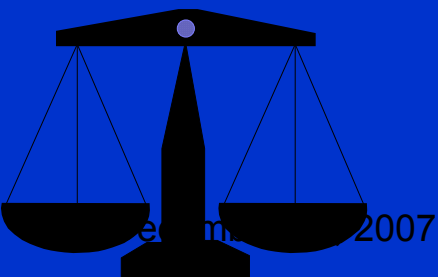
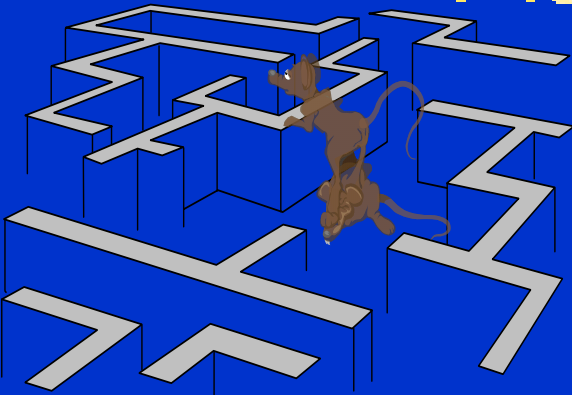


It's Getting Better All the Time (with Mixed Integer Programming)



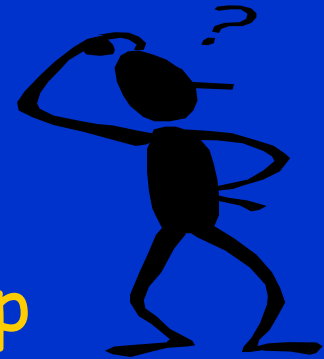
Richard O'Neill
Chief Economic Advisor
Federal Energy Regulation
Commission

richard.oneill@ferc.gov

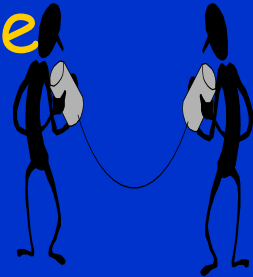
Harvard Electricity Policy Group
Los Angeles, CA

6 Dec 2007

Views expressed are not necessarily those of
the Commission



Innovation in electric markets

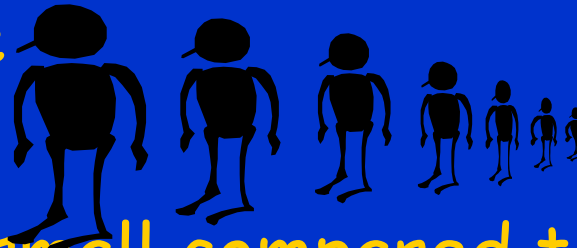


- ⇒ 1882 to 1900: Edison, Telsa and Westinghouse
 - ☞ AC v DC; Light bulb
 - ☞ Competition
- ⇒ 1900-30 Financial scale economies? (Morgan, Insull)
 - ☞ holding company
 - ☞ cost-of-service regulation
- ⇒ 1930-70 bigger is better
 - ☞ Scale economies increase
 - ☞ Lower heat rates and better equipment
 - ☞ Nukes
 - ☞ blackouts

Technology eliminates some market failures 1970-



- ⇒ Computing hardware and software
- ⇒ Communication: fiber optics and the Internet
 - ⇒ vertical integration not required: ISOs
 - ⇒ allows the load to participate in the market
 - ⇒ Smart grid [Who could ask for more]
 - ⇒ Faster response
- ⇒ Energy market
 - ⇒ Generator size small compared to market
 - ⇒ QFs and IPPs
- ⇒ Market design: cost-based to market-based



What is at stake?



