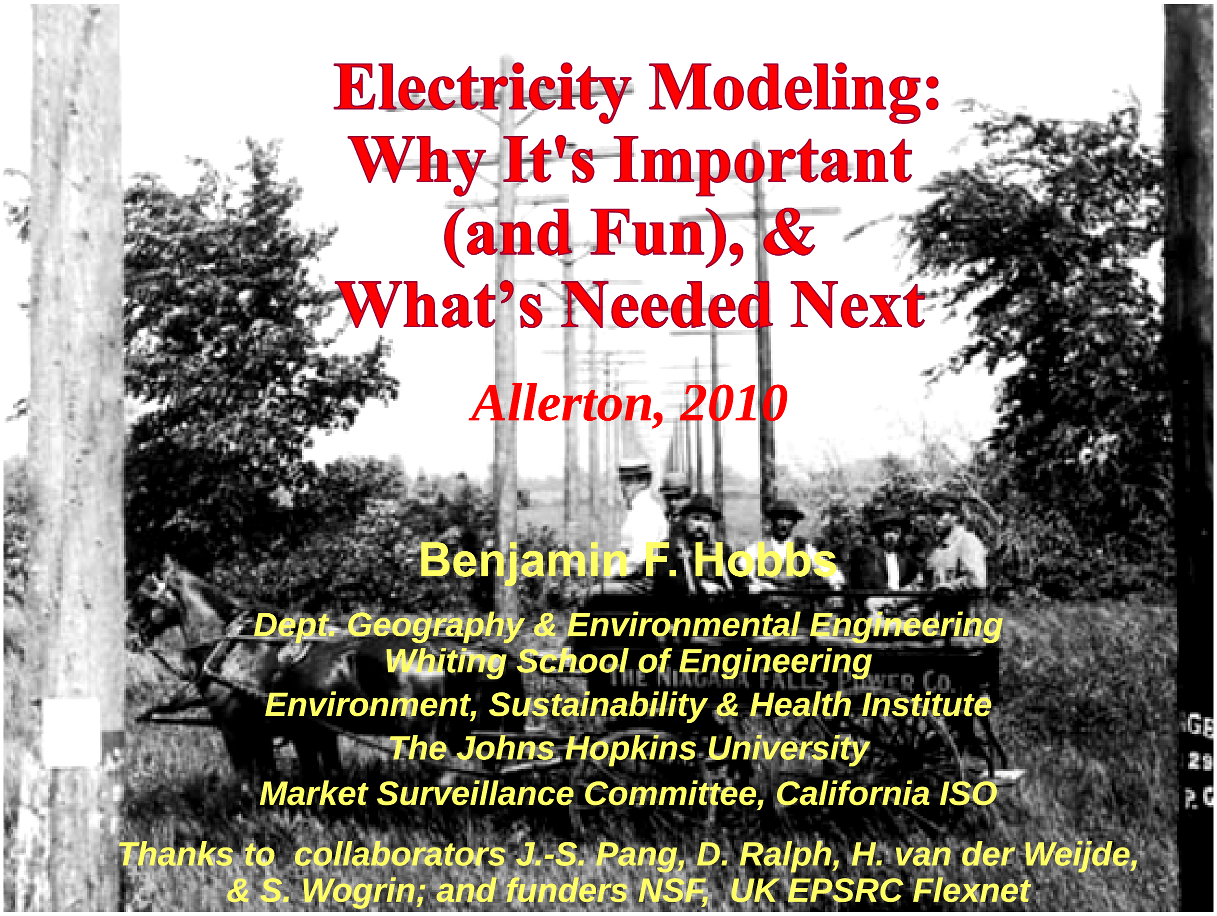

Electricity Modeling: Why It's Important (and Fun), & What's Needed Next

Allerton, 2010

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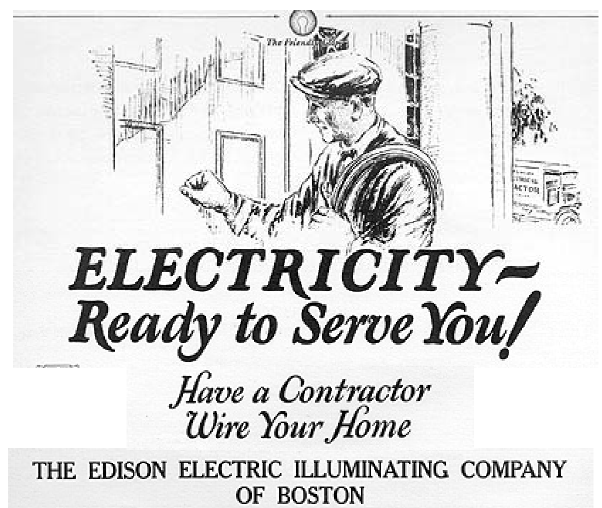
Outline



I. Why power?
II. Example models
III. Model uses
IV. Examples of wrong & useful models
V. Two modeling needs & some results
   -- Better game models
   -- Stochastic decision models

Definition of Electric Power Models

- *Models that:*
  - simulate or optimize …
  - operation of & investment in …
  - generation, transmission & use of electric power …
  - and their economic, environmental & other impacts …
  - using mathematics &, perhaps, computers

- *Focus here: "bottom-up" or "process" engineering economic models*
  - Technical & behavioral components
  - Used for:
    - firm-level decisions
      - e.g., MAX profits
    - policy-analysis
      - simulate reaction of market to policy

1. Why Power & Power Models?

- Why is modeling electricity fun?
  - Mathematically/computationally challenging
  - Interesting economic behavior
  - Lots of data
  - Prediction is so hard
  - Practically important: Big stake decisions
    - Done wrong, it hurts the economy & environment
    - Done right, it could help to create a more efficient & cleaner future

Why Power?
(1) Economy's Lynchpin

Economic impact

- ~50% of US energy use
- >$1000/person/y in US (~oil)
  - 2.5% of GDP (10x water sector)
- Most capital intensive

Consequences when broken

- 2000-2001 California crisis
- Chronic third-world shortages

Ongoing restructuring

- Margaret & Fred
- Spot & forward markets
- Horizontal disintegration, mergers
- Vertical disintegration
  - Generation—transmission—distribution
  - Access to transmission

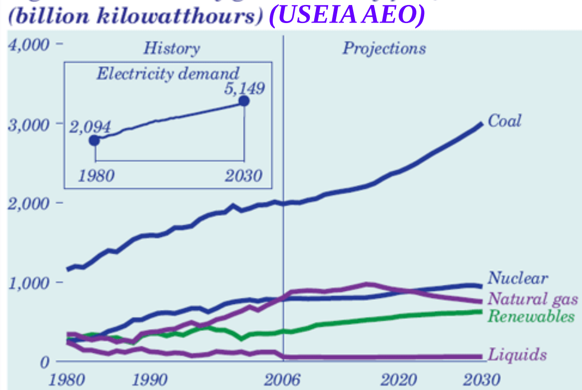
Why Power?
(2) Environmental impact

Environmental impact

- 'Conventional' air pollution: 3/4 US SO_2, 1/3 NO_x
- 40% of CO_2 in US

  .. and growing

Figure 4. Electricity generation by fuel, 1980-2030 (billion kilowatthours) (USEIA AEO)



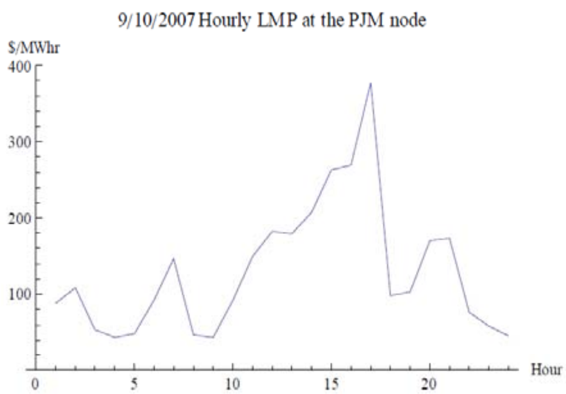
- Landscapes vs. transmission, wind mills, …
- Headaches: Fuel depletion, nuclear waste
- But could solve problems – e.g., electrify vehicles

