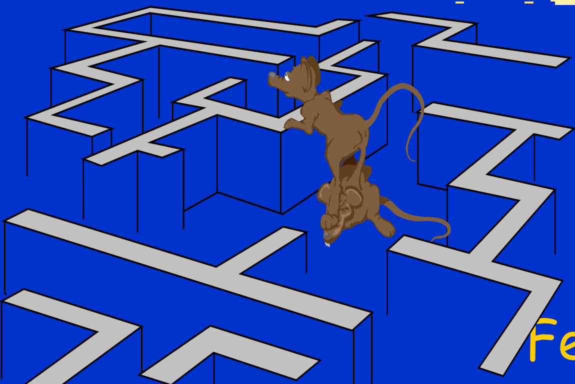
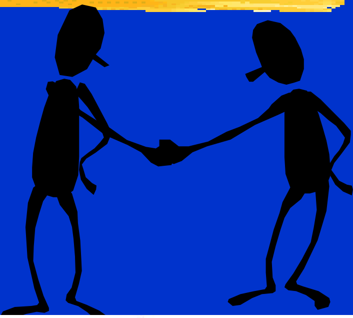
Modeling and Computational Enhancements for Efficient Transformation Wind, Rain and Fire into Electricity

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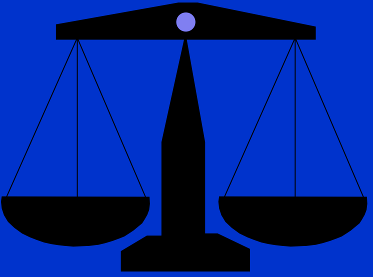
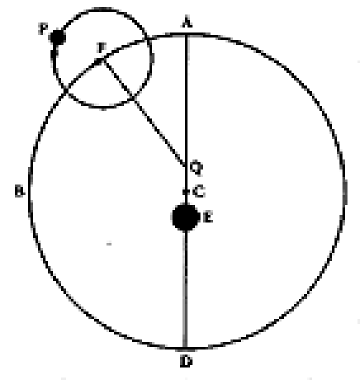
March 9, 2010

Views expressed are not necessarily those of the Commission



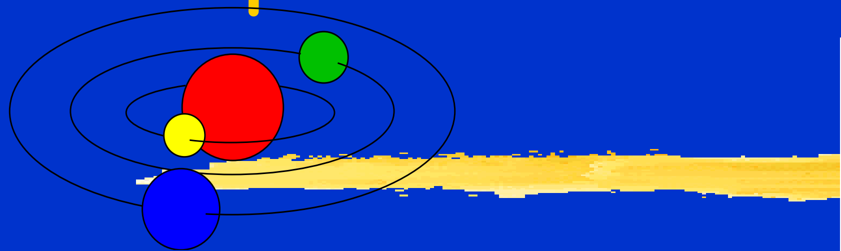

Early fictions, frictions, paradigm changes and politics



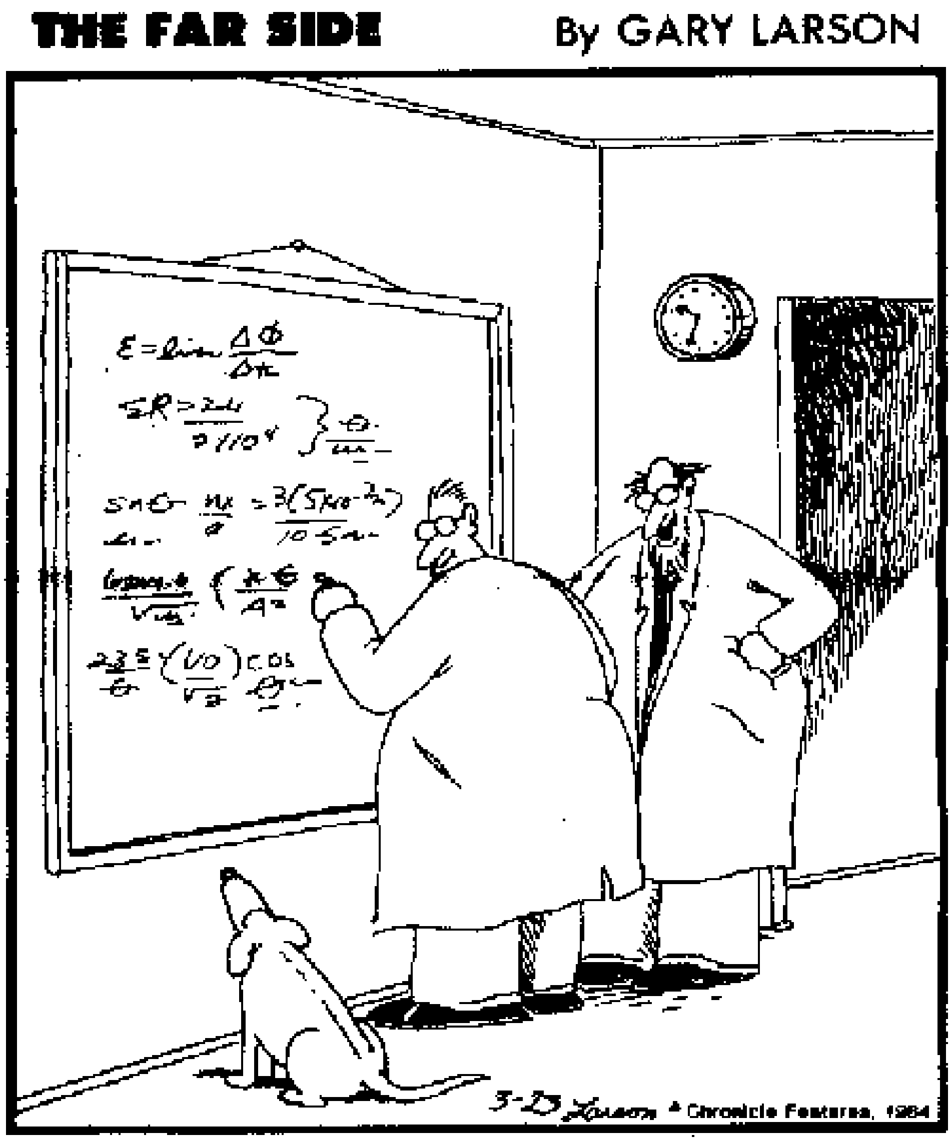
- 300 BC Aristotle's elements
  - Air, Water, Fire, Earth, Aether
  - 'proved' voids impossible
  - aether fills all potential voids
- Middle Ages Church adopts Aristotle's view
  - Punished for contrary views
  - Retarded the development of zero

- 1865 Maxwell (Did he have a silver hammer?)
  - publicly believed in aether but
  - his equations did not have it
- 20th century: aether paradigm gradually disappears
- Is aether reappearing as dark energy/matter?

