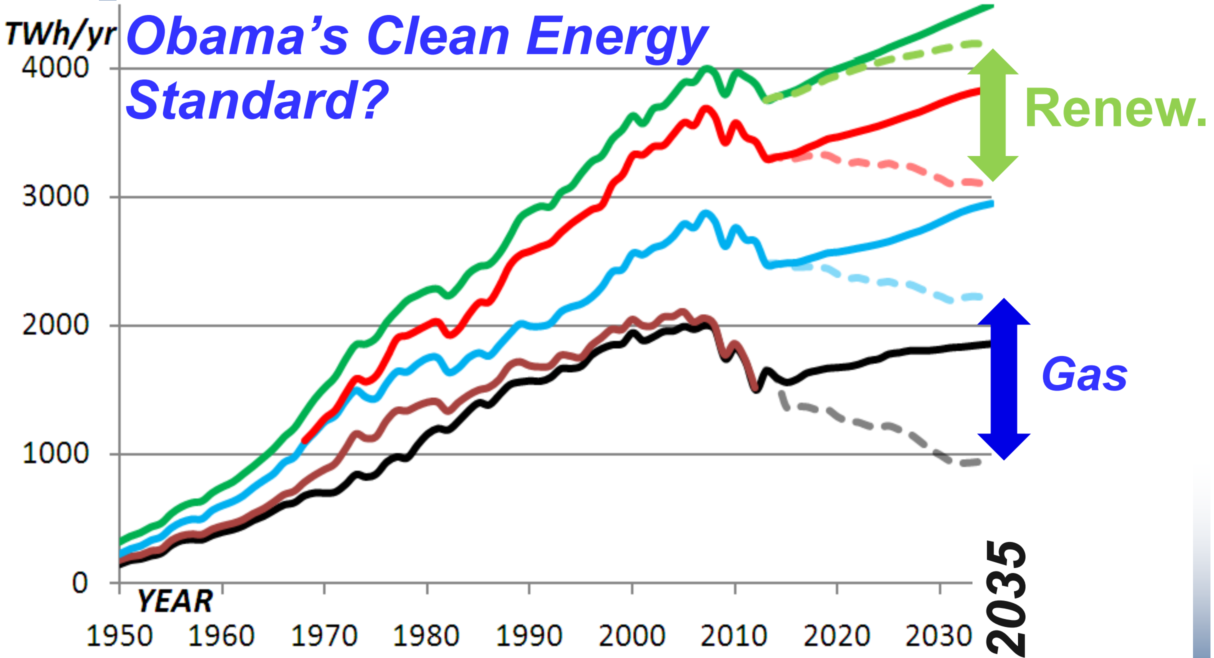
Upcoming: The Biggest Turn?

The future – Vers. 2: Obama's Clean Energy Standard?



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Yet More Surprises: Wind

Source: http://fresh-energy.org/2012/06/skeptical-about-renewable-energy-predictions-you-should-be/

IEA World Energy Outlook **(2000):**

- **3% of global energy will be non-hydro renewable by 2020**
  - **Reached in 2008**
- **30 GW world wind by 2010**
  - **Actually: 200 GW**
    - **40 GW in US (DOE(1999) predicted 10 GW)**
    - **45 GW in China (IEA said 2 GW)**

Upshot of surprises

- **Is modeling useless?**
- **Nieubuhr's *Serenity Prayer***

II. Why is power *modeling* fun?

- Math & computing challenges
- Counterintuitive economic behavior
- Lots of data
- Lots at stake!
  - Done wrong →hurt economy & environment
  - Done right, → an efficient & cleaner future

Definition of Electric Power Models

- *Models that:*
  - optimize or simulate …
  - operations & design of …
  - production, transport, & use of power …
  - & its economic, environmental, & other impacts …
  - using math & computers

- *Focus here: "bottom up" engineering-economic models*
  - Technical & behavioral components
  - Used by:
    - Companies
      - *max profits*
    - Policy analysts
      - *simulate market's reaction to policy*

Elements of Eng-Econ Models

- ***Decision variables***
- ***Objective(s)***
- ***Constraints***

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Example: Operations Optimization