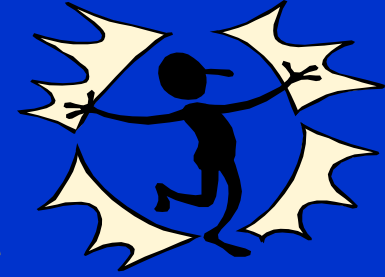
| | load | generation | revenues | price |
|-------|--------|------------|----------|--------|
| | PetaWh | TW | T\$/yr | \$/kwh |
| US | 3.71 | 0.95 | 0.27 | 0.07 |
| world | 15.80 | 3.62 | ~2.0 | |

↪ The efficiency/innovation target is measured in $\$10^{12}/\text{year}$

↪ 1% savings is greater than $\$10^{10}/\text{yr}$

☹ money can't buy me love

Optimization Modeling Paradigm



minimize $c(x)$
subject to $A(x) = b,$
 $l \leq x \leq u,$
some $x \in \{0,1\}$

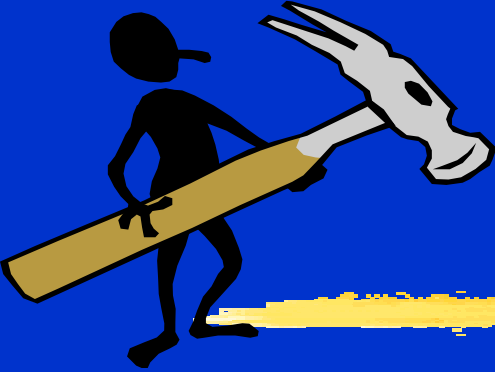


Very powerful paradigm

Very hard to solve

Use heuristics, Lagrangian relaxation and linear programming (All things must pass)

