Outline

1. Why do incentives matter?
2. Market design: Goals & Model roles
3. Two key results: competitive market simulation & supporting prices
4. Two simple analyses of supporting prices in power:
   • Can spot energy prices support optimal (i) capital & (ii) ramping decisions?
5. Four market designs to overcome market failures
   i. Ramsey pricing to efficiently recover fixed network costs
   ii. Make-whole payments to recover nonconvex costs by generators in spot markets
   iii. Clean Power Plan to fix environmental externalities (CO₂ control)
   iv. Capacity markets to fix “missing money” in spot markets
6. Conclusion: we need your O.R. and econ skills!
1. Incentives matter!

Getting incentives right is tricky!
(thanks to Cindy Bothwell for this example)

PNM offers two incentives that reduce your electric bill:

- **PNM REC Purchase Program:** Because you're adding renewable-fueled power to the PNM system, and that helps us meet our environmental goals, we credit your account 15 cents per kilowatt-hour for energy that your facility generates and consumes on site within a given billing period.

7/6/2010

**Alamogordo Daily News**

Kloepfer said he set up a system to waste power in a small building at the site in order to recoup the value of his RECs from PNM, and showed the system to Teague. He explained a water heater heats 30 gallons of water to about 120 degrees, then the water is circulated through 450 feet of garden hose inside a refrigerator to cool back down and is then piped back into the water heater. The process repeats 12 times per day.
Why focus on the Power Sector?

Why is getting incentives in *power* so crucial?

- **It’s important**
  - Economy
  - Environmental problems & potential

- **Market failures need attention**
  - Externalities $\rightarrow$ Kirchhoff’s laws
  - Nonconvexities $\rightarrow$ supporting prices, natural monopoly
  - Market power $\rightarrow$ California 2001
  - Incomplete markets $\rightarrow$ Lack of investment, reliability problems, half a market

- **Opportunity presented by restructuring…**
  - Vertical unbundling & the missing consumer
  - New technologies & environmental mandates

  ... *Which is a process, not a destination*
2. Market Design: Goals & Model Roles

- **Can’t escape**
  - Local regulation: Samuel Insull
  - Federal Power Act: “Fair & Reasonable Prices”
  - Political demands for environmental benefits, control of market power

- **Goals ... and the debate over them**
  - Reliability/adequacy
  - Market efficiency: MAX social surplus
  - Supports optimal solution (no incentives to lie)
    - Incentives linked to ultimate objectives
  - Surplus for individual parties:
    - Fair distribution of benefits
    - Consumer surplus, consumer prices
    - Producer surplus
  - Sustainability
    - \( \text{CO}_2 \), Conventional pollutants (e.g., High Electric Demand Days)
    - Human health
  - Technology promotion
    - Renewables & storage
Roles for Models

- **What’s the optimal solution look like?**
  - For social surplus maximization?
  - Under multiple objectives?

- **What prices/policies support the optimal solution?**
  - And how can they be calculated?
  - Market failures & the theory of the “second best”

- **How distorted are present prices/policies?**
  - Are optimal choices supported or not?
  - What market outcomes are likely?

- **What are the net benefits of better market designs?**
  - Metrics:
    - social surplus
    - consumer surplus, producer surplus, interregional distribution
    - revenue adequacy for grid owner, system operator
    - sustainability

---

3. A “Couple” of Key Modeling Results

Focus of politics: Income redistribution is ~10X as large as efficiency gain
Key result #1: Equivalence of competitive market equilibrium to optimization

- **Competitive Market equilibrium problem:**
  - Let each market party solve a (convex) profit maximization problem:
    \[
    \text{MAX}_{\{s_i, x_i\}} p^T s_i - C_i(x_i) = \text{Revenue} - \text{Cost} \tag{1}
    \]
    s.t. \( G_i(s_i, x_i) \leq 0 \) = Production function \tag{2}
  - With the equilibrium satisfying market clearing:
    \[
    \sum_i s_i = 0 \quad (p) \quad \text{Supply} = \text{Demand} \tag{3}
    \]