MW output generator *i* during period *t*

MIN Variable Cost $= \Sigma_{i,t} C_{it} g_{it}$

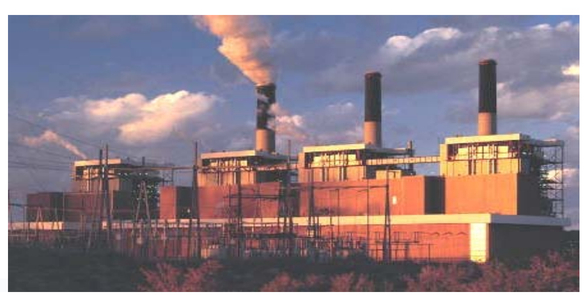
Subject to:

Meet demand: $\Sigma_i g_{i,t} = D_t \;\; \forall t$ ***Dual*** λ_t ***= marginal price***

Respect plant limits:

$$0 \le g_{i,t} \le CAPACITY_i \qquad \forall i,t$$

D and CAPACITY also can be decisions



All Models are Wrong … Some are Useful

- ***Small models***
  - Quick insights in policy debates
    - Theorems → general conclusions
    - Examples → possibility proofs
  - Need:
    - transparency to show implications of assumptions
- ***Large models***
  - Actual grid operations & planning
  - Need:
    - implementable numerical solutions
- ***In-between models***
  - Forecasting & impact analyses of policies
  - Need:
    - ability to simulate many scenarios
    - represent "texture" of actual system

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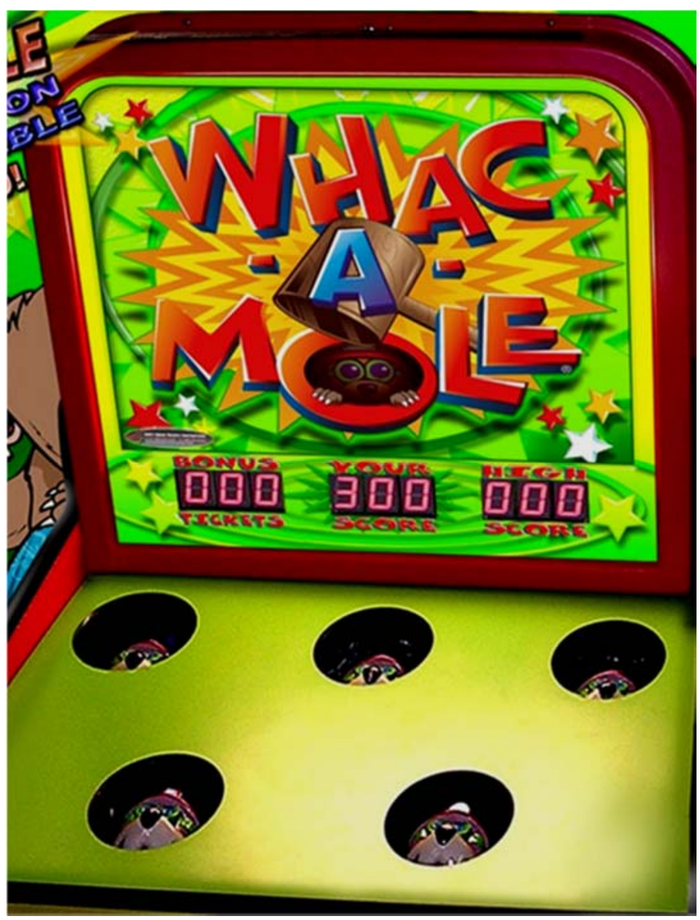
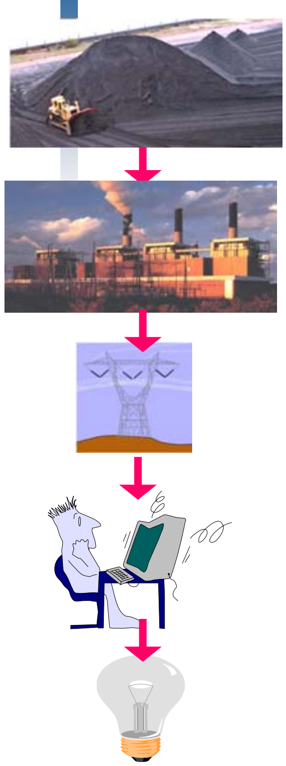
Fun with Models

Fun **≡**
Conclusions that surprise & overturn policy beliefs



III. *Fun with Simple Models: Complementarity Model of AB32 CO_2 Market*

Who should be responsible for reducing CO_2?