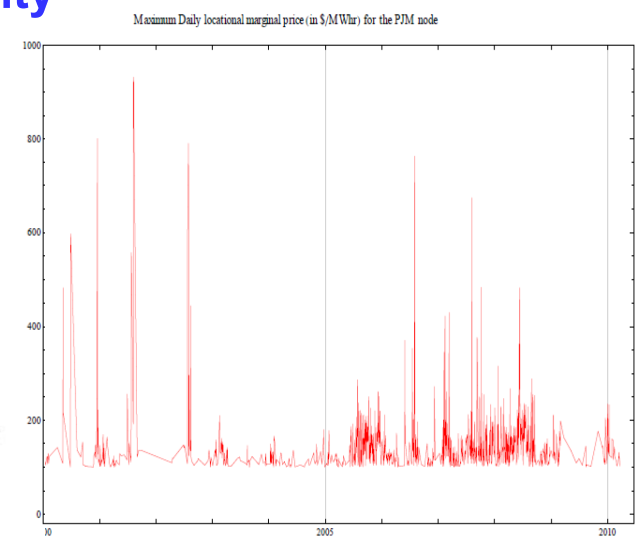
Why Power? (3) The Ultimate Just-In-Time Product

<u>Little storage/buffering</u>

- Must balance supply & demand in real time

⇒ Huge price volatility





Why Power? (4) Dumb Grids

- Physics of networks
  - North America consists of 3 synchronized machines
  - What you do affects everyone else ⇒ must carefully control to maintain security.
    - E.g., parallel flows due to Kirchhoff`s laws
- Valveless networks

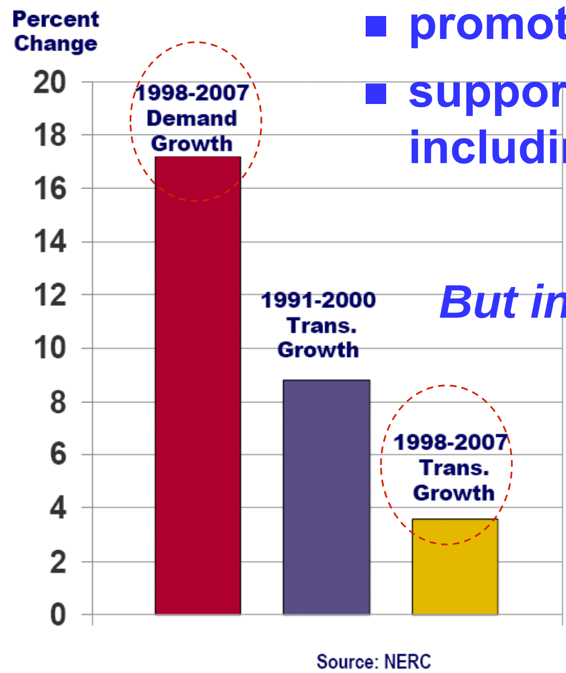
- St. Fred's dream remains just that
  - Broken demand-side of market

grtu.net/data/index.php?Itemid=44&id=689&option=com_content&task=view

Why Power?

(5) Society demands that the grid:

- improve reliability and security
- promote contestability of markets
- support new supply development, including renewables



But inadequate response

Why Power?

(6) Economic fundamentals ease modeling

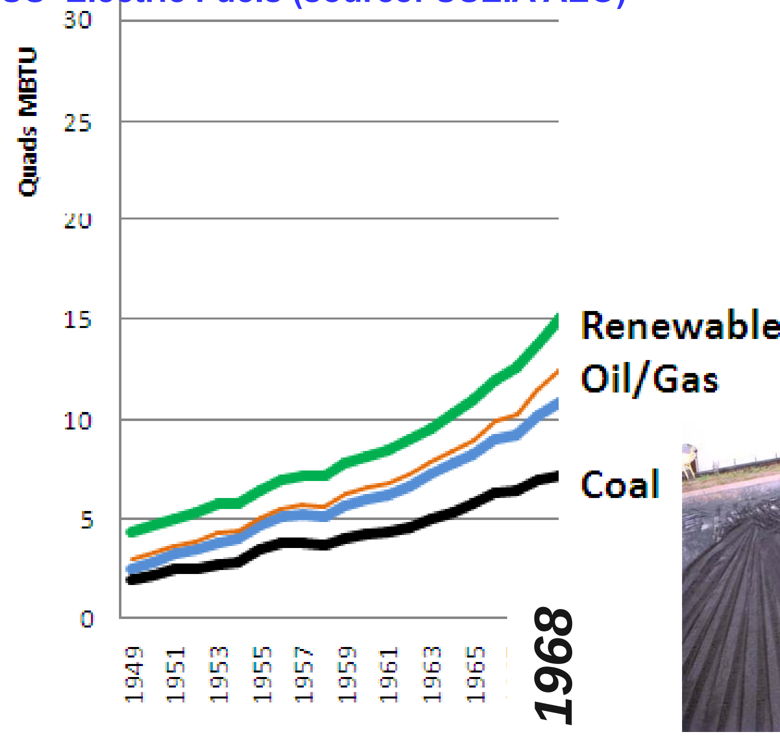
- Since 1980 in energy & environmental sectors:
  - Liberalized markets increasingly make decisions
  - Decisions increasingly reflect fundamentals

  ⇒Rational resource allocation easier to model

- However, recent reversals in EU:
  - UK lost confidence in power markets
  - EU CO_2 trading system sets price “too” low
- … and in the US:
  - Court overturned EPA CAIR’s NO_x trading system
  - US Congress failed to pass CO_2 legislation
  - So EPA & states stepping in with (depressingly) inefficient and inconsistent rules

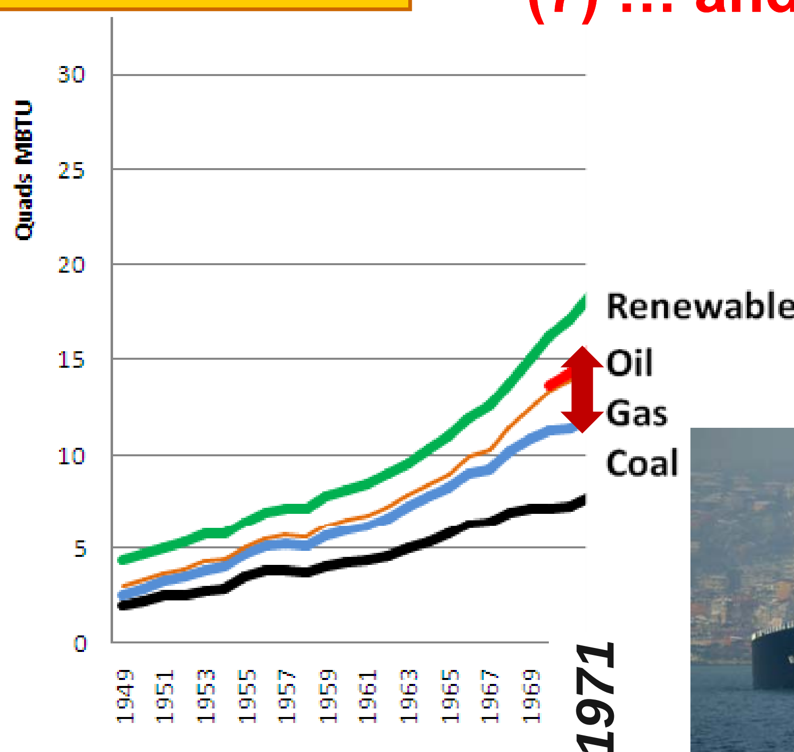
Why Power?
(7) Surprising Twists..