Acceptance of Paradigm Shifts



"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



"Ohhhhhhh . . . Look at that, Schuster . . . Dogs are so cute when they try to comprehend quantum mechanics."

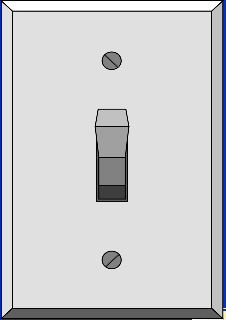
The magical mystery tour is waiting to take you away, waiting to take you away.

Electricity fictions, frictions, paradigm changes and politics

- 19th century competition: Edison v. Westinghouse
- 20th century: Sam Insull's deal
  - franchise 'unnatural' monopoly
  - cost-of-service rates
- 1927 PJM formed
- 1965 Blackout: Edward Teller
  - "power systems need sensors, communications, computers, displays and controls"
- End of 20th: Is there a natural monopoly?
  - 1988 Joskow & Schmalensee Markets for Power
  - 1889 FERC just and reasonable market based rates
  - 1996 Order 888 open assess/ISO rule
  - monopoly paradigm starts to disappear gradually

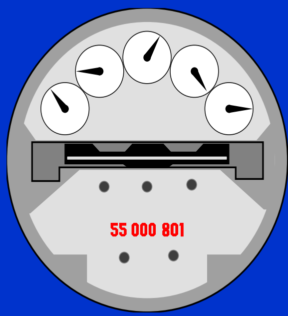
Structural change

- "natural monopoly" concept is no longer relevant to current technologies and scale of markets
  - 17,000 generators with 994 GW of capacity
  - 159,000 miles of high voltage transmission
  - Reliability rules require redundancy
  - Millions of interconnected end users
- Franchised monopoly shadow persists
  - Market power in non divested franchised areas
  - Transmission market power
- ISO market design: Competitive game embedded in a cooperative game



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
  - monthly meter; No real time price
  - On a hot summer day
    - wholesale price = $1000/MWh
    - Retail price < $100/MWh
- Solution: smart appliances
  - real time pricing, interval meters and
  - Demand-side non-convex bidding
- Large two-sided market!!!!!!!!!



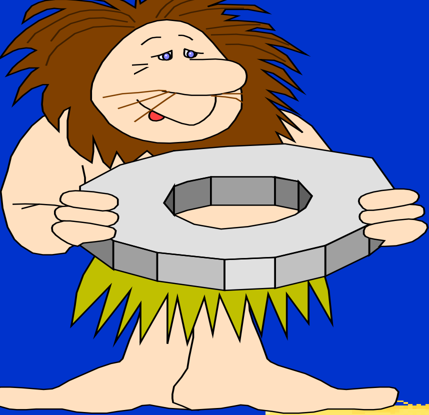
He's as blind as he can be just sees what he wants to see

What is at stake in electricity markets? roughly

	load	generation	revenues	price
	PetaWh	Giga Watts	$\$10^{12}$/yr	\$/kwh
US	4	1	0.3	0.1
world	16	4	~2.0	

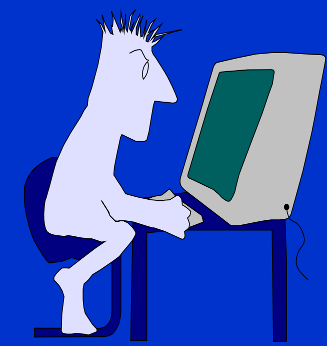
- The efficiency/innovation target is measured in $\$10^{12}$/year
- 1% savings is greater than $\$10^{10}$/yr

☹ **money can't buy me love**



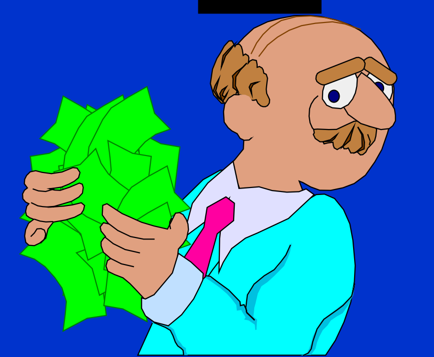
Paradigm change Smarter Markets 20??

- What will be smarter?
  - Generators, transmission, buildings and appliances
  - communications, software and hardware
  - markets and incentives