Fuel extractors?

Oil producers/importers (US Waxman-Markey bill)

Power plants?

Power plants (EU Emissions Trading System)

US: Title IV SO_2; State greenhouse gas initiatives (RGGI)

Transmission grid/system operator?

In a single-buyer "POOLCO"-type power market

Retail suppliers/Load serving entities?

California, Western US "Load-Based" proposals

Consumers?

Tradable Quotas, Personal Carbon Allowances

Example: The California Debate

(Hobbs, Bushnell, Wolak, *Energy Policy*, 2010;
Liu, Chen, Hobbs, *Operations Research*, 2011)

Gov. Schwarzenegger is joined by international leaders with a consistent record of addressing the global threat of climate change, New York Governor George Pataki and other environmental and industry leaders at a bill signing for AB 32 on Treasure Island in San Francisco on Tuesday, September 27, 2006.

- ***California AB32:***
  - Goal: Reduce CO_2 to 1990 levels
- ***Debate: 'Point of Compliance'***
  - I.e., Who must hold permits to cover their emissions?
    - Power plants (sources)?
    - Load serving entities (LSEs) (acting for consumers)?
  - Elsewhere, <u>source</u>-based dominates
    - Allocate allowances to power plants, and then trade
      - Total emissions can't exceed cap
    - US Title IV SO_2 , US RGGI, EU ETS
  - <u>Load</u>-based proposed in 2007 for California
    - ~~Average emissions of LSE bulk power purchases ≤ cap~~
    - ~~Cheaper (Synapse Energy, 2007)?~~
    - ~~Provide more motivation for energy efficiency (NRDC)?~~

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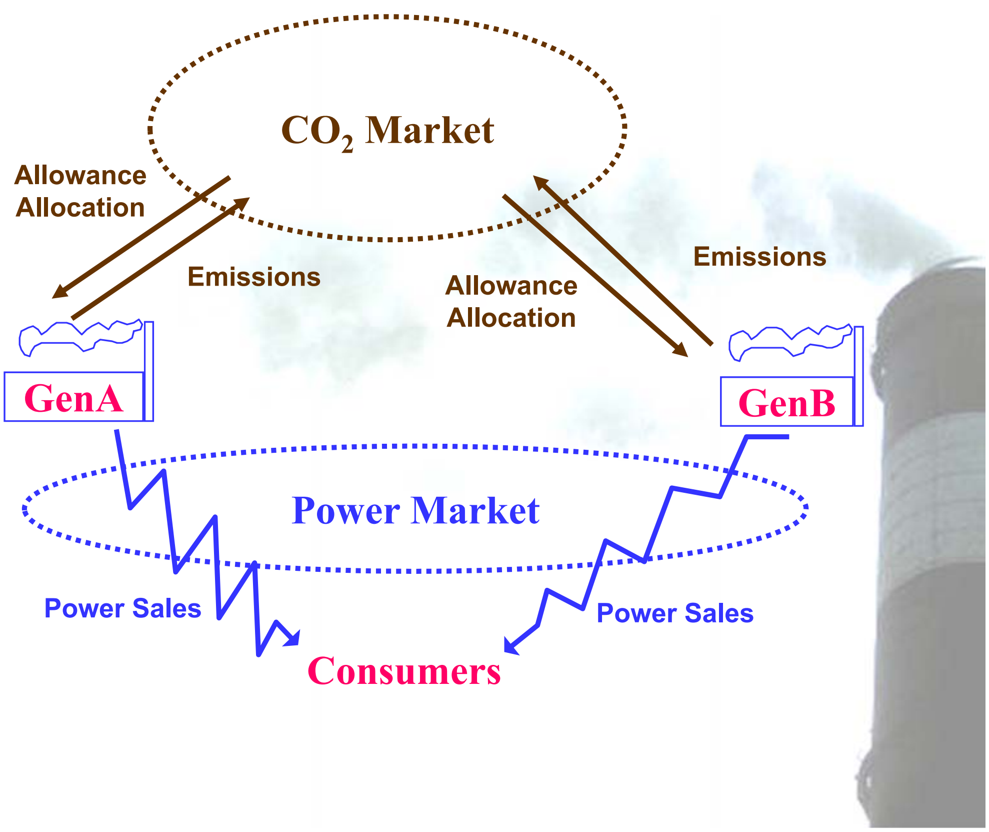
www.wingas-uk.com