Nothing you can sing
that can't be sung



Linear Program

minimize cx

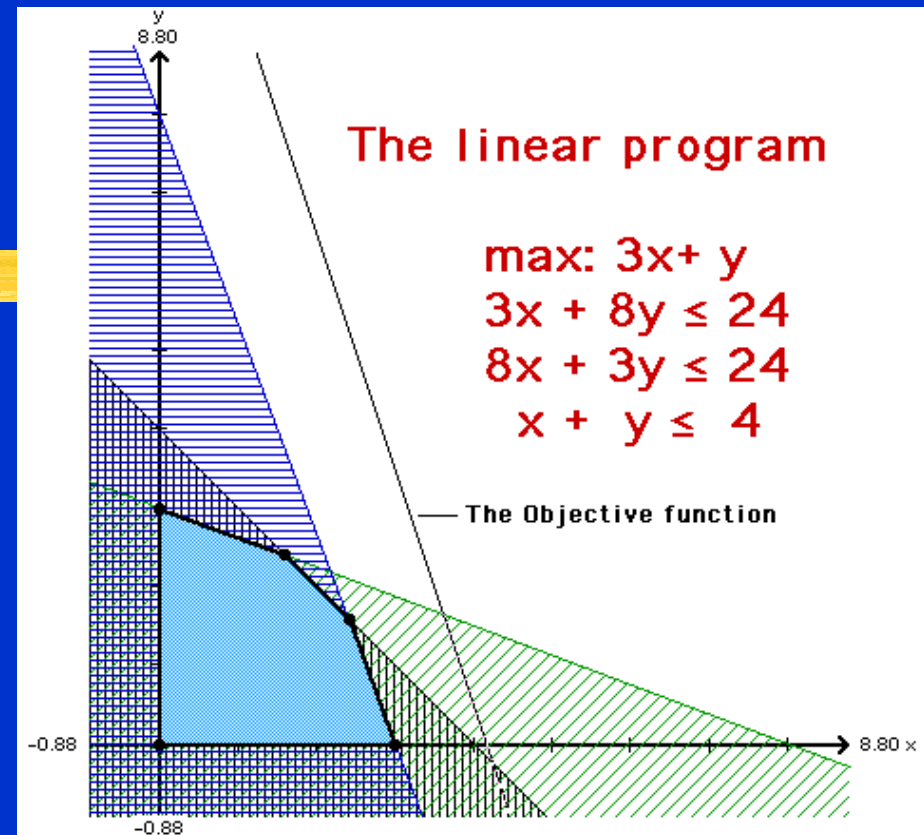
subject to $Ax = b$

$l \leq x \leq u$

Hammer looking for a nail

1996: 300 nodes; No transmission constraints

1990s: solution times improved by 10^6

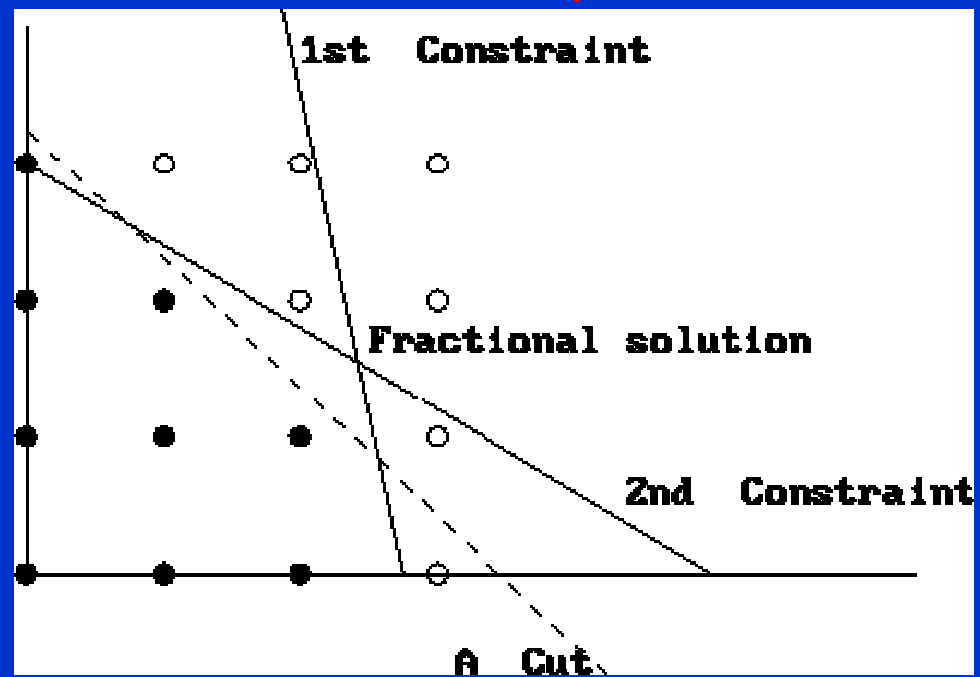


Cut type Factor ranking

Ad hoc, ad loc, and quid pro quo! So little time, so much to know!"

| | |
|----------------|------|
| Gomory cut | 2.52 |
| MIR | 1.83 |
| Knapsack cover | 1.40 |
| Flow cover | 1.22 |
| Implied bound | 1.19 |
| Path | 1.04 |
| Clique | 1.02 |
| GUB cover | 1.02 |
| Disjunctive | 0.53 |

They've been going in and out of style



Mixed Integer Program

I didn't know what I would find there.

$$\begin{aligned} & \text{minimize } cx \\ & \text{subject to } Ax = b, \\ & \quad l \leq x \leq u, \\ & \quad \text{some } x \in \{0,1\} \end{aligned}$$

Better modeling for

Start-up and shutdown

Transmission switching

Investment decisions

It was twenty
years ago today

solution times improved by $> 10^7$ in last 20 years

2007: 10^4 nodes; 10^4 transmission constraints; 10^3
binary variables

Improvements in MIP (same hardware) one day unit commitment problem

| year | Cplex version | Time in sec | B&B nodes |
|------|---------------|-----------------|-----------|
| 1993 | 2.2 | 1646 (unsolved) | 110792 |
| 1995 | 4.0 | 88.8 | 22549 |
| 1997 | 5.0 | 66.5 | 18488 |
| 1999 | 6.5 | 4.2 | 396 |
| 2001 | 7.1 | 1.7 | 91 |
| 2003 | 9.0 | 1.8 | 98 |
| 2005 | 10.0 | 1.1 | 72 |
| 2007 | 11.0 | 1.1 | 75 |