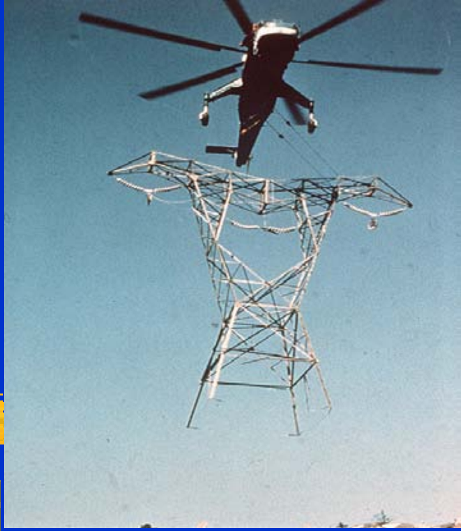


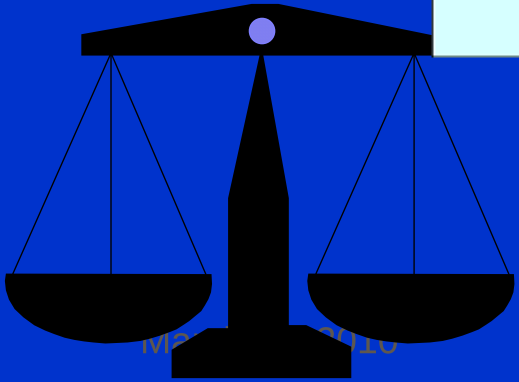
- what is the 21st century market design?
  - Locationally and stochastically challenged:
  - Wind, solar, hydro
  - Fast response: batteries and demand
  - Harmonize wind, solar, batteries and demand
  - Greater flexibility more options

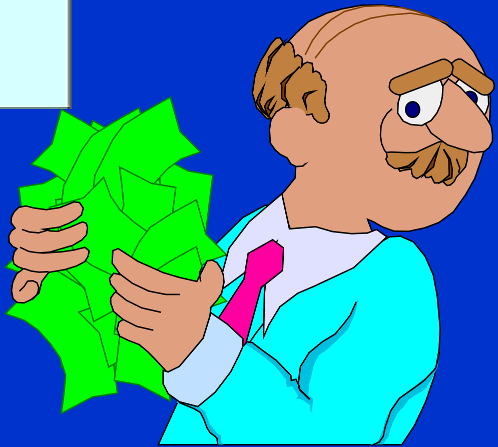
- FERC strategic goal: Promote efficiency through better optimization software



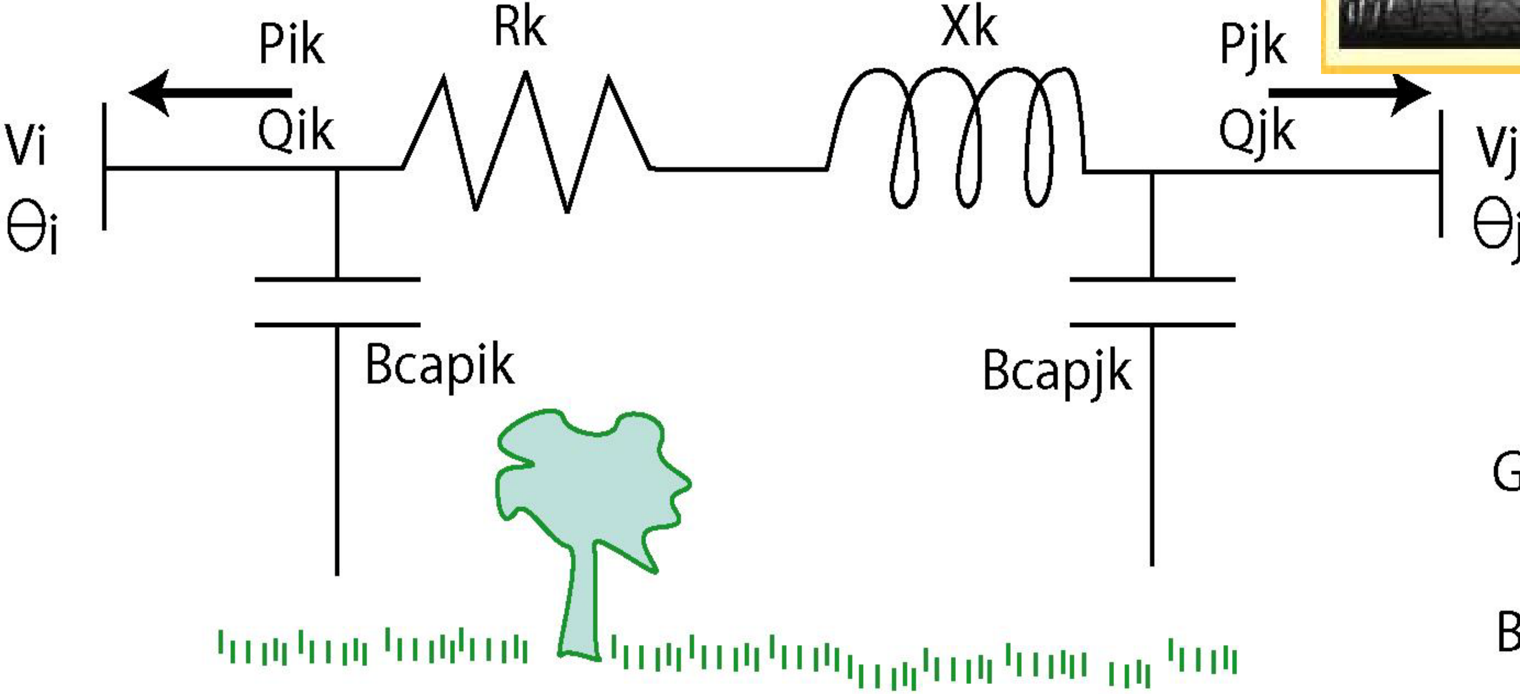
Electric Network Markets







Power Flow and Admittance



$$G = \frac{R}{R^2 + X^2}$$

$$B = \frac{-X}{R^2 + X^2}$$

AC Model (physics)

$$Pik = Gk*Vi^2 - Gk*(Vi*Vj)*\cos(\Theta i - \Theta j) - Bk*(Vi*Vj)*\sin(\Theta i - \Theta j)$$

$$Qik = -Bk*Vi^2 - Gk*(Vi*Vj)*\sin(\Theta i - \Theta j) + Bk*(Vi*Vj)*\cos(\Theta i - \Theta j) - Bcapik*Vi^2$$

DC Model (market model approximation. Can we do better?)

$$Pik = -Bk*(\Theta i - \Theta j)$$

Network analogies and their problems

analogy	owners	Commodity /conduit	Displacement network	other issues	pricing
highways	public	unbundled	No	congestion	Gas tax and toll roads
water	public	bundled	yes	other uses	usage
Natural gas	private	unbundled	yes	storage and valves	Price caps and no withholding
Air traffic	public	unbundled	no	No pricing	Ticket tax
parks	public	unbundled	no	congestion	Income tax
telecom	private	mixed	No	Busy signal	Price caps
railroads	private	bundled	no	congestion	Loose price caps

Air traffic controller as control area operator

- Trip from DC to LA
  - 1/3 goes thru Toronto on Air Canada
  - 1/3 goes thru Chicago on United
  - 1/3 goes thru Dallas on American
- trip time: milliseconds
- Who gets the money from the ticket?
- Is your Mother-in-law fungible?