Source-Based Market Schematic



Source-Based (Competitive) Market: Market Participants' Optimization Problems

CO_2 Market:

$E_A g_A + E_B g_B$

$\leq ALLOW_A + ALLOW_B \;\; (= E_{max})$

(Price = p_{CO2})

GenA chooses $g_A \geq 0$:

MAX $(p_A - C_A - p_{CO2} E_A) g_A + p_{CO2} ALLOW_A$

subject to: $g_A \leq G_A$

GenB chooses $g_B \geq 0$:

MAX $(p_B - C_B - p_{CO2} E_B) g_B + p_{CO2} ALLOW_B$

s.t.: $g_B \leq G_B$

Power Market

$g_A = d_A$
(Price = p_A)

$g_B = d_B$
(Price = p_B)

Consumers choose $d_A, d_B \geq 0$:

MIN $p_A d_A + p_B d_B$

s.t.: $d_A + d_B = D$

What's the equilibrium?

Source-Based Market Equilibrium Problem: Find $\{p_A, p_B, p_{CO2}; g_A, \mu_A; g_B, \mu_B; d_A, d_B, \lambda\}$ satisfying:

$E_A g_A + E_B g_B$

$\leq ALLOW_A + ALLOW_B \; = E_{max}$

(price = p_{CO2})

$0 \leq g_A \perp p_A - C_A - p_{CO2} E_A - \mu_A \leq 0$

$0 \leq \mu_A \perp g_A - G_A \leq 0$

$0 \leq g_B \perp p_B - C_B - p_{CO2} E_B - \mu_B \leq 0$

$0 \leq \mu_B \perp g_B - G_B \leq 0$

$g_A = d_A$
(price = p_A)

$g_B = d_B$
(price = p_B)

$0 \leq d_A \perp p_A - \lambda \leq 0$

$0 \leq d_B \perp p_B - \lambda \leq 0$

$d_A + d_B = D \quad (\lambda)$

10 Conditions, 10 Unknowns

Load-Based Market: Market Participant Optimization Problems

GenA chooses $g_A \geq 0$:
MAX $(p_A - C_A)g_A$
subject to: $g_A \leq G_A$

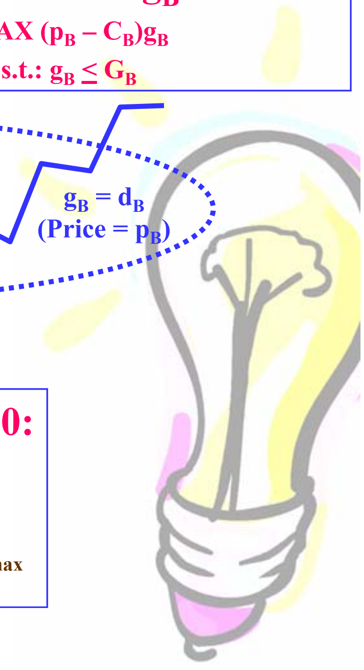
GenB chooses $g_B \geq 0$:
MAX $(p_B - C_B)g_B$
s.t.: $g_B \leq G_B$

Power Market

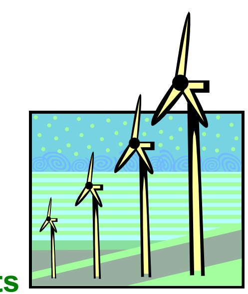
$g_A = d_A$
(Price = p_A)