- **Solution methods:**
  i. Derive equilibrium problem: KKT conditions for each party \( i \)’s problem (1)–(2), concatenated with market clearing (3)
    - \( \rightarrow \) Complementarity problem
    - Directly solve with PATH
  ii. Equivalent single optimization problem (Samuelson, 1954)
    \[
    \text{MAX}_{\{s_i, x_i, \forall i\}} - \sum_i C_i(x_i) = \text{Social surplus} = \text{Market efficiency}
    \]
    s.t. (2) \( \forall i \), (3)
    - Its KKTs = equilibrium problem (i)
    - This “market model” is solved by the ISOs

Key result #2: Supporting prices

- **Corollary of Samuelson’s theorem:**
  - Duals of (3) (=prices) in market model “support” the profit–maximizing problem for each party

- **Implications:**
  1. **Definition of “supporting”:** Given optimal commodity prices, no competitive firm wants to deviate from the optimal “schedule” (primal solution \( s_i \)) that the ISO gives them
    - Avoid incentives to misrepresent physical characteristics or costs in order to obtain a higher profit schedule
    \( \rightarrow \) **incentive compatibility**
  2. Market parties make socially optimal decisions for other primals \( x_i \)
  3. Revenues cover each party’s costs
Simple applications to two common market design questions (thanks to Saint Fred Schweppes for inspiration)

1. Won’t revenues in short-run energy markets fail to cover capital costs of new generators, endangering reliability?

2. Renewables increase the need for “ramping” capability…but since generators are only paid for energy, won’t there be inadequate incentive for flexible generation?
(1) Won't revenues in short-run energy markets fail to cover capital costs of new generators, endangering reliability?

- **Caramanis (IEEE TPWRS, 1982); Schwegge et al. (1988)**
  - Market equilibrium model:
    - Consumers: \[ \text{MAX}_{\{d_{jt} \geq 0\}} \sum_t B_{jt}(d_{jt}) - p_t d_{jt} \]
    - Generators: \[ \text{MAX}_{\{g_{it}, c_{api} \geq 0\}} \sum_t (p_t - CG_i) g_{it} - CC_i c_{api} \]
    - Market clearing: \[ \sum_j d_{jt} - \sum_i g_{it} = 0 \quad (p_t) \forall t \]
  - By Result 1: Samuelson competitive market model:
    \[ \text{MAX}_{\{d_{jt}, g_{it}, c_{api} \geq 0\}} \sum_j B_{jt}(d_{jt}) - \sum_t \left[ \sum_i CG_i g_{it} + CC_i c_{api} \right] \]
    \[ \text{s.t.} \quad (3) \forall i, t; (4), \forall t \]
  - By Result 2, energy prices \( p_t \) not only support optimal generation \( g_{it} \), but also the optimal investment \( c_{api} \)

---

**How does a power system with low operating costs pay for its capital?**

**Short run supply and demand:**

- Low demand/high wind period:
  - Demand (marginal benefits \( \partial B / \partial d \))
  - Marginal fuel cost likely to set price

- High demand/low wind hour:
  - Demand (marginal benefits \( \partial B / \partial d \))
  - Marginal benefits \( \partial B / \partial d \)
  - "scarcity pricing"

**Today:** active demand absent from the short-term market,
  \( \Rightarrow \) scarcity prices must come from elsewhere
(2) Renewables increase the need for “ramping” capability; yet generators are only paid for energy, so won’t there be inadequate incentive for flexible generation?