ISO Markets and Planning

- **Four main ISO Auctions**
  - Real-time: for efficient dispatch
  - Day-ahead: for efficient unit scheduling
  - Generation Capacity: to ensure generation adequacy and cover efficient recovery
  - Transmission rights (FTRs): to hedge transmission congestion costs
- **Planning and investment**
  - Competition and cooperation

- All use approximations due to software limitations

Complete ISO market design

Not quite there yet

- Smarter markets
  - Full demand side participation with real-time prices
  - Smarter hardware, e. g., variable impedance
  - Better approximations, e. g., DC to AC
  - Flexible thermal constraints and transmission switching
  - smarter software with Petaflop computers
- electric network optimization has roughly
  - 10^5 nodes
  - 10^5 transmission constraints
  - 10^4 binary variables
- Potential dispatch costs savings: 10 to 30%

Approach to AC modeling

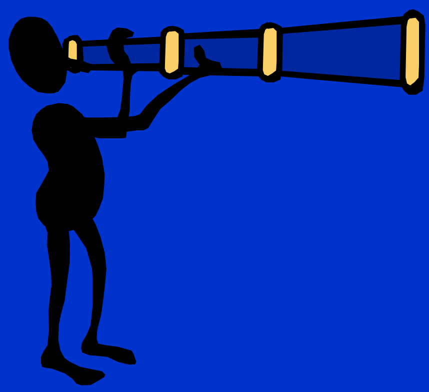
- A nonlinear optimizer will find a local optimum
- How do we avoid local optima?
- 1. Solve the DC unit commitment
  - with a first order AC approximation
  - Real/reactive decoupling
- 2. Refresh the approximation
- 3. stop or go to 1
- Model gets large

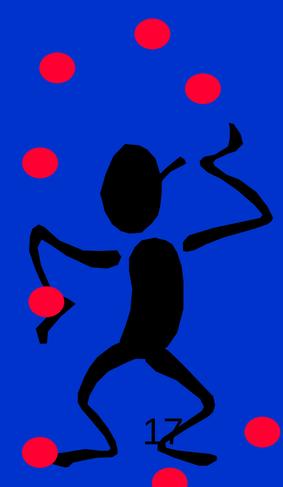
When the world is not convex market clearing can get funky

- when the market is non-convex, linear prices do not necessarily clear the market
- efficient solution settlements to do not address equities
- Naïve Uplift Settlement
  - Make-whole payments
  - Charged to average load
- 'Sophisticated' Multi-part Settlement
  - Nonconvex equilibria
  - Cooperative game theory
  - Convex hull theory