$g_B = d_B$
(Price = p_B)

Consumers choose $d_A, d_B \geq 0$:
MIN $p_A d_A + p_B d_B$
s.t.: $d_A + d_B = D$
$E_A d_A + E_B d_B \leq \text{Load*ERate}_{max} = E_{max}$



Analytical Conclusions



- *Power prices:*
  - *Same* for all plants in source-based system
  - *Differentiated* in load-based system
    - higher for cleaner plants
    - endangers efficiencies of PJM-like spot markets
- *Allowance prices the same*
- ~~*"Load side carbon cap is likely to cost California consumers significantly less than supply side cap--Potentially billions of dollars per year."* (*"Exploration of Costs for Load Side and Supply Side Carbon Caps for California," B. Biewald, Synapse Energy, Inc., Aug. 2007*)~~
  - Actually, net costs to consumers same …
  - … *If* auction permits to generators, & consumers get proceeds

    …and *if* no damage to spot markets

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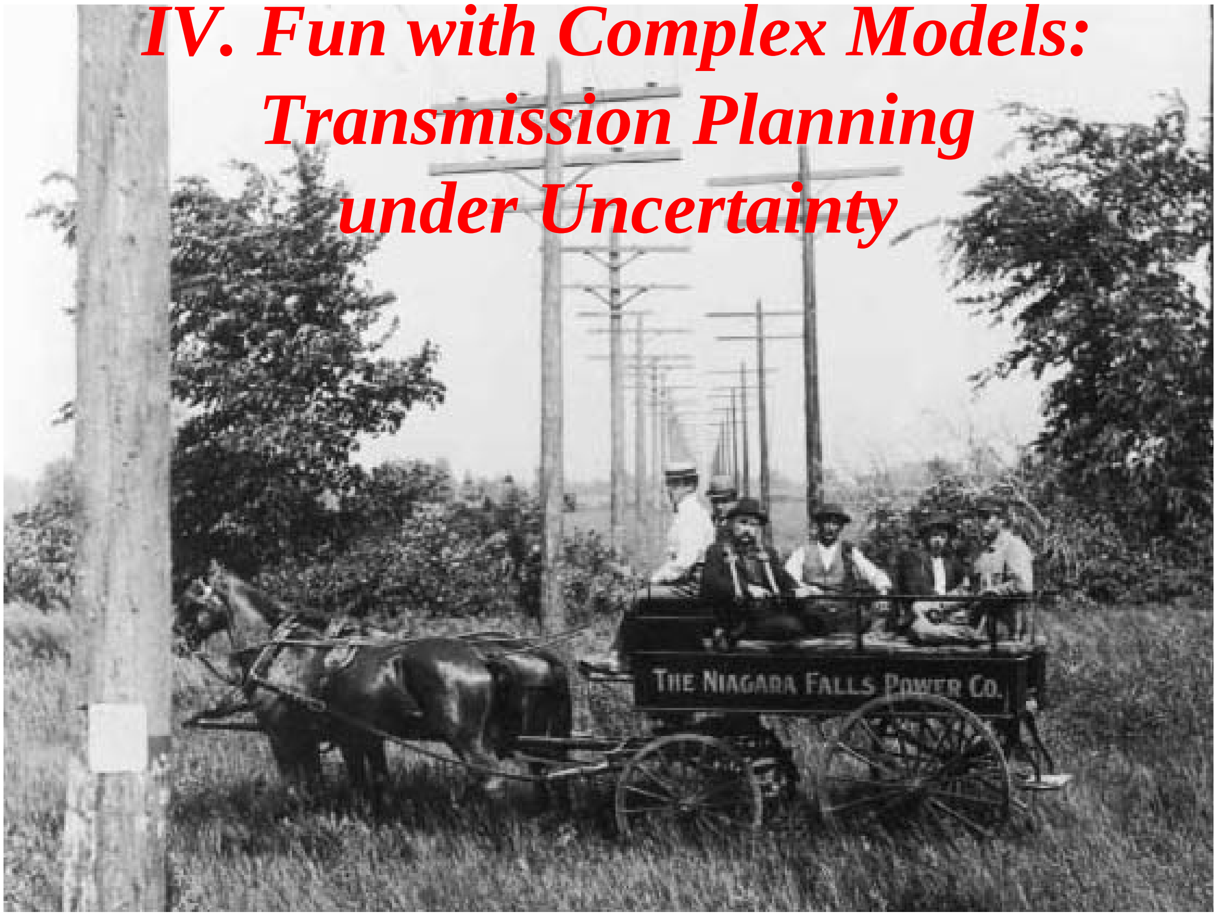
IV. Fun with Complex Models: Transmission Planning under Uncertainty