US Electric Fuels (source: USEIA AEO)



Early:
Old King Coal
… + Hydro
& Gas Steam

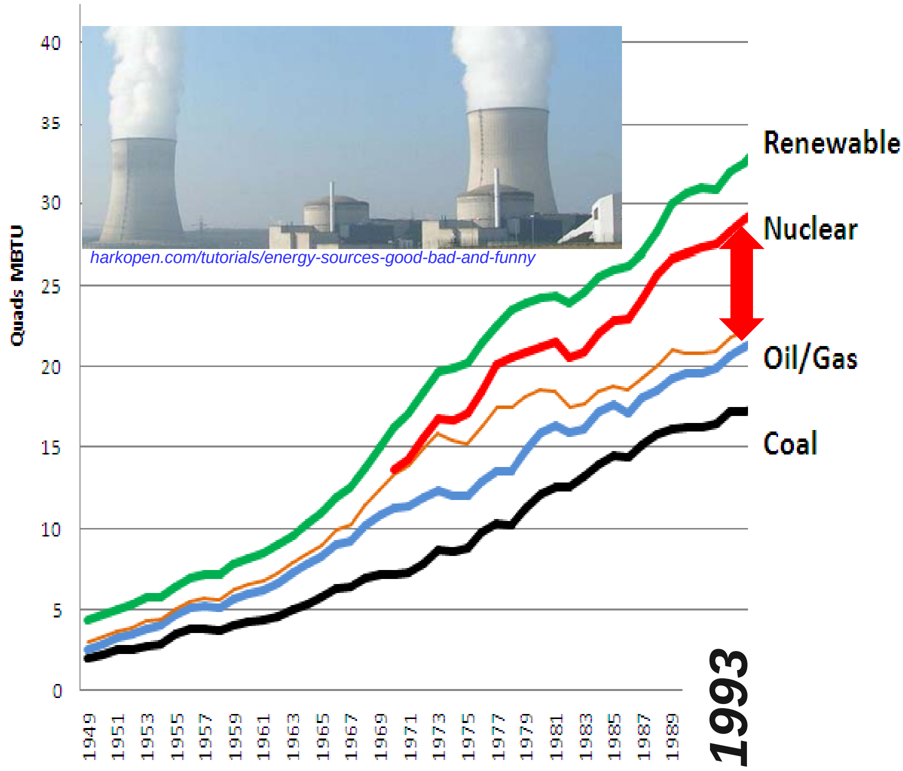
Why Power?
(7) … and Turns



1960's:
Rise of Oil

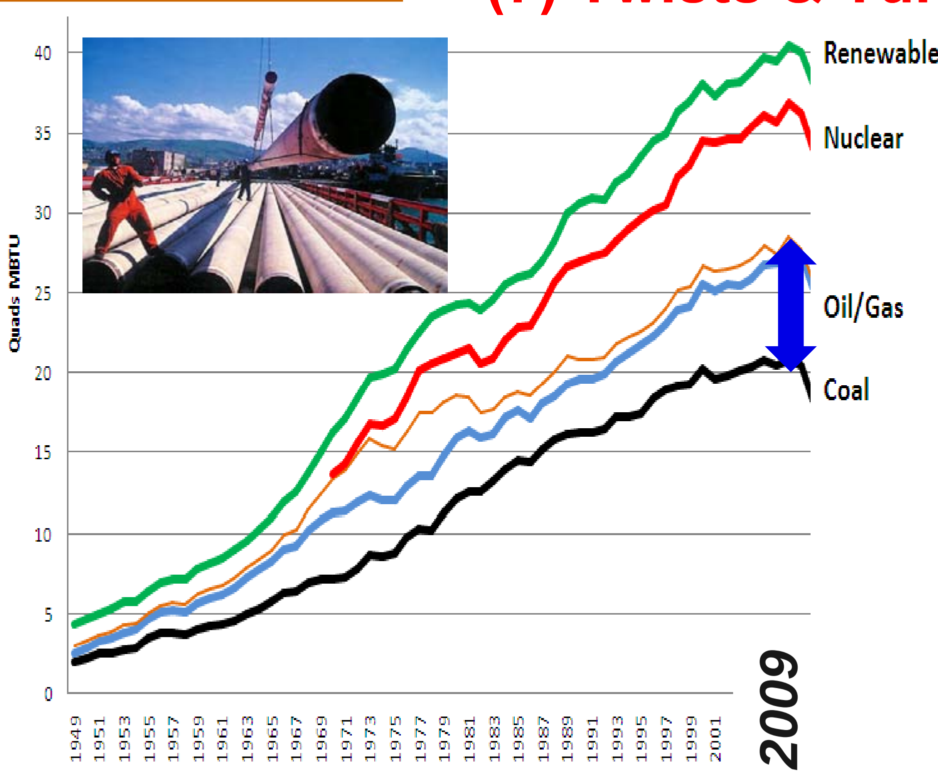
bakersfieldinternational.com/products.html