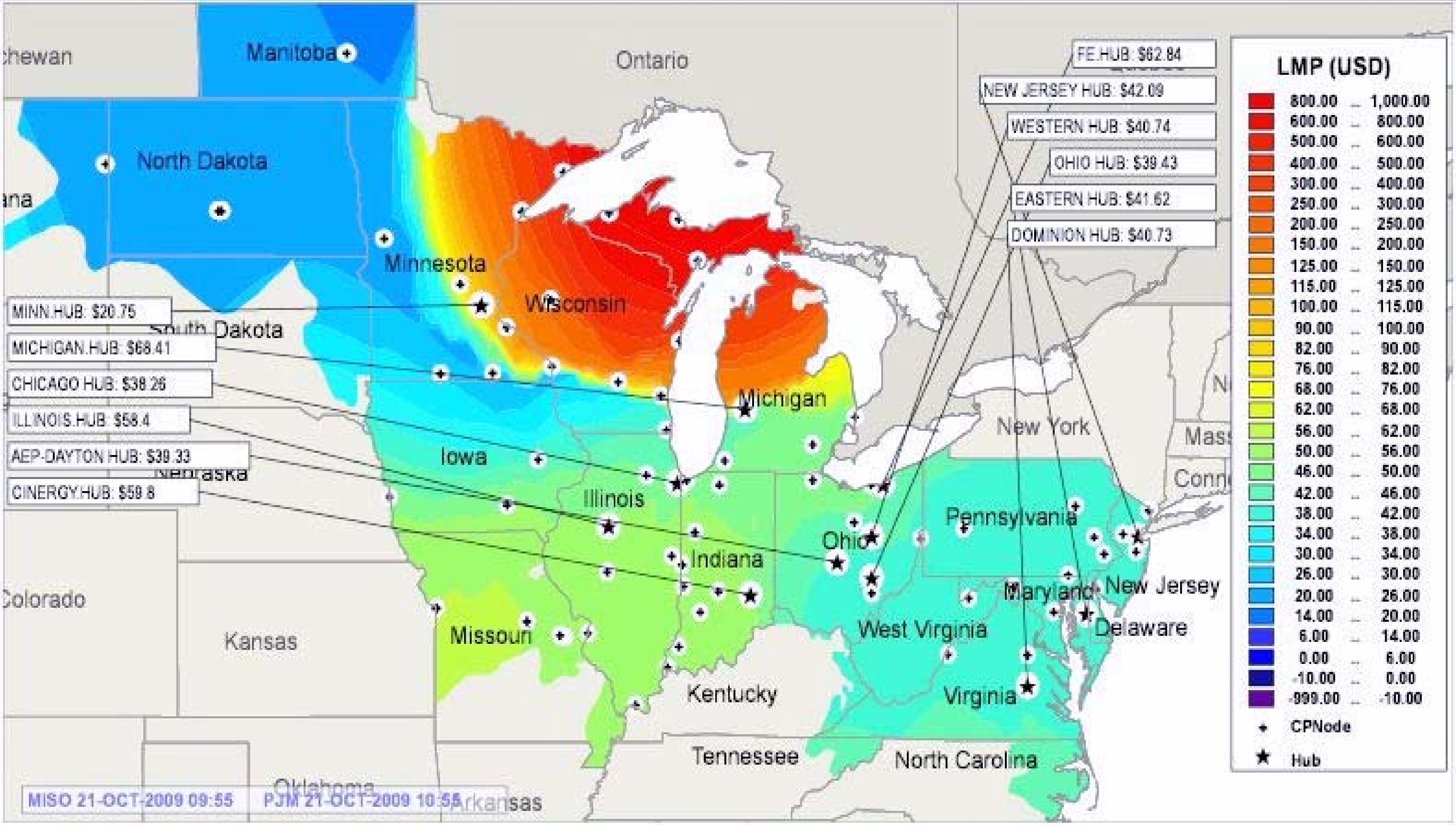
Real-time Market

- balancing market plus a look-ahead
- efficiently dispatch generation, load, transmission and ancillary services every 5 minutes
- Subject to explicit N-1 reliability constraints
- Within the flexible limits of generators and transmission





PJM/MISO 5 minute LMPs 21 Oct 2009 9:55 AM



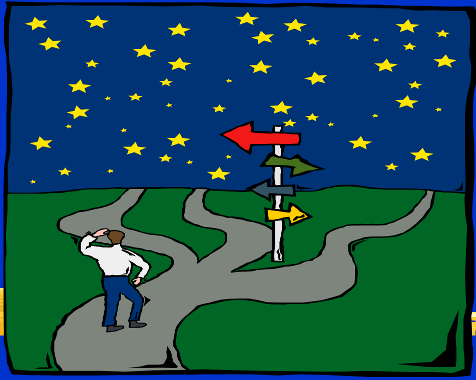
Day-ahead Market

Woke up, got out of bed, …

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

Eight days a week is not enough to show I care

MIP Paradigm shift:
Let me tell you how it will be



- Pre-1999 Lagrangian Relaxation
  - MIP can not solve in time window
  - LR solutions are usually primal infeasible
  - LR inhibits modeling
    - Simplified generators
    - No optimal switching
- 1999 unit commitment conference and book
  - MIP provides new modeling capabilities
  - New capabilities may present computational issues
  - Bixby demonstrates MIP improvements

Mixed Integer Program

I didn't know what I would find there.

maximize cx

subject to $Ax = b$,

$l \le x \le u$,

some $x \in \{0,1\}$

And though the holes were rather small
They had to count them all

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 30 years
- 10 years becomes 10 minutes

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

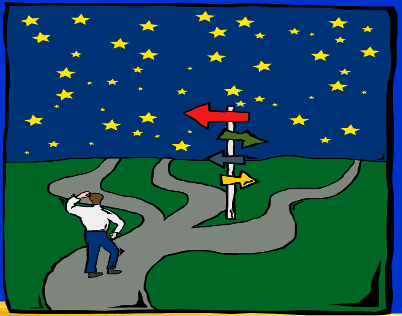
year	Cplex version	Time in sec	B&B nodes
1993	2.2	1646 (unsolved)	110792
1995	4.0	88.8	22549
1997	5.0	66.5	18488
1999	6.5	4.2	396
2001	7.1	1.7	91
2003	9.0	1.8	98
2005	10.0	1.1	72
2007	11.0	1.1	75

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
	Eight days a week Is not enough to show I care.		

MIP Paradigm shift:
Let me tell you how it will be



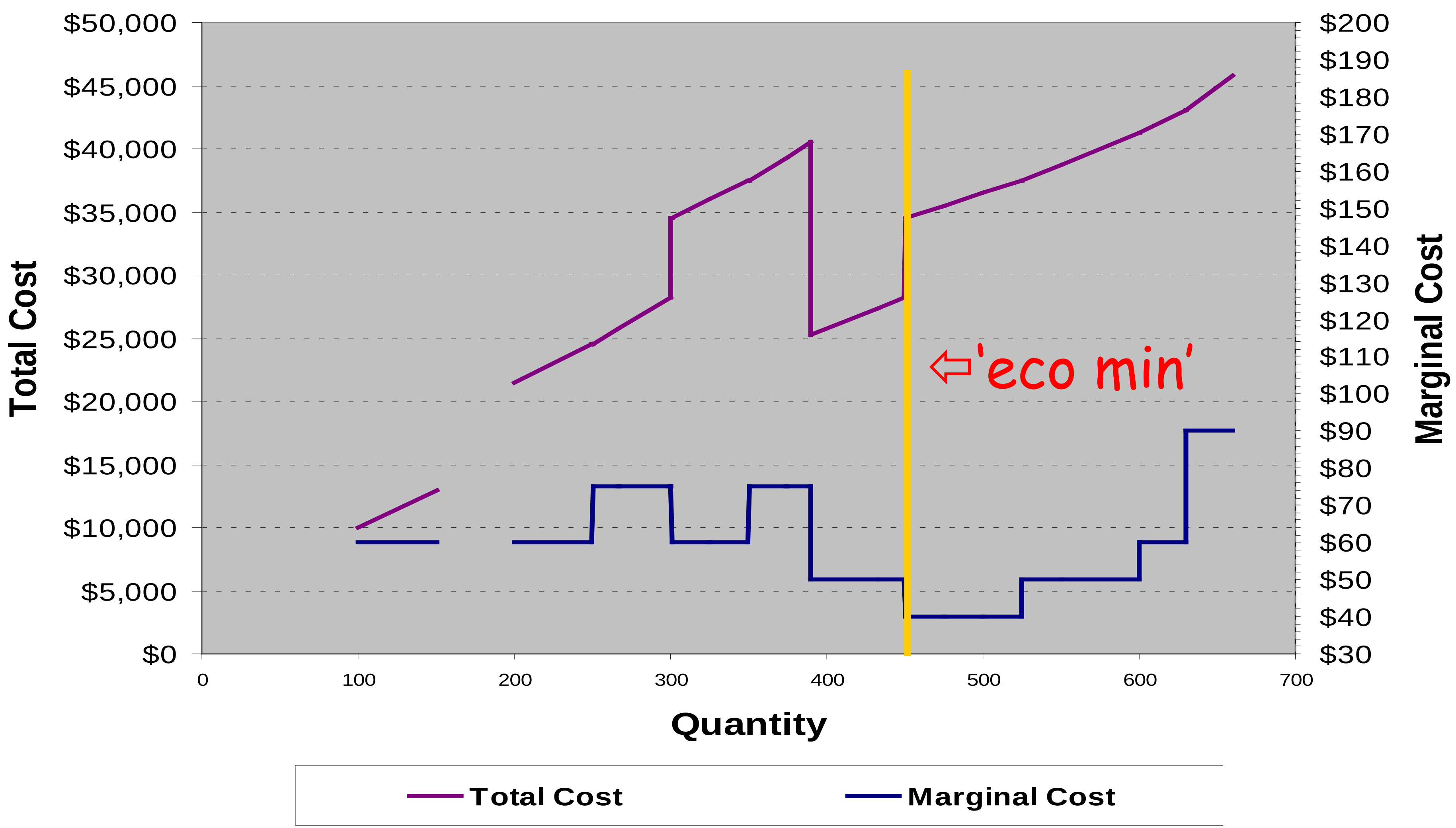
ISO	previous approach	Date for MIP	Estimated annual savings
PJM	LR	2006	$250 million
ISONE	LR/LP	Tbd	No estimate
SPP	LP	2013	No estimate
NYISO	LR/LP	Tbd	No estimate
MISO	LR	2008	No estimate
CAISO	LR	2009	>$25 million