The Challenge: Hyperuncertainty:

What's a Poor Transmission Planner to do?

(van der Weijde, Hobbs, *Energy Economics*, 2012; Munoz & Hobbs, *IEEE Trans. Power Systems, 2014*)

Dramatic changes a-coming!

- Renewables
  - How much?
  - Where?
  - What type?
- Other generation
  - Centralized?
  - Distributed?
- Demand
  - New uses? (electric cars)
  - Controllability?
- Policy

???

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The problem

Planning

- Decisions can be postponed: *multi-stage*
- Uncertainties & variability: *stochastic*

Important questions:

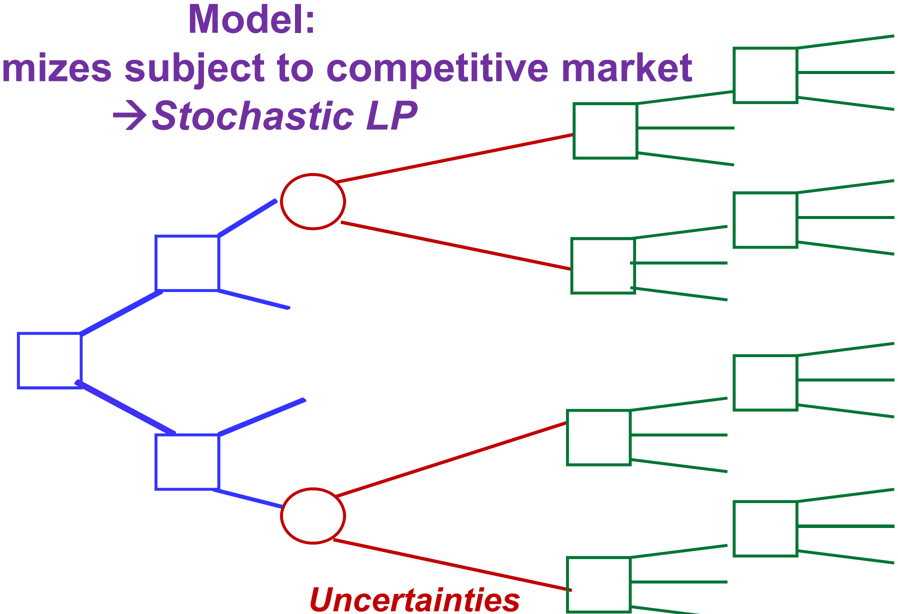
- Optimal strategy under uncertainty?
- Value of information?
- Cost of ignoring uncertainty?
- Option value of being able to postpone?

Deterministic planning can't answer!

- Stochastic multilevel can! (*Fun*)

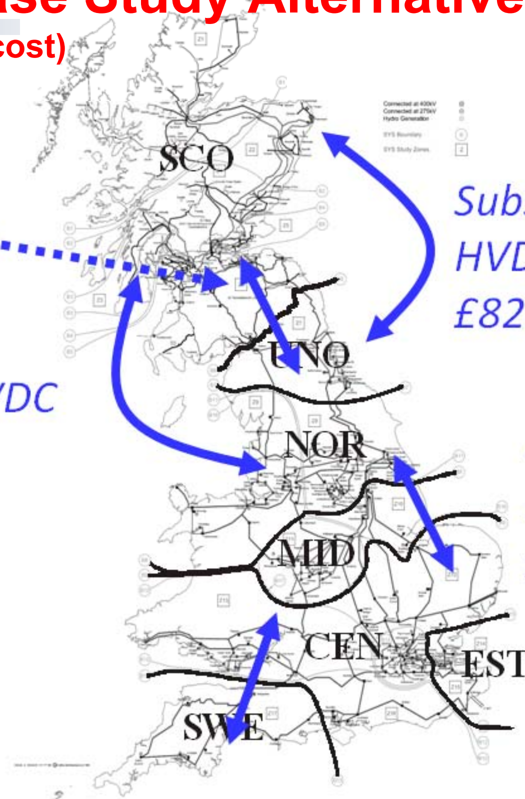
Two Stage Transmission Planning Under Uncertainty