- It turns out that energy prices support optimal ramping decisions. Example:

A system with two types of generation:
- 1000 MW of quick start peakers @ $70/MWh
- 2100 MW of slow thermal @ $30/MWh, with max ramping = 600 MW/hr

Morning ramp up and resulting generation:

<table>
<thead>
<tr>
<th>Time (hours)</th>
<th>Fast MW</th>
<th>Slow MW</th>
<th>Price ($/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1000</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td>400</td>
<td>1000</td>
<td>-10</td>
</tr>
<tr>
<td>2</td>
<td>1600</td>
<td>1600</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>2000</td>
<td>2000</td>
<td>30</td>
</tr>
</tbody>
</table>
5. Four Applications of Models to Correct Market Failures
Case 1: Optimizing regulated prices to recover fixed network costs (thanks to F. Alvarado for inspiration)

- **Approach:** Use analysis to define “2nd-best” (surplus maximizing) prices, subject to cost recovery: Ramsey(1927)–Boiteux(1956) Pricing
  - “2nd best”: in an economy with market failures, the surplus maximizing $P$ doesn’t necessarily $=$ $MC$.
  - *I.e.*, one distortion might be best countered by another
- **Model:**
  - 3 Features: Fixed costs to be recovered; Multiple consumers with demand functions; You can price discriminate
  - $\text{MAX}_{x, d_j, p_j \geq 0} \sum_j B_j(d_j) - C(s)$ (Market surplus)
  - s.t. $\sum_j p_j d_j = C(s) + \text{Fixed Cost}$ (Revenue recovery)
  - $p_j = \partial B_j(d_j)/\partial d_j \quad \forall j$ (Demand function)
  - $\sum_j d_j - s = 0 \quad (p_j)$ (Energy balance)
- **Lagrangian $\rightarrow$ Inverse elasticity rule for “2nd best” price:**
  - $(p_j - MC)/p_j \propto 1/\text{Elasticity}_j$
Example: Recover $50K in distribution costs from two customer classes (elastic, inelastic)

Assumptions

Price Results:
Ramsey Pricing
Identical Prices

Contributions to $50K fixed costs

Ramsey Pricing
Identical Prices

The differences in who pays is >> the efficiency gain on the next slide
Market efficiency impacts: “Dead Weight” loss of efficiency

Ramsey Pricing

Identical Prices

Ramsey Pricing imposes 47% less efficiency loss

- Ramsey: $0.74/MWh loss (1.5% of cost)
- Uniform: $1.41/MWh loss (3% of cost)

Crucial research:

How to appropriately incent behind-the-meter generation & demand-response, s.t. financial sustainability for network?
Case 2: Optimizing “make whole payments” to recover nonconvex costs (thanks to R. O’Neill, B. Hogan, A. Conejo, S. Siddiqui for inspiration)

Example Case 2: Nonconvex operating costs \( \rightarrow P \) might not support optimal unit commitment schedules

- Can we define optimal “side payments” to scheduled generators who lose money to keep them in the market?
  - ... And optimal “penalties” to unscheduled generators to keep them out?
- Approach: Use analysis to define side payments that support the equilibrium
- Present practice:
  1. “Make Whole Payments”: If a generator loses money in a schedule (due to fixed costs of start-up or minimum-run), then operator writes a check
     - Ad hoc, revenue inadequate for operator
  2. “Dispatchable Model”: Separate scheduling & pricing runs: in pricing run, relax 0–1 binary constraints for small inflexible units (CAISO, NYISO, MISO Extended LMP)
     - Higher energy prices, but prices not supporting
Step 1: Solve MILP for optimal primal unit commitment schedule (simple example):

\[
\begin{align*}
\text{MIN } & \sum_i \sum_t \left[ CG_i g_{it} + CZ_i z_{it} \right] \\
\text{s.t. } & g_{it} \geq z_{it} \cdot MR_i \\
& -g_{it} \geq -z_{it} \cdot CAP_i, \quad \forall i, t \\
& \sum_i g_{it} = D_t(p_t), \quad \forall t
\end{align*}
\]

Let \( z_{it}^* \) be the optimal commitment

Step 2: Solve LP for supporting prices, given \( z_{it}^* \)

\[
\begin{align*}
\text{MIN } & \sum_i \sum_t \left[ CG_i g_{it} + CZ_i z_{it} \right] \\
\text{s.t. } & (2)-(4), \quad \text{and } z_{it} = z_{it}^* \cdot \mu_{it}, \quad \forall i, t
\end{align*}
\]

Step 3: Settlement:

- If \( z_{it}^* = 1 \), then pay: \( p_t g_{it} + \max(0, \mu_{it} z_{it}) \)
- If \( z_{it}^* = 0 \), then pay nothing, but assess penalty of \(-\mu_{it} z_{it}\) if unit starts up

Results:

- The payments support equilibrium
  - A scheduled generator gets a “make whole” payment if otherwise would lose money
  - Unscheduled generator will not earn profit if it self-schedules
  - System operator not necessarily revenue adequate
    - Worst case: revenue shortfall = make whole payments

- Annoyingly:
  - Massively degenerate → many possible sets of payments
  - Unsuccessful in search for transparent, practical method to MIN “side payments” & resulting uplift

- Present debate:
  1. “Extended LP”/Convex Hull pricing (see Bill Hogan’s talk)
    - Originally proposed by MISO
    - Too complex for stakeholders, settled for a CAISO/NY system
  2. Choose uplifts as optimal tradeoff between objectives of MAX short run efficiency & MIN payments (Conejo; Siddiqui)
    - MPEC structure, would require FERC policy change
Simple example:

- **One period, $D = 250$ MW**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Flex Baseload</td>
<td>0</td>
<td>100</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>Flex Cycling</td>
<td>0</td>
<td>100</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>Inflex Peaker</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

- **Results of “restricted model” (O’Neill et al.) $\rightarrow p = 60$/MWh:**

<table>
<thead>
<tr>
<th>Generator</th>
<th>$z^*$</th>
<th>$g^*_i$ [MW]</th>
<th>Cost</th>
<th>$p^*g_i$</th>
<th>$M_i$</th>
<th>Make Whole Payment</th>
<th>Profit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flex Baseload</td>
<td>1</td>
<td>100</td>
<td>$4,000$</td>
<td>$6,000$</td>
<td>-$2,000$</td>
<td>$0$</td>
<td>$2,000$</td>
</tr>
<tr>
<td>Flex Cycling</td>
<td>1</td>
<td>50</td>
<td>$3,000$</td>
<td>$3,000$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
<tr>
<td>Inflex Peaker</td>
<td>1</td>
<td>100</td>
<td>$10,000$</td>
<td>$6,000$</td>
<td>$4,000$</td>
<td>$4,000$</td>
<td>$0$</td>
</tr>
</tbody>
</table>

- **Results of “dispatchable model” (NYISO/CAISO method):**
  - Solve pricing model (relax peaker’s $z$ from $\{0,1\}$ to $[0,1]$) $\rightarrow p =$100

<table>
<thead>
<tr>
<th>Generator</th>
<th>$z^*$</th>
<th>$g^*_i$ [MW]</th>
<th>Cost</th>
<th>$p^*g_i$</th>
<th>Make Whole Payment</th>
<th>Profit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flex Baseload</td>
<td>1</td>
<td>100</td>
<td>$4,000$</td>
<td>$10,000$</td>
<td>$0$</td>
<td>$6,000$</td>
</tr>
<tr>
<td>Flex Cycling</td>
<td>1</td>
<td>50</td>
<td>$3,000$</td>
<td>$5,000$</td>
<td>$0$</td>
<td>$2,000$</td>
</tr>
<tr>
<td>Inflex Peaker</td>
<td>1</td>
<td>100</td>
<td>$10,000$</td>
<td>$10,000$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
</tbody>
</table>
Case 3: Optimal pricing for CO₂ reductions (inspired by Anthony Paul, JHU & RFF)
The huge economic stakes

A 29–36% reduction in power sector CO₂ by 2030 (EIA, 2015)
→ loss of 0.17–0.25% of GNP by 2040

Example 3: CO₂ regulation under Clean Power Plan

- Two types of carbon caps by state. Max allowed either:
  - Tons/MWh (rate-based)
  - Total tons (mass-based)

- Different cap types will be adopted by states. What does this imply for electricity & CO₂ market efficiency?
  - Rate-based cap states may have lower wholesale power P’s than mass-based states
    → Output expands in former, shrinks in latter
  - Rate-based cap
    → Total CO₂ might increase