And though the holes were rather small

They had to count them all

Improvements in MIP (same hardware) one week unit commitment problem

| Year | Cplex version | Time in sec | B&B nodes |
|------|---------------|-----------------|-----------|
| 1998 | 6.0 | 8000 (unsolved) | 44900 |
| 1999 | 6.5 | 907 | 35683 |
| 2001 | 7.1 | 278 | 5308 |
| 2002 | 8.0 | 152 | 3575 |
| 2003 | 9.0 | 172 | 3928 |
| 2005 | 10.0 | 118 | 2090 |
| 2007 | 11.0 | 103 | 2220 |

December 17, 2007
Eight days a week
Is not enough to show I care.

Real-time Market



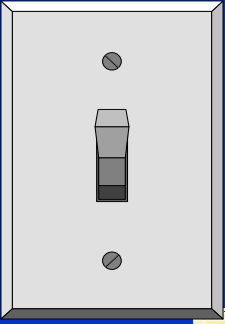
- ⇒ balancing market plus a look-ahead
- ⇒ efficiently dispatch generation, load, transmission and ancillary services
- ⇒ Subject to reliability constraints
- ⇒ Within the limits of generators and transmission

Real-time market Survey Results

Let me tell you how it will be



| ISO | Current or previous approach | Date or planned date of MIP | Estimated savings on an annual basis |
|-------|------------------------------|-----------------------------|--------------------------------------|
| PJM | MIP | 2006 | \$100 million |
| ISONE | LR/LP | 2008 | No estimate |
| SPP | LP | none | N/A |
| NYISO | LR/LP | none | N/A |
| MISO | judgment with LR | 2008 | No estimate |
| CAISO | LR. | 2008 | ~\$1 million |



End-use markets got to get you into my life



- ↪ Vertical demand curve in ISO markets
- ↪ Consumers receive very weak price signals

- ↪ See monthly average price

- ↪ No real time meter; No real time price

- ↪ On a hot summer day

- ↪ wholesale price = \$1000/MWH

- ↪ Retail price = \$100/MWH

He's as blind as he can
be just sees what he
wants to see

- ↪ Solution:

- ↪ real time pricing and

- ↪ Demand-side non-convex (MIP) bidding

- ↪ Two-sided market using MIP!!!!!!!!!!

Day-ahead Market



Woke up, got out of bed, ...

- ⇒ scheduling market
- ⇒ efficiently (from bids) schedule generation, load, transmission and ancillary services
- ⇒ Subject to reliability constraints
- ⇒ Within the limits of generators and transmission