Why Power?
(7) Twists & Turns



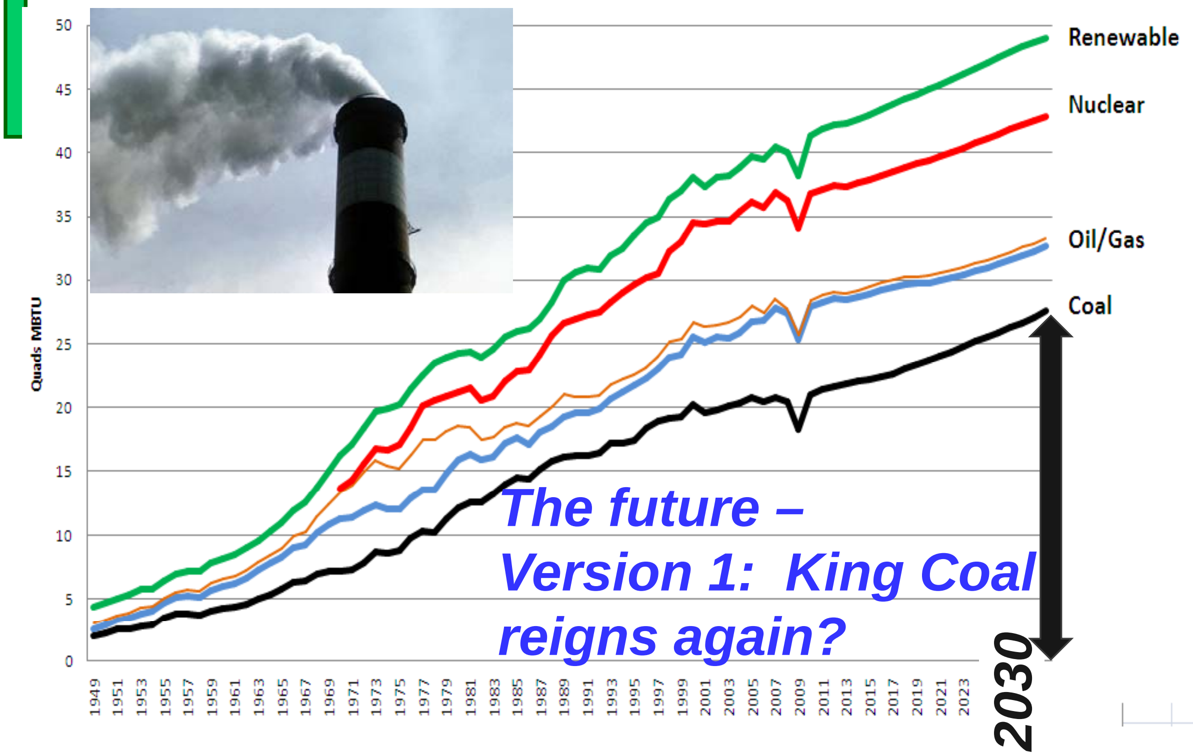
Nuclear Growth

Why Power?
(7) Twists & Turns

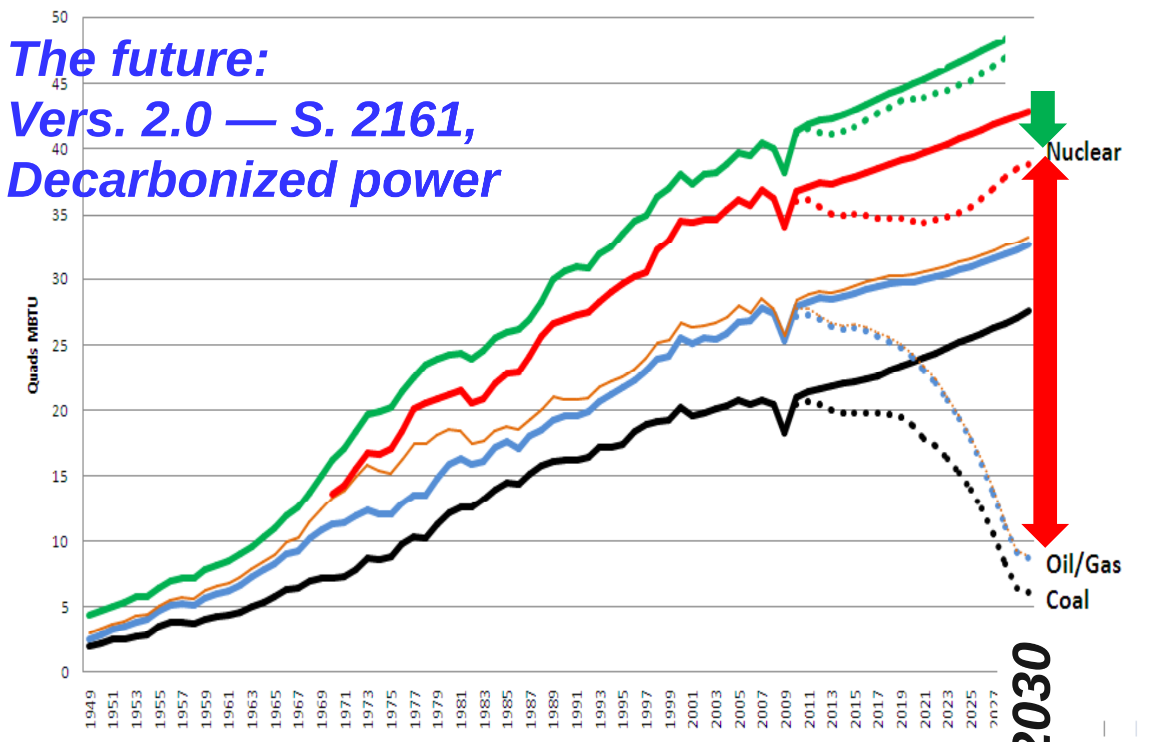


Dash to Gas

Why Power?
(7) Twists & Turns



Why Power?
(7) Upcoming: The Biggest Turn?



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

II. Process Optimization Models

Elements:

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

Operations Model: System Dispatch Mathematical Program

In words:

- Choose output for each generator
- …to MIN total system cost
- … subject to capacity limits, demand

Decision variable:

g_{it} = megawatt [MW] output of generating unit *i* during hour *t*

Coefficients:

CG_i = variable cost [$/MWh] for g_{it}
CAP_i = MW capacity of generating unit *i*
CF_i = maximum capacity factor [ ] for *i*
D_t = MW demand to be met in *t*

Operations Math Program (MP)

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

subject to:

Meet load: $\Sigma_i\, g_{it} = D_t \quad \forall t$ *Dual is marginal price*

Respect plant limits:

$0 \leq g_{it} \leq CAP_i \qquad \forall i,t$

$\Sigma_t\, g_{it} \leq CF_i * T * CAP_i \qquad \forall i$

Towards a Smart Grid: Price Responsive Demand in an Operations MP

MAX Net Benefits from Market =

$$\Sigma_t \int_0^{d_t} P_t(x)dx \; - \; \Sigma_{i,t}\, CG_{it}\, g_{it}$$

subject to:

$\Sigma_i\, g_{it} - d_t = 0 \quad \forall t$

$0 \leq g_{it} \leq CAP_i \qquad \forall i,t$

$\Sigma_t\, g_{it} \leq CF_i\, 8760\, CAP_i \qquad \forall i$

("Smart Grid" also involves better state estimation, & control of flows on grid)

findcheapgas.co.uk/category/saving-elecricity

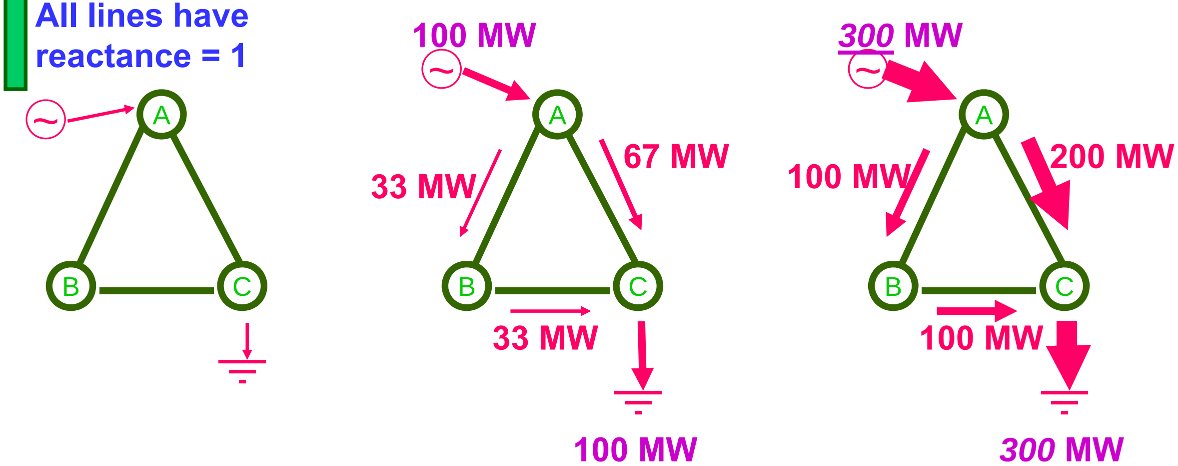
Let's Learn a Little about Power *Before* Having Fun…

needcowbell.blogspot.com/2007_10_01_archive.html

"DC Linearization" of AC Load Flow equations (Kirchhoff's Laws)

Yields proportionality & superposition

All lines have reactance = 1



$PTDF_{n,k}$ = the MW flowing thru line *k*, if:

- 1 MW injected at *n*, and
- 1 MW is removed at an assumed "hub"

E.g., $PTDF_{A,BC}$ = 0.33 if the hub is C

Linearized Transmission Constraints: The Optimal Power Flow Problem

g_{int} = MW from plant *i*, at "bus" *n*, during *t*

z_{nt} = Net MW injection at *n*, during *t*

MIN Variable Cost = $\Sigma_n \Sigma_{i,t} CG_{int}\, g_{int}$

subject to:

Net Injection: $\Sigma_i g_{int} - D_{tn} = z_{nt}$ $\forall t,n$

GenCap: $0 \leq g_{int} \leq CAP_{in}$ $\forall i,n,t$

Hub Balance: $\Sigma_n z_{nt} - Losses = 0$ $\forall t$

Transmission: $\Sigma_n PTDF_{nk}\, z_{nt} \leq Transcap_k$ $\forall k,t$

Investment Analysis: MP Snap Shot Analysis

Let generation capacity cap_i now be a variable, with:

- (annualized) cost = CRF [1/yr] * $CCAP_i$ [$/MW]

MIN $\Sigma_{i,t} CG_{it}\, g_{it} + \Sigma_i CRF*CCAP_i\, cap_i$

s.t. $\Sigma_i g_{it} = D_t$ $\forall t$

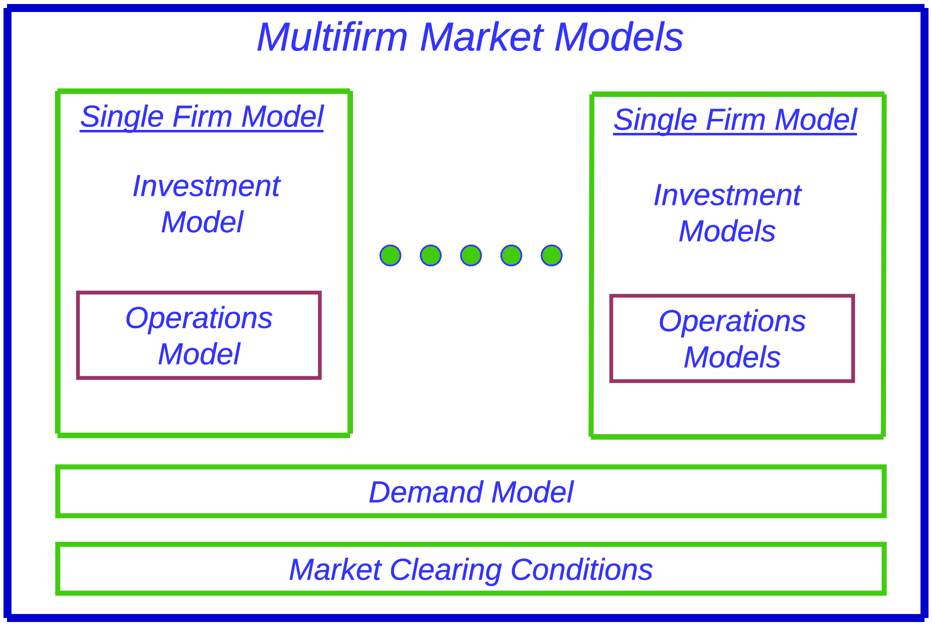
$g_{it} - cap_i \leq 0$ $\forall i,t$

$\Sigma_t g_{it} - CF_i\, 8760 cap_i \leq 0$ $\forall i$

$\Sigma_i cap_i \geq D_{PEAK}(1+M)$ ("reserve margin" constraint)

$g_{it} \geq 0$ $\forall$i,t; $cap_i \geq 0$ $\forall i$

Structure of Market Models



- *If each firm assumes it can't affect price → competitive model*
- *If each assumes others won't change sales → Nash-Cournot oligopoly model*

III. All Wrong, Yet Some Useful: Advantages of Bottom-Up Models

Explicitness:

- **You can model changes in fundamentals by altering:**
  - **decision variables**
  - **objective function coefficients**
  - **constraints**
- **Assumptions laid bare**

Descriptive uses:

- **Texture! Detailed impacts of changes in fundamentals (economics, technology, policy)**
- **Costs, emission, technology choices, market prices, consumer welfare**

Normative:

- **Identify better solutions via optimization**
- **Show tradeoffs among policy objectives**

Process Model Uses: Company Level Decisions

Real time operations:

- Automatic protection and generator control (<1 sec ↔ 5 minutes)

Operator Controls

- Dispatch (5 ↔ 15 minutes)

Market Controls

Operations Planning:

- Unit commitment (8 ↔ 168 hours)
- Maintenance & production scheduling (1 ↔ 5 yrs)

Company Decisions Made Using Process Models, Cont.

Investment Planning

- Demand-side planning (3 ↔ 15 yrs)
- Transmission & distribution planning (5 ↔ 15 yrs)
- Resource planning (10 ↔ 40 yrs)

Company Decisions Made Using Process Models, Cont.

Pricing Decisions

- Bidding (1 hr ↔ 5 yrs)
- Market clearing price determination (15 min ↔ day ahead ↔ years ahead)

Policy Uses of Process Models

Use models of *firm*'s decisions to simulate *market*

- Approaches
  - Via single optimization (Paul Samuelson):

    MAX {consumer + producer surplus}

    ⇔ Marginal Cost Supply = Marg. Benefit Consumption

    ⇔ Competitive market outcome

    Other formulations for imperfect markets
  - Attack equilibrium conditions directly
- Uses
  - Project effects of policies / market design / structural reforms upon …
  - … market outcomes of interest (costs, prices, emissions & impacts, income distribution)

IV. Predicting Twists & Turns with Models

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

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

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

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

Poorly Predicted Inputs: Demand

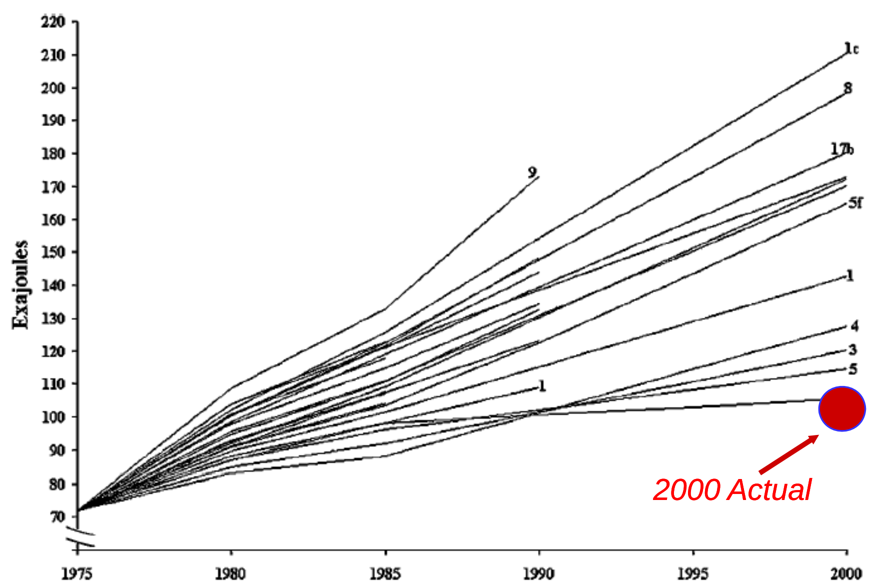
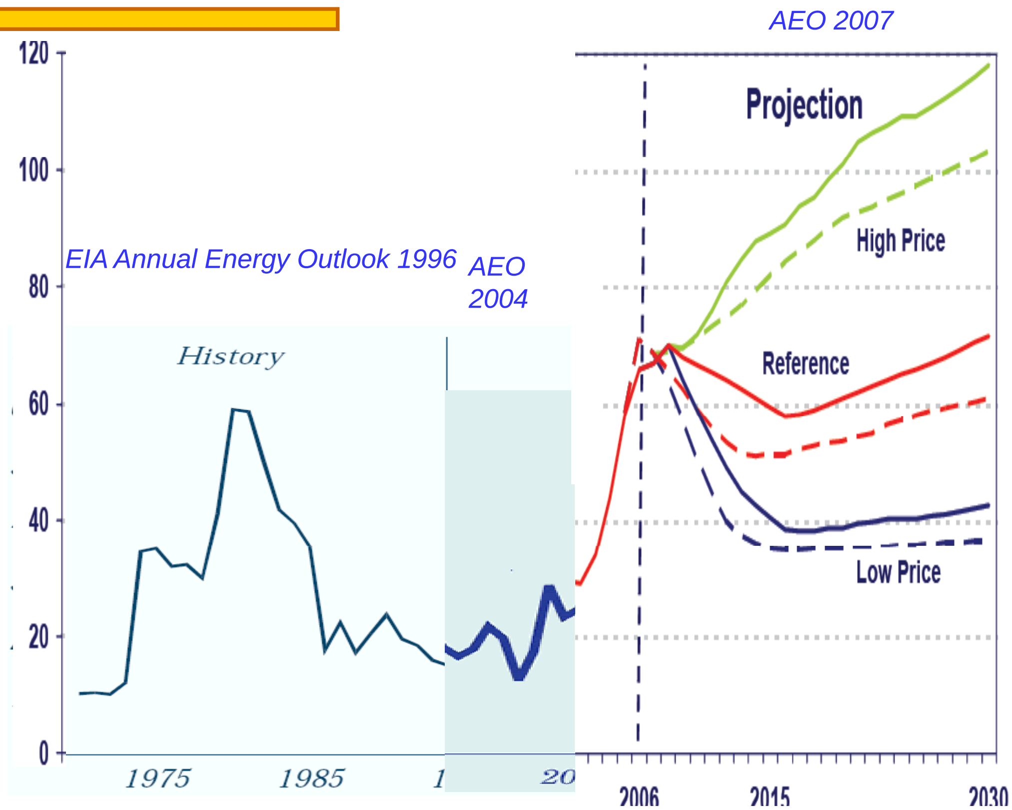