- How important is correct pricing of CO₂ for economic & environmental efficiency?
Each mass–based state $i$ has problem:

$$\begin{align*}
\text{MIN} \{0 \leq g_{ik} \leq \text{CAP}_{ik}; \ t_{ji}, \text{co2cri} \} & \quad \sum_k C_{ik}(g_{ik}) + \sum_{j \in j(i)} p_{ji} (t_{ji} - t_{ij}) = D_i \\
& \quad \sum_k \text{CO2}_{ik}(g_{ik}) - \text{co2cri} \leq \text{MBCAP}_i
\end{align*}$$

Each rate–based state $i$ has problem:

$$\begin{align*}
\text{MIN} \{0 \leq g_{ik} \leq \text{CAP}_{ik}; \ t_{ji}, \text{erci} \} & \quad \sum_k C_{ik}(g_{ik}) + \sum_{j \in j(i)} p_{ji} (t_{ji} - t_{ij}) = D_i \\
& \quad [\sum_k \text{CO2}_{ik}(g_{ik})] / [\sum_k g_{ik} + \text{erci}] \leq \text{RBCAP}_i
\end{align*}$$

Market clearing:

- Power trade: $t_{ji} - t_{ij} = 0 (p_{ij}, p_{ji})$; $-T_{ij} \leq t_{ij} \leq T_{ij}$, $\forall i; j \in j(i), j \neq I$
- Mass–based CO2: $\sum_{i \in \text{MB}} \text{co2cri}_i = 0 (p_{\text{co2cr}})$
- Rate–based CO2: $\sum_{i \in \text{RB}} \text{erci}_i = 0 (p_{\text{erc}})$

Solve by concatenating KKTs of problems with market clearing, or a single equivalent optimization

Case study: Plant redispacth for CO2 reduction

- Two systems, each with the following generation mix:

  - Renewables
  - Coal
  - Gas

- Load in each area=750 MW; $\infty$ transmission capacity
- CO2 Rules
  1. No control
  2. Goal of 6.9% decrease: Different rules among states:
     - System 1: Rate based (0.6 tons/MWh)
     - System 2: Mass–based (450 tons)
  3. Both systems with mass–based
Inefficient!

- Mix of Cap types fails to achieve 6.9% reduction goal, and is inefficient

- Major reason: Rate-based policy subsidizes power sales
  → System 1 produces 11% more (at higher cost) and exports to System 2

The differences in who pays is >> the efficiency gain

Price Results

1. Inefficiently low power price discourages energy efficiency as CO₂ control
2. Inefficient CO₂ prices → 40% higher cost of control
3. Consumers pay more under all MB (10–20X efficiency gain)
Crucial research:

How to design C markets so that they yield efficient C reductions, and don’t mess up power markets?

Case 4: Supporting prices in capacity markets

(Lead author: Ph.D. student Cindy Bothwell)
Supporting Prices in Generation Capacity Markets

- **Market failure**: Caps on energy P’s mean that generators do not earn the full value of their production during periods of scarcity → underinvestment
  - Also: missing markets (for long-term contracts), regulatory uncertainty

- **Policy response**: Markets for capacity in several ISOs
  - PJM Reliability Pricing Model (administrative demand curve for centralized 3 yr-ahead capacity market)
  - CAISO: requirement 1 yr ahead for “capacity showing” by load serving entities, met through bilateral contracts

- **Issue**: what “credit”/capacity payment to give to renewables …. and what (if any) distortions result from the wrong credit?