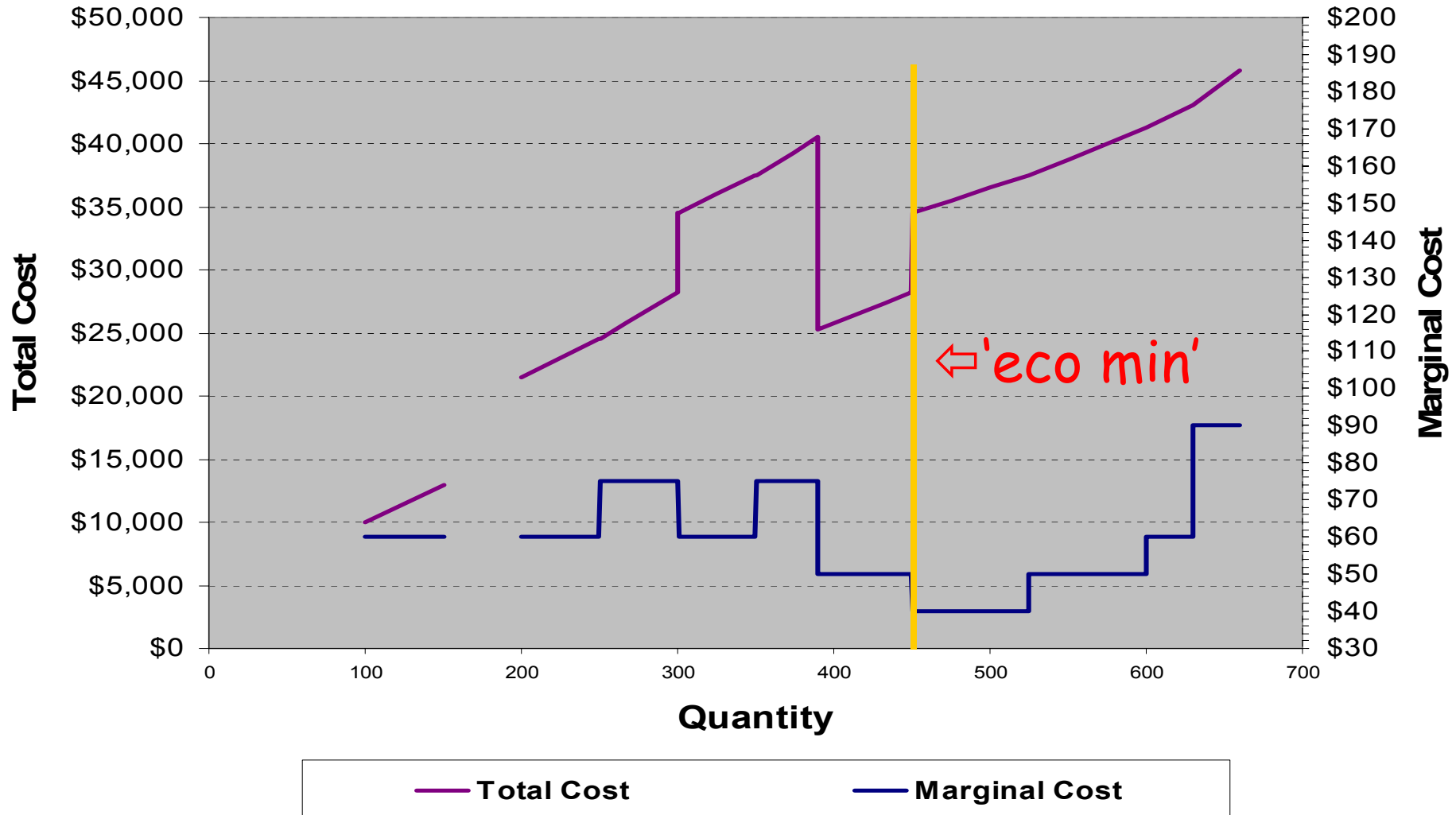
day-ahead market Survey Results

Let me tell you how it will be



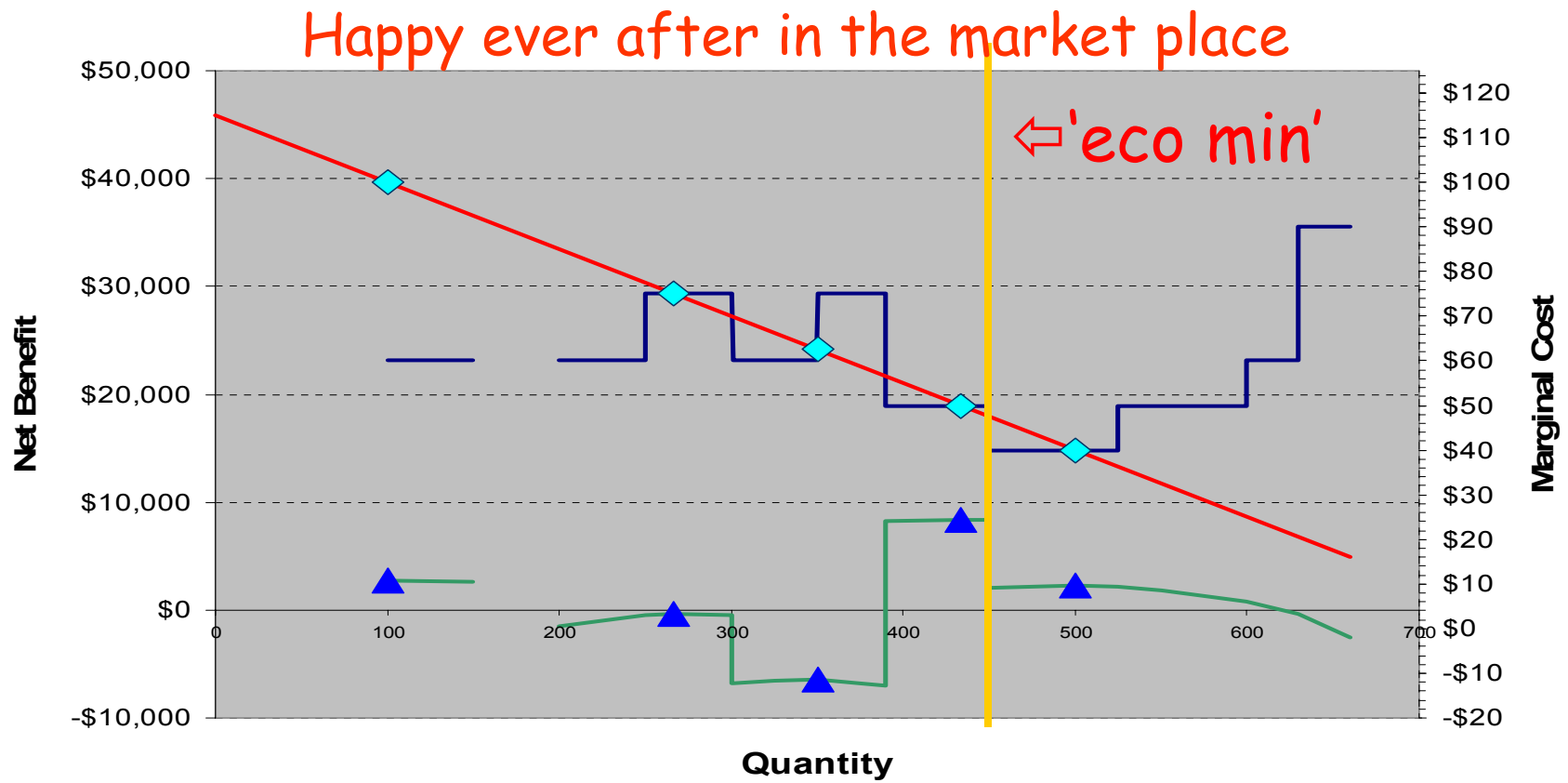
| ISO | Current or previous approach | Date or planned date of MIP-based implementation | Estimated savings on an annual basis |
|-------|------------------------------|--|--------------------------------------|
| PJM | LR | 2004 | \$60 Million |
| ISONE | LR/LP | 2008 | None |
| SPP | N/A | N/A | N/A |
| NYISO | LR/LP | none | N/A |
| MISO | LR | 2008 | None |
| CAISO | LP | 2008 | \$23 million |

Total and Marginal Costs for CCCT



Linear Residual Demand and Local Optima

Equilibrium Points - Local Optima



— Total Benefits ▲ Local Optima — Marginal Costs — Derived Demand ◆ Equilibrium Points