Figure 1 Projections of total U.S. primary energy use from the 1970s. The figure is redrawn from a Department of Energy report (3) and simplified from a summary of dozens of forecasts.

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

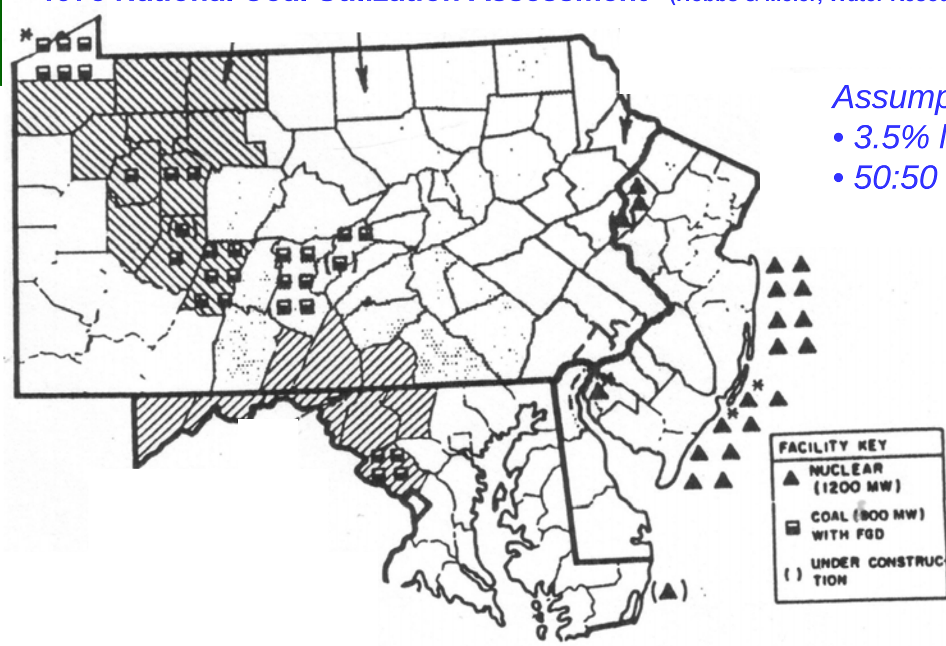
Poorly Forecast Inputs: Fuel Prices
EIA Lower 48 Crude Oil Price Forecasts



Uncertain Inputs: Regulation & Technology

Example: 1985-2000 Power Plant Siting Scenario

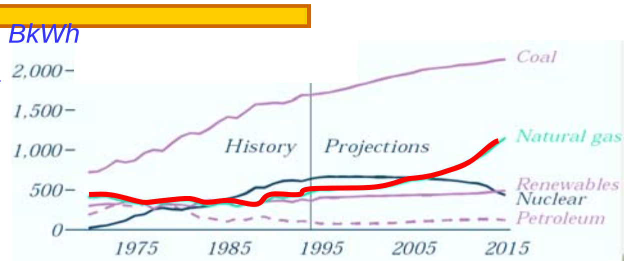
1978 National Coal Utilization Assessment (Hobbs & Meier, Water Resources Bulletin, 1979)

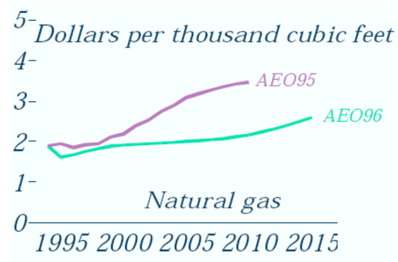


Assumptions:
- *3.5% load growth*
- *50:50 Coal:Nuclear*

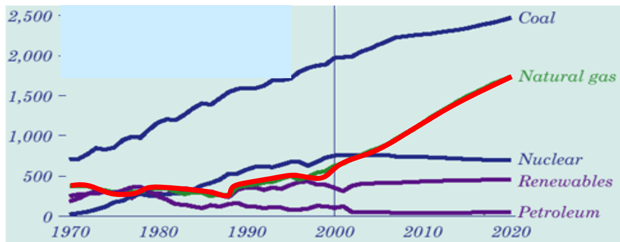
Volatile Outputs from Uncertain Inputs: Gas Prices

1996 AEO

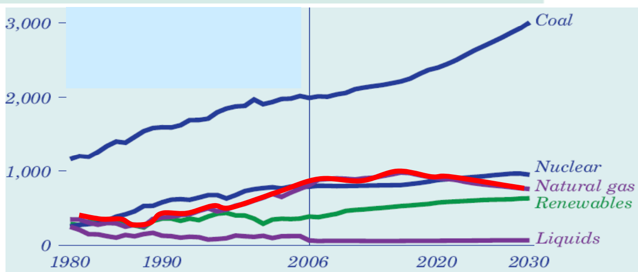




2000 AEO

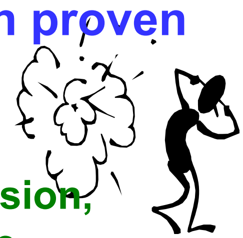


2008 AEO



Poor Predictions, Continued

- *California dreaming, 1995:* Restructuring unanimously passed by legislature
- *California scheming, 2000-2001:* Design proven uncrashworthy by "7 plagues"
  - demand growth (+13.7% 6/99-6/00)
  - drought (-23% hydropower), pipeline explosion, power line fires, kelp, NO_x permits shortage
  - alleged manipulation (maintenance)



- Consequences:
  - Prices \$100-\$200 typically (400% higher than before),
  - Cost of power: 1999 \$7B; 2000 \$28B

V. Fun with Models

Fun ≡
Conclusions that surprise & overturn policy beliefs

V.A Strategic Market Modeling

Market Power = The ability to manipulate prices persistently to one's advantage, independently of the actions of others

Digression: History Quiz

- What was the profession of John Nash's father?