Model:
Grid optimizes subject to competitive market
→*Stochastic LP*



Great Britain Case Study Alternatives

(overnight construction cost)



Various new/ upgrades £353M

Subsea HVDC £829M

Subsea HVDC £805M

Onshore HVDC £593M

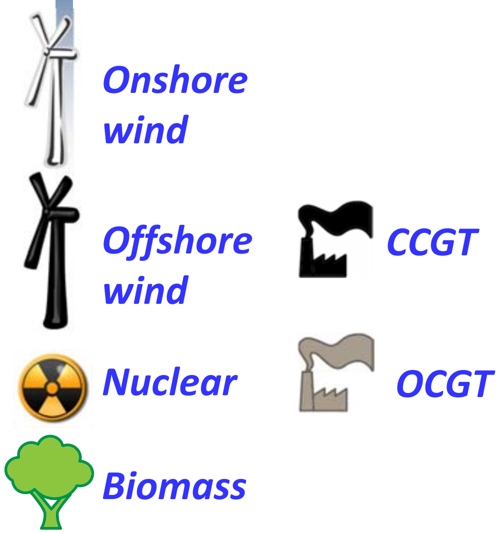
Various new/ upgrades £286M

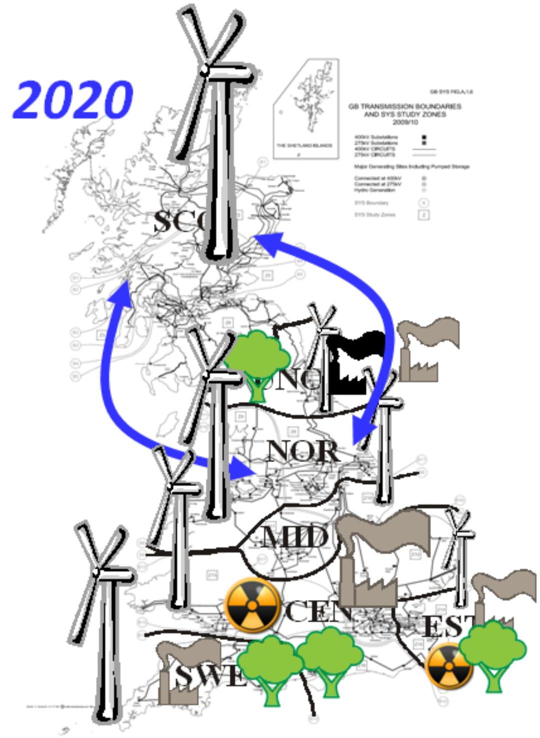
All Are Recommended By UK National Grid

Scenarios

Variables: / Scenarios	Gen. inv. cost	Var. gen cost	Trans. inv. cost	Demand	CO_2 price	Others
Status Quo						
Low cost DG						
Low Cost Large Scale Green						
Low Cost Conventional						
Paralysis						
Techno+						

Optimal stochastic solution





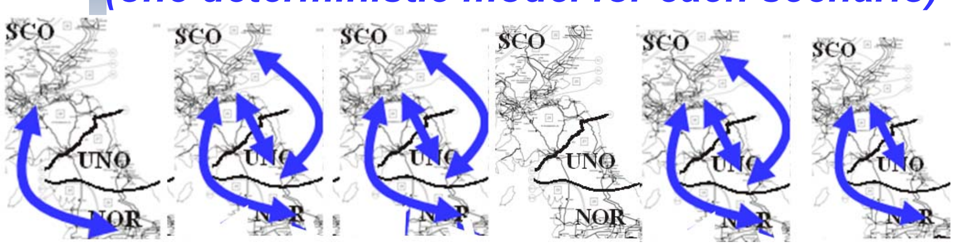
Fun: Uncertainty Means Optimal to Delay

Cf. Traditional robustness analysis

2020 Installations by Scenario

(one deterministic model for each scenario)

"Robust?"