Better generator bidding (e.g. CCCT)

| ISO | Current or previous approach | Planned or actual MIP implementation date | |
|-------|------------------------------|---|--|
| PJM | MIP | June 2004 | |
| NYISO | LR with modeling | evaluation 2008 | |
| ISONE | LP | none | |
| SPP | none | N/A | |
| MISO | Bidder selection | 2008 | |
| CAISO | Aggregated | 2008 | |

transmission switching



- ⇒ Open or close circuit breakers using DCOPF
- ⇒ IEEE 118 bus provided 25% savings
- ⇒ N-1 for IEEE 118 & RST 96 system showed savings from 1% to 16%
- ⇒ ISONE networks ranged from 5% to 15% savings or \$500 Million annual (all solutions have gaps so higher savings may be found)

Generation Capacity Market

- ⇒ ensure generation adequacy for reliability
- ⇒ Adequate compensation (missing money from mitigation)
- ⇒ Collective call option in spot market

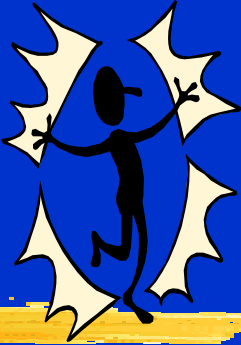
Generation Capacity Survey Results

Let me tell you how it will be



| ISO | Current or previous algorithmic approach | Date or planned date of MIP-based implementation | Estimated savings on an annual basis |
|-------|--|--|--------------------------------------|
| PJM | MIP | 2007 | N/a |
| ISONE | N/A | 2008 | \$45 Million |
| SPP | N/A | N/A | N/A |
| NYISO | n/a | N/A | N/A |
| MISO | n/a | N/A | N/A |
| CAISO | None | considering | None |

Transmission rights Markets



- ⇒ hedge transmission congestion costs
- ⇒ Pay difference in LMPs
- ⇒ Options and obligations
- ⇒ Full property rights (no there yet)
- ⇒ Include investments use MIP

Benefits of better market modeling

Say the words you long to hear



- ⇒ Benefit/cost can be over 100
- ⇒ MIP in PJM day-ahead market:
 $\$54 \times 10^6$ /year
- ⇒ CCCT modeling: 'forbidden zones'
- ⇒ Topology estimators for reliability:
priceless
- ⇒ Better reactive power modeling
- ⇒ Transmission dispatch: 5 to 24% savings
- ⇒ Worldwide: \$10 to \$200 billion/year

When the world is not convex market clearing can get funky

- ⇒ when the market is non-convex, linear prices do not necessarily clear the market
- ⇒ Naive Uplift Settlement
 - ☞ Make whole
 - ☞ Average load
- ⇒ 'Sophisticated' Uplift Settlement
 - ☞ Cooperative game theory
 - ☞ Convex hull





Research questions



⇒ Decomposition and Grid (parallel) computing

⌚ Real/reactive

⌚ Time

⌚ Market participant

⇒ Good approximations

⌚ Linearizations

⌚ convex

⇒ Avoiding local optima

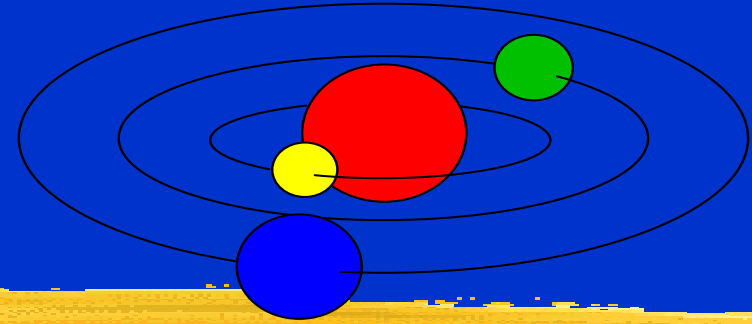
⇒ Nonlinear prices v linear prices

⇒ Improved market power analysis

⇒ More rational market power mitigation

If you really like
it you can have
the rights
It could make a
million for you
overnight





"A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."

Max Planck, "Scientific Autobiography and Other Papers"

"The magical mystery tour is waiting to take you away,
Waiting to take you away."