What do renewables contribute?
ERCOT example with 40% wind energy
Capacity market model

- Market model (no energy P cap):
  - Consumers:
    \[
    \text{MAX}_{0 \leq d_t \leq D_t} \ VOLL \ d_t - p_t \ d_t
    \]
  - Generators:
    \[
    \text{MAX}_{\{git, cap_i \geq 0\}} \ \sum_t (p_t - CG_i) \ s.t. \ g_{it} - \text{cap}_i \leq 0 \ \forall t
    \]
  - Market clearing (energy):
    \[
    \sum_j d_{jt} - \sum_i g_{it} = 0 \ (p_t) \ \forall t
    \]
  - Market clearing (capacity):
    \[
    \sum_i \beta_i \text{cap}_i \geq (1+RM) \ D_{\text{Peak}} \ \forall t
    \]

- Policy experiments:
  - Base case: no market failure (energy-based market, no price cap)
  - Market failures: price cap < VOLL; wrong capacity credits \( \beta_i \)

Data

- ERCOT 2013 existing system using normalized hourly actual load, wind, and solar data
- Load scaled to 50,000 MW Peak
- New generation costs (EIA), except 22.5 GW existing coal (lower “going forward” costs)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Fixed Cost $$/MW/yr</th>
<th>Variable &amp; Fuel $</th>
<th>Variable Subsidy $</th>
<th>Availability Factor %</th>
<th>EFORD</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACT</td>
<td>$80,154</td>
<td>$79.6</td>
<td></td>
<td>90%</td>
<td>11.0%</td>
</tr>
<tr>
<td>ACC</td>
<td>$136,419</td>
<td>$53.6</td>
<td></td>
<td>86%</td>
<td>5.4%</td>
</tr>
<tr>
<td>Conv Coal</td>
<td>$120,253</td>
<td>$29.4</td>
<td></td>
<td>85%</td>
<td>7.0%</td>
</tr>
<tr>
<td>Wind</td>
<td>$222,329</td>
<td>$-</td>
<td>$23.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar PV - 45%</td>
<td>$159,257</td>
<td>$-</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Results: Compare reserve margin solutions with optimal VOLL solution
...reserve margin adjusted to achieve same unserved energy

Energy P Cap $1,000/MWh; $\beta_{\text{Wind}} = 40\%$, $\beta_{\text{Solar}} = 75\%$

$\beta_{\text{Wind}} = 25\%$, $\beta_{\text{Solar}} = 50\%$

$\beta_{\text{Wind}} = 14.6\%$, $\beta_{\text{Solar}} = 50\%$

$\beta_{\text{Wind}} = 0\%$, $\beta_{\text{Solar}} = 0\%$

Optimal Energy: VOLL $10,000$, No Price Cap

~Also: $\beta_{\text{Wind}} = 54.5\%$, $\beta_{\text{Solar}} = 10\%$

*Assumed W/S capacity contribution: 40%/75%
Actual marginal W/S contribution: 8%/40.5%
Actual average W+S contribution: 23%

Results: Investment Mix

<table>
<thead>
<tr>
<th>Type</th>
<th>Optimal</th>
<th>40%W/75%S</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT</td>
<td>21,071</td>
<td>22,754</td>
</tr>
<tr>
<td>CC</td>
<td>4,932</td>
<td>1,029</td>
</tr>
<tr>
<td>Coal</td>
<td>22,500</td>
<td>22,500</td>
</tr>
<tr>
<td>Wind</td>
<td>13,816</td>
<td>24,465</td>
</tr>
<tr>
<td>Solar</td>
<td>3,476</td>
<td>6,480</td>
</tr>
</tbody>
</table>
Crucial research:

What’s the capacity value of new technologies, and how can we correctly reward it?

Conclusions
Market design: a journey, not a destination
• **We need optimal solutions, supporting prices, & market designs for many issues!**
• **You need economic insights & modeling skills**

When ought you kludge, and when start from scratch?

In July of 2004, Microsoft announced that the release of Vista, the next generation of the Windows operating system, would be delayed until late 2006. Jim Allchin famously walked into the office of Bill Gates and proclaimed, “It’s not going to work.” Development of Windows had become unmanageable and Allchin decided that Vista would have to be rewritten essentially from scratch.

Mr. Allchin’s reforms address a problem dating to Microsoft’s beginnings. PC users wanted cool and useful features quickly. They tolerated—or didn’t notice—the bugs riddling the software. Problems could always be patched over. With each patch and enhancement, it became harder to strap new features onto the software since new code could affect everything else in unpredictable ways.