Combined Cycle Combustion Turbine

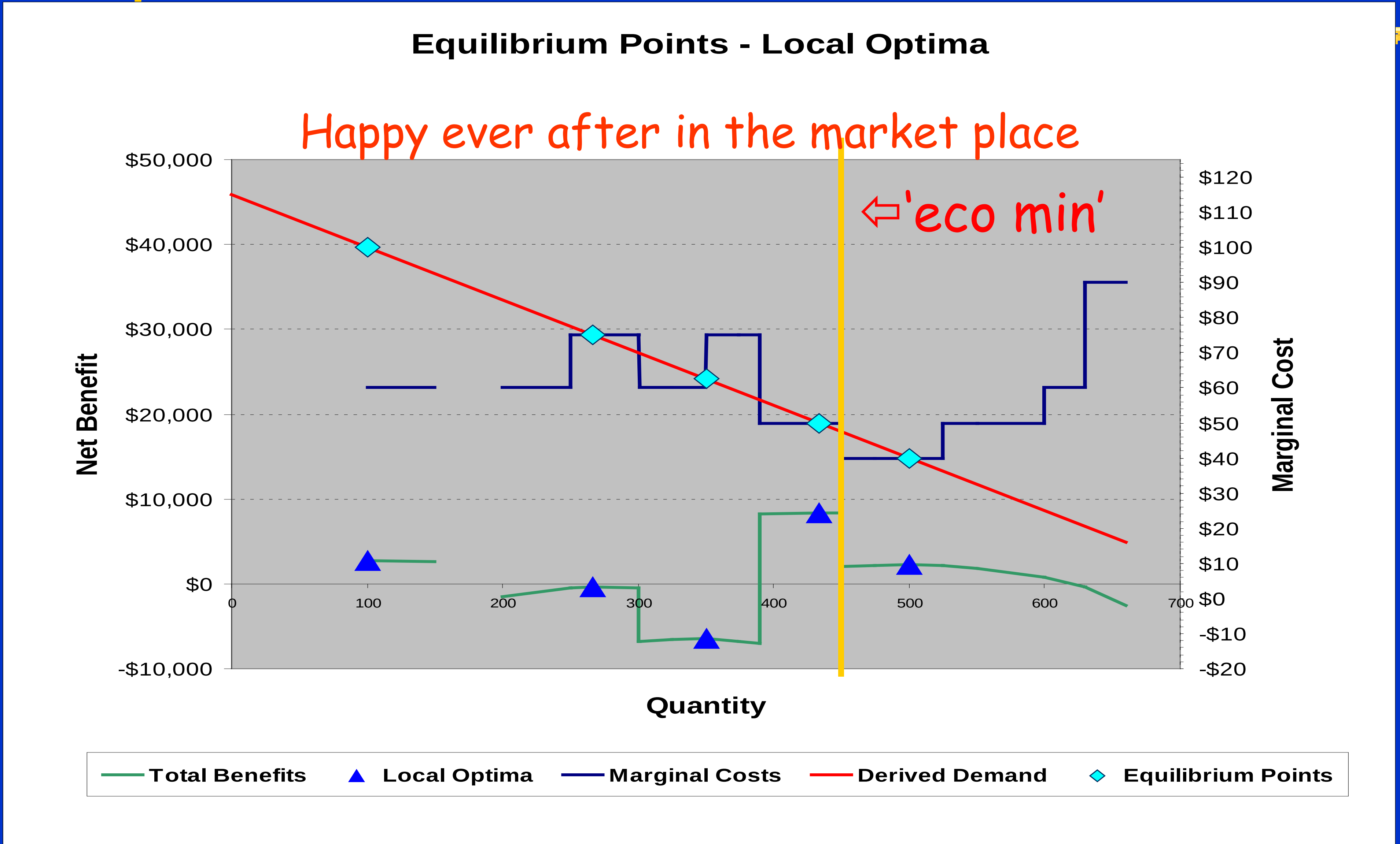
CT = combustion turbine
ST = steam turbine