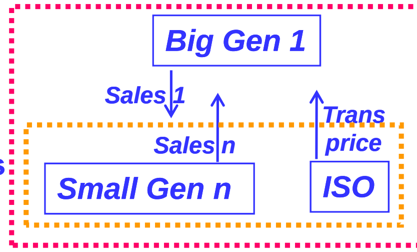
Electric power engineering

Three Common Types of Equilibrium Problems

1. Simultaneous (Nash) Game: Each takes other's decisions as fixed

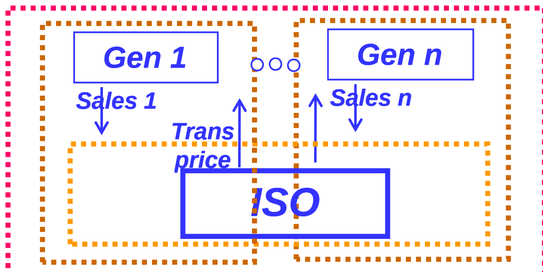
C.P.
(Complementarity Problem)

2. Sequential (Stackelberg) Game:
--A *Leader* anticipates *Follower*'s reactions
--Followers take Leader's decisions as fixed



M.P.E.C.
(Math Program with Equilibrium Constraints)

3. Multiple Leader-Follower:
--Each Leader anticipates follower's reactions
--Each Leader takes other's decisions as fixed



E.P.E.C.
(Equilibrium Problem with Equilibrium Constraints)

2 Stage Closed-Loop Game (EPEC): Capacity, then Operations

Sonja Wogrin, Ben Hobbs, & Danny Ralph, WP, Comillas Pontifical University, Madrid, 9/2010

2 Stages:

1st: Capacity decisions taken independently by each generator, correctly anticipating effect on …

2nd: Short-term market operations & prices

Interesting because:

- Computational, analytical challenges
  - Nonconvex firm problem; equilibrium may not exist
- Unexpected economic result
  - Short run oligopoly can be better than competition
- Practically important
  - Ireland, other markets try to force short-run competition

2nd Stage: Short-Run Equilibrium Problem

- Each firm *f*'s problem: Given *f*'s 1st stage capacity decisions x_{1f}, choose generation x_{2f}

$$\underset{\{x_{2f}\}}{MAX} \quad \pi_{2f}(x_{2f} | x_{1f}) = P(x_{2f} + x_{2,-f}(x_{2f}))^* x_{2f} - C_{2f}(x_{2f})$$

Revenue – Variable Cost

$$s.t. \quad 0 \leq x_{2f} \leq x_{1f} \qquad (\lambda_{2f})$$

where: $x_{2,-f}(x_{2f})$ = "Conjectural variation"

= Output response of rest of market

Possible responses:

$\partial x_{2,-f} / \partial x_{2f} = 0$ ⇒ Cournot-Nash game

$\partial x_{2,-f} / \partial x_{2f} = -1$ ⇒ Bertrand (price-taker) game

$\partial x_{2,-f} / \partial x_{2f} = -1/2$ ⇒ Allaz-Vila (approximation) game

First order conditions: $KKT_{1f}(x_{2f}, \lambda_{2f} | x_{1f})$:

$$0 \leq x_{2f} \perp \pi_{2f}' - \lambda_{2f} \leq 0; \qquad 0 \leq \lambda_{2f} \perp x_{2f} - x_{1f} \leq 0;$$

Short- and Long-Run Equilibria

- *Let* $\underline{X}_1 = \{x_{1f}, \forall f\}$, $\underline{X}_{1,-f} = \{x_{1f'}, \forall f' \neq f\}$, $\underline{X}_2 = \{x_{2f}, \forall f\}$
- *Short-Run Equilibrium Problem* $SR(\underline{X}_1)$*:*

  Find $\underline{X}_2$ that solves:
  - $KKT_{1f}(x_{2f}, \lambda_{2f} | x_{1f}), \forall f$
  - Market clearing conditions
- *f*'s 1st stage problem $LR_f(\underline{X}_{1,-f})$ is an MPEC:

$$\underset{\{x_{1f}, x_{2f}, x_{2,-f}\}}{MAX} \quad \pi_{1f} = \pi_{2f}(x_{2f} | x_{1f}) - C_{1f}(x_{1f})$$

SR Gross Margin – Investment Cost

$$s.t. \quad x_{1f} \in G_{1f}$$

$$SR(\underline{X}_1)$$

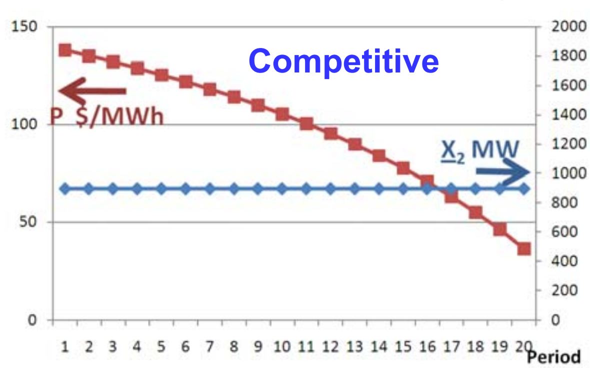
- *LR Equilibrium is a (tough) EPEC:*
  - *Find* $\underline{X}_1$=that simultaneously solves $LR_f(\underline{X}_{1,-f}), \forall f$

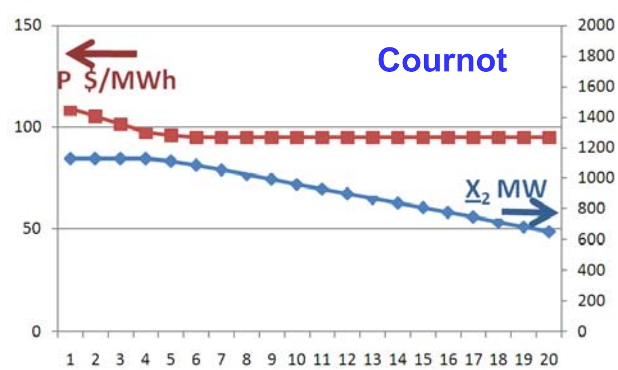
Surprising Economic Result: Fun!

- More oligopolistic short-run market can be better for consumers
  - More capacity $\underline{X_1}$, average output
  - Lower average prices
  - Higher market surplus
  - Cf. Classic Krebs-Scheinkman equivalency result
- Irish, US market power mitigation could make things worse
  - You can force companies to bid marginal cost
  - But you can't force them to build
  - Low short-run profits could discourage long-run entry, resulting in more scarcity

Surprising Results: Fun!

- Two GenCos
  - Nuclear – costly to build, cheap to run
  - Combined Cycle Gas-Fired – cheap to build, costlier to run
- Energy demand
  - Linear demand curve
  - Varies over 20 periods/yr (peak↔off-peak), grows over 10 yr
- Comparison
  - Yr 1 Capacity: 896 MW (Competitive spot market), 1127 MW (Cournot)
  - Consumers better off with Cournot by \$3/MWh (15% of levelized cost)
    - Tradeoff: lower peak prices, higher off-peak prices
  - Intermediate market-power (Allaz-Vila) best – Consumers gain \$13/MWh





V.B Hyperuncertainty: *What's a Poor Transmission Planner to do?*

(Harry van der Weijde, B. Hobbs, WP, Electricity Policy Research Group, University of Cambridge, Oct. 2010)

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

???

The problem

Transmission planning

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

Important questions:

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

Deterministic planning can't answer these!