Scenario

Status Quo

Low Cost Distributed Gen

Low Cost Green

Low Cost-- Conventional

Paralysis

Techno+

"Robust"= Lines chosen by every deterministic model

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Cost of ignoring uncertainty

- How much do costs worsen *if* we naively plan for one scenario but others can happen?
  1. Smart solution: solve stochastic model
  2. Naïve solution:
     a. Solve (deterministic) model assuming "base case" scenario
        → naïve stage 1st decisions
     b. Then solve stochastic model, but imposing naïve 1st stage decisions
        → 2nd stage decisions
  3. Compare cost of (1) and (2)

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Cost of ignoring uncertainty (for Transmission Planner only)

Scenario planned for	Cost of Ignoring Unc.
Status Quo	£111M
Low Cost Distributed Gen	£4M
Low Cost Large Scale Green	£4M
Low Cost Conventional	£487M
Paralysis	£4M
Techno+	£7M
Average	£103M (0.1%)

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Large Problem: Western US 240-bus Test Case ~ 10^6 -10^7 Variables

(Munoz et zl. IEEE Trans. Power Systems, 2014)

WECC 240-bus system:

(Price & Goodin, 2011)

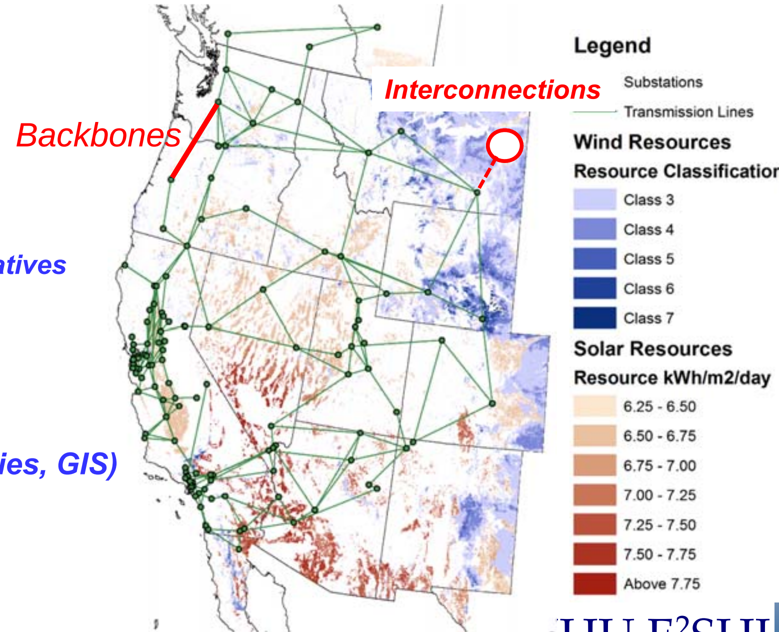
140 Generators (200 GW)
448 Transmission elements
21 Demand regions

Candidate Transmission Alternatives

Renewables data (Time series, GIS)

(NREL, WREZ, RETI)

54 Wind profiles
29 Solar profiles



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V. Conclusions

- ***Need insight in policy & market design ⇒***
  - **Models that are simple, transparent, general**
  - **Economic fundamentals**
- ***Need implementable solutions that recognize uncertainty ⇒***
  - **Particular solutions for particular places**
  - **Computational technology needed for large-scale stochastic, non-convex problems**
- ***Power will only become more important***
  - **Goals: competition benefits + sustainability**
  - **Planning & operations to include lots of renewables -- reliably & economically**

HAVE FUN!

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Questions?
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The Johns Hopkins University
Google images / foreverinhell.com