Unit	Startup Costs $	Cost per MWh $	Minimum Output MW	Maximum Output MW
CT1	4000	60	100	150
CT2	4000	75	100	150
CT3	4000	90	100	150
ST	0	0	130	210

Total and Marginal Costs for combined cycle combustion turbine CCCT



Linear Residual Demand and Local Optimal Solutions

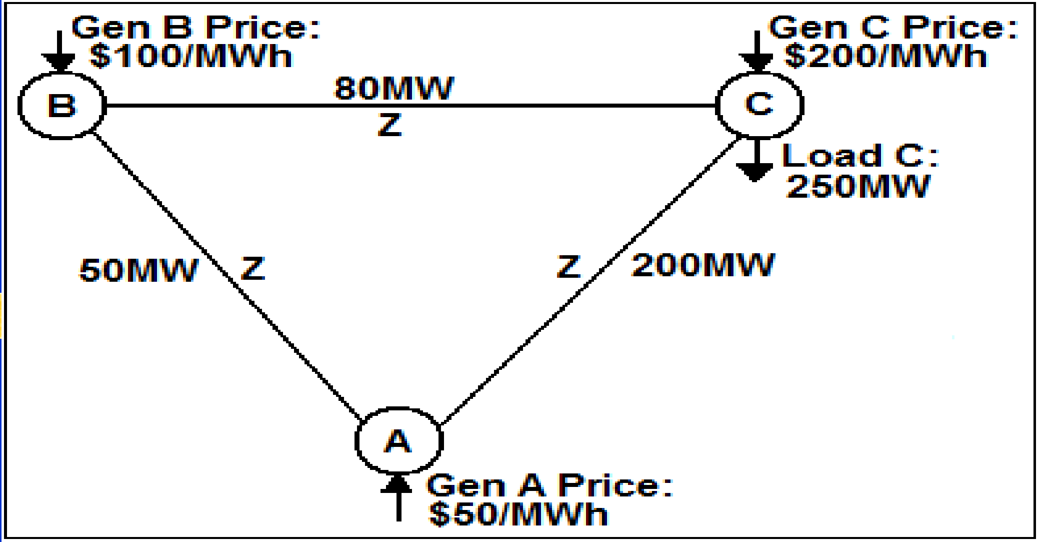


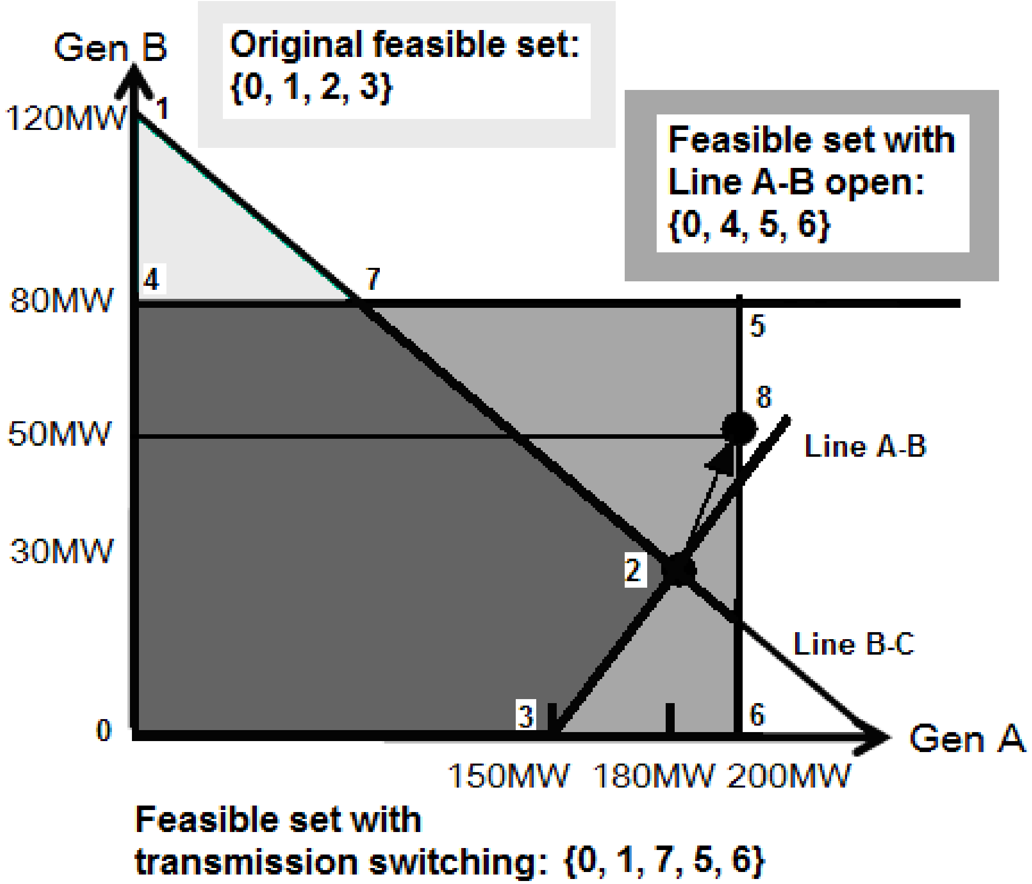
transmission switching

- Open or close circuit breakers
- Proof of concept savings using DCOPF
  - IEEE 118 bus provided **25% savings**
  - N-1 for IEEE 118 & RST 96 **up to 16%** savings
  - ISO-NE network **15% savings** or **$.5 billion/yr**
- Potential
  - all solutions have optimality gaps so higher savings may be found
  - Currently takes too long to solve to optimality
  - Suboptimal solutions are acceptable

Three bus example

- Feasible sets for Gen A and Gen B with transmission switching
- No switching [2]: cost =$50×180+$100×30+ $200×40 = $20,000
- remove AB [8]: cost =$50×200+$100×50 = $15,000