- Stochastic can! (Fun)

Planning considering multiple scenarios

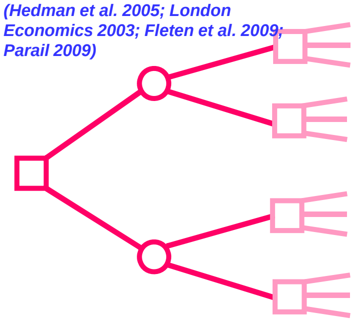
- **Math programming with recourse**
  - scenarios s=1,2,..,S, each with probability PR^s
- **Simplest: Assume 2 decision stages:**
  1. Choices made "here and now" before future is known
     - *E.g.,* investments in 2010
     - These are x^1
  2. "Wait and see" choices, which are made after the future s is known.
     - *E.g.,* dispatch/operations, investments in 2020
     - These are x^{2s} (one set defined for each scenario s)
- **Model:**

$$\text{MIN} \quad C^1(x^1) + \Sigma_s PR^s C^{2s}(x^{2s})$$
$$\text{s.t.} \quad A^1(x^1) = B^1$$
$$A^{2s}(x^1, x^{2s}) = B^{2s} \qquad \forall s$$

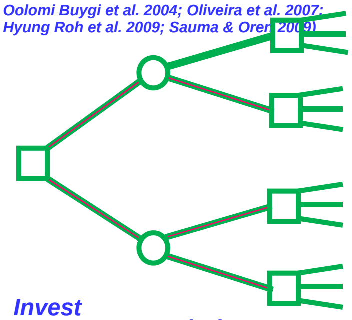
Decision making under uncertainty

-----------Previous Work-----------

Real options analysis of single lines, usually based on exogenous price processes *(Hedman et al. 2005; London Economics 2003; Fleten et al. 2009; Parail 2009)*

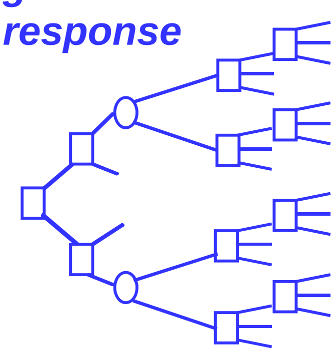


Single-stage transmission planning under uncertainty with generator response *(Awad et al. 2009; Crousillat et al. 1993; De la Torre et al. 1999; Oolomi Buygi et al. 2004; Oliveira et al. 2007; Hyung Roh et al. 2009; Sauma & Oren 2009)*



-----------Our Work-----------

Two-stage transmission planning under uncertainty with generator response

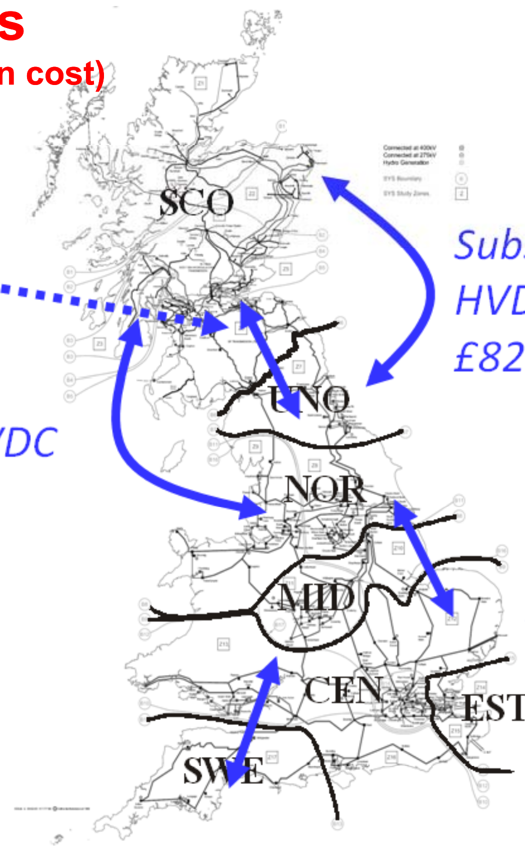


Alternatives
(overnight construction cost)

Various new/ upgrades £353M

Subsea HVDC £805M

Various new/ upgrades £286M



Subsea HVDC £829M

Onshore HVDC £593M

Optimal stochastic solution

 Onshore wind

 Offshore wind

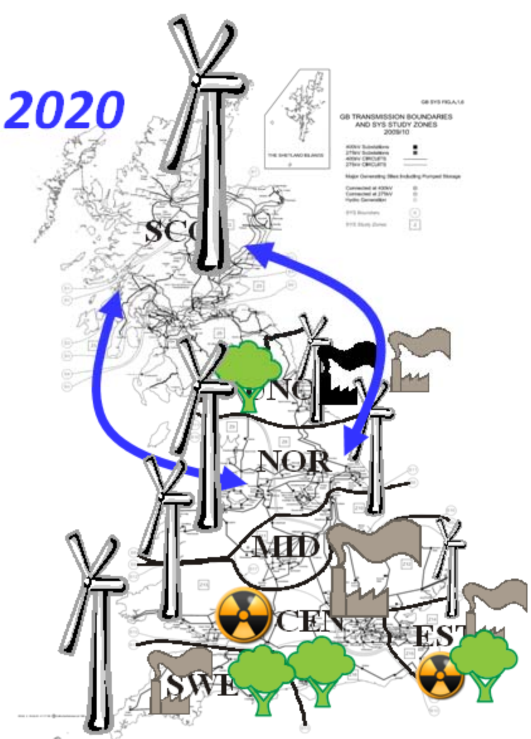
 Nuclear

 Biomass

 CCGT

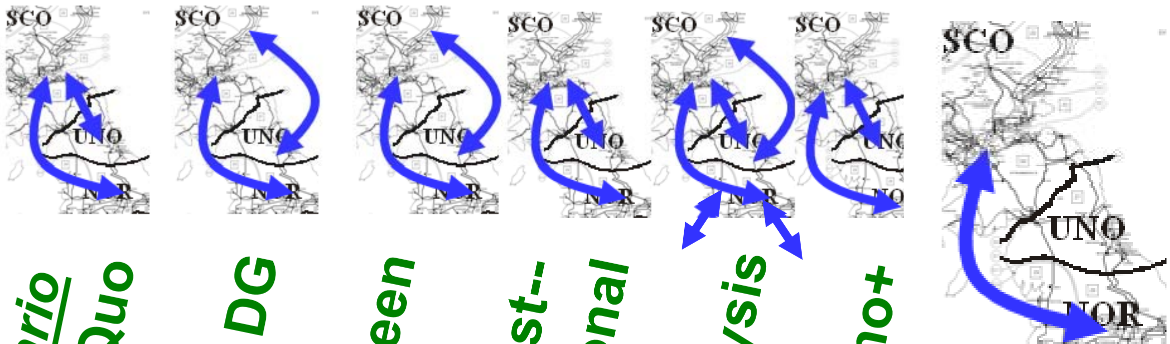
 OCGT

2020



Cf. Traditional robustness analysis

2020 Installations by Scenario *"Robust"*



Scenario

Status Quo

Low Cost DG

Low Cost Green

Low Cost--
Conventional

Paralysis

Techno+

Value of perfect information

- How much average savings if we knew which scenario would happen?
  1. Solve stochastic model
  2. Solve deterministic model for each scenario
  3. Compare objectives (1) and (2)

- Results:
  - For gen & transmission: £3,729M (3%)
  - For trans alone £101M (0.1%)

Cost of ignoring uncertainty

- **How much do costs go up if we naively plan for one scenario but other scenarios can happen?**
  1. Solve stochastic model
  2. Solve naïve (deterministic) model for each scenario
  3. Solve stochastic model, imposing 1st stage naïve transmission decisions
  4. Compare objectives (1) and (3)

Cost of ignoring uncertainty (for Transmission Planner only)

Scenario planned for	Cost of Ignoring Unc. (Present worth)
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%)**

Conclusions

- *Power problems are only going to get more important*
  - **Get competition's benefits while moving towards sustainability**
  - **Planning & operations to include lots of renewables and demand response -- reliably & economically**
- *Fun with Multilevel games:*
  - **Nonconvex problems!**
  - **Counter-intuitive results**
  - **Help understand how markets can be gamed**
- *Fun with Stochastic optimization:*
  - **Big problems!**
  - **Ignoring risk has quantifiable economic consequences**
  - **Useful for planning**