Kirchhoff's second law for AC transmission elements

Big M method with non-negative variables and full N-1 reliability

$-B_k\theta^-_{kct} - P^+_{kct} - M_k(2 - z_{kt} - N1_{kc}) \leq 0$

$-B_k\theta^+_{kct} - P^-_{kct} - M_k(2 - z_{kt} - N1_{kc}) \leq 0$

$B_k\theta^-_{kct} + P^+_{kct} \leq 0$

$B_k\theta^+_{kct} + P^-_{kct} \leq 0$

$\theta^-_{kct}, P^+_{kct}, \theta^+_{kct}, P^-_{kct} \geq 0$

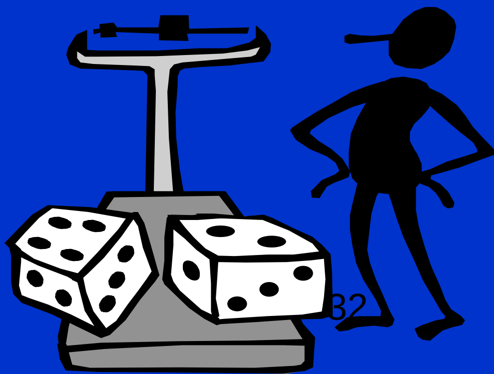
$z_{kt} \in \{0, 1\}$

Enhanced wide-area planning models

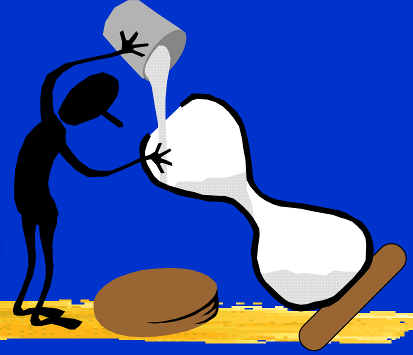
- enable a more efficient planning and cost allocation through a mixed-integer stochastic program.
- Integration of more components of the planning process into a single modeling framework to improve planning efficiency.
- Better models are required to
  - economically plan efficient transmission investments
  - compute cost allocations
- in an environment of competitive markets with locationally-constrained variable resources and criteria for contingencies and reserve capacity.

A Possible Planning Model

- decide on a set of future scenarios
- assign probabilities to each scenario
- Take transmission proposals
- **Solve a large-scale stochastic MIP.**
- find the investments with the highest expected net benefits
- Determine the beneficiaries
- Allocate costs & rights



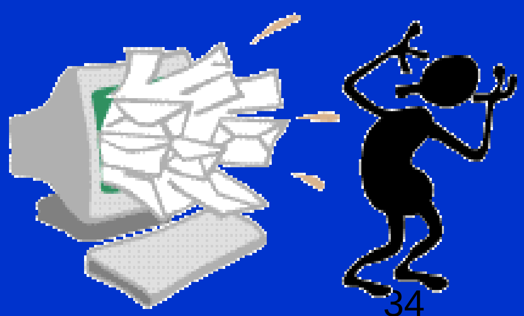
Five Year Strategic Plan



- identify opportunities to enhance operational efficiency particularly RTOs and ISOs
- Promote operational efficiency in wholesale markets through the exploration and encouragement of the use of improved software and hardware that will optimize market operations
- to deploy new modeling software and optimize their market operations.

Future ISO Software

- Real-time:
  - AC Optimal Power Flow with <5 min dispatch, look ahead and N-1 reliability
- Day-ahead:
  - N-1 ACOPF with unit commitment and transmission switching with <15 min scheduling
- Investment/Planning:
  - extension of day-ahead market
  - Greater detail and topology
  - more time to solve

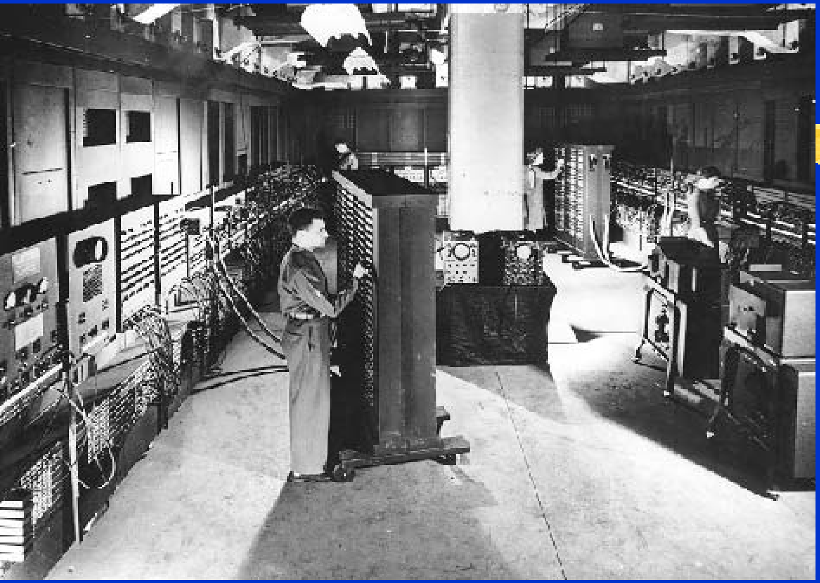


Computational Research Questions

- Decomposition and Grid (parallel) computing
  - Real/reactive
  - Time
- Good approximations
  - Linearizations
  - convex
- Avoiding local optima
- Nonlinear prices
- Better tree trimming
- Better cuts
- Advance starting points

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

New hardware



1945, **ENIAC**

30 tons, 19,000 vaccum tubes, 1,500 relays,

and 200 kilowatts

350 flops, 400 bytes

IBM Supercomputer Jump

32 processors 1.7 GHz and 128 Gbytes. 8.9 teraflops

5 terabyte memory

Harness "perennial gale of creative destruction" Schumpeter

New software

"Everything should be made as simple as possible ... but not simpler." Einstein

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