AUCTION DESIGN
FOR
WHOLESALE ELECTRICITY MARKETS

by

Haso Peljto

EMCon² - Energy Market Consulting, Inc.

www.EMCon2.com

FERC June 25, 2012

(763) 245-8150 haso.peljto@emcon2.com

Auction Design for Wholesale Electricity Markets
Outline

- Electricity Market Design
  - Structure/concepts/objectives
- Market Commodity Clearing
  - Economic efficiency
  - Fenchel decomposition
  - Coordination process and convergence criterion
- Market Commodity Pricing
  - Vickrey payments and participation tickets
  - Incentive compatibility
  - Voluntary participation
  - Market budget balancing
- Summary

Electricity Market Design
Proposal History

- 1986: Economic Reform of Electricity Industry
  - Generators, loads and network as atomic economic entities
- 1990: Existence and Optimality of Market Equilibrium
  - Walras model and Pareto optimality
- 1995: Fenchel Duality and Decomposition
  - Convex and continuous market model formulation
- 1999: Standard Market Design
  - Pricing scheme: worse of ex-ante LMP or ex-post as-bid price
- 2005: MIP Co-Optimization Engine
  - Industry leading performances and functionality
- 2010: Auction Design
  - Efficient, incentive compatible, rational and budget balanced

Electricity Market Design
Theoretical Concepts

- Microeconomics
  - Mathematical modeling instead of “economic lab”
  - Existence and optimality of competitive equilibrium
- Game Theory
  - Information availability and game strategy concepts
  - Existence and value of core of game
- Auction theory
  - Incentive compatibility and volunteer participation
  - Allocation efficiency and budget balance
- Convex Analysis
  - Duality theory and decomposition
  - Optimization software technology

Note:

- *All these concepts converged into Algorithmic Mechanism Design*

Electricity Market Design
Auction Design Principles

1. Economic Efficiency
   - Maximal overall market benefits; *optimal equilibrium*
2. Incentive Compatibility
   - Truthful submission of operating costs; *no market power*
3. Volunteer Participation
   - No negative market outcomes; *no need for uplift*
4. Market Balance
   - Market commodity and budget balance; *no market subsidiary*

- *Impossibility Theorem*

  It is not possible to comply with all four principles under general conditions with three or more market participants

Electricity Market Design

LMP Market vs. Design Principles

LMP-Based Market		Design Principles
Market efficiency maximization •Clearing non-truthful bids/offers	⊗	1. Economic Efficiency • Maximize total market profit
Market power always exists •Market power mitigation is necessary	⊗	2. Incentive Compatibility •Truthful submissions
No guarantied profitability •Uplift payments are necessary	⊗	3. Volunteer Participation •Non-negative market outcomes
Market budget deficit •Due to out-of-market payments	⊗	4. Market Balance •Commodity and budget balance

Needed: Payment System Improvements

- *Incentive compatible pricing scheme*
- *Energy block pricing*

Market Commodity Clearing

Economic Efficiency

- Maximize economic efficiency of overall electricity market

$$\max_{x^G, x^L} \left\{ \sum_L f^L(x^L) - \sum_G f^G(x^G) \middle| (x^G, x^L) \in (X^G \times X^L) \cap X^N \right\}$$

$$\begin{aligned} f^L(x^L) = &-Load\ Curtailment\ Costs \\ &+ Min\ En\ Demand\ Block\ Benefits \\ &+ Inc\ En\ Demand\ Benefits \\ &- AS\ Costs \end{aligned}$$

$$\begin{aligned} f^G(x^G) = &\ Generation\ Startup\ Costs \\ &+ Min\ En\ Supply\ Block\ Benefits \\ &+ Inc\ En\ Supply\ Benefits \\ &+ AS\ Costs \end{aligned}$$

Market Commodity Clearing
Technology Sets

- Supply Technology Set

$$X^{G} = conv\begin{cases} Power\ Output\ Limits: & x^{G}_{\min} \leq x^{G} \leq x^{G}_{\max} \\ Ramping\ Limits: & R^{G}_{dn} \leq \Delta x^{G} \leq R^{G}_{up} \\ Minimum\ ON/OFF\ Time & \\ Max\ Number\ of\ Starts & \end{cases}$$

- Demand Technology Set

$$X^{L} = conv\begin{cases} Power\ Demand\ Limits: & x^{L}_{\min} \leq x^{L} \leq x^{L}_{\max} \\ Ramping\ Limits: & R^{L}_{dn} \leq \Delta x^{L} \leq R^{L}_{up} \\ Maximum\ Curtailment\ Time & \\ Max\ Number\ of\ Curtailments & \end{cases}$$

Market Commodity Clearing
Technology Sets cont.

- Network Technology Set

$$X^N = conv\begin{cases} Active\ Power\ Balance: & P_i^G - P_i^L = \sum_{j \to i} P^{ij}(V^i, V^j, \theta^{ij}) \\ Reactive\ Power\ Balance: & Q_i^G - Q_i^L = \sum_{j \to i} Q^{ij}(V^i, V^j, \theta^{ij}) \\ Transmission\ Constraints: & \left|S^{ij})\right| = \sqrt{P^{ij^2} + Q^{ij^2}} \le S_{ij}^{\max} \\ Voltage\ Limits: & V_{min}^i \le V^i \le V_{max}^i \end{cases}$$

• *Note*

The supply, demand and transmission network technology sets are extended to form convex hulls

Market Commodity Clearing

Fenchel Decomposition

$$\max_{x^G, x^L} f(x^G, x^L) = \max_{x^G, x^L} \left\{ \sum_L f^L(x^L) - \sum_G f^G(x^G) \middle| (x^G, x^L) \in (X^G \times X^L) \cap X^N \right\} =$$

$$\min_{c^G, c^G} \left\{ \sum_G \varphi^G(c^G) + \sum_{G,L} \varphi^N(c^G, c^L) + \sum_L \varphi^L(c^L) \right\} = \min_{c^G, c^G} \left\{ \varphi\ (c^G, c^L) \right\}$$

$$\varphi^G(c^G) = \max_{x^G} \left\{ c^G \cdot x^G - f^G(x^G) \middle| x^G \in X^G \right\}$$

$$\varphi^N(c^G, c^L) = \max_{x^G, x^L} \left\{ c^L \cdot x^L - c^G \cdot x^G) \middle| (x^G, x^L) \in X^N \right\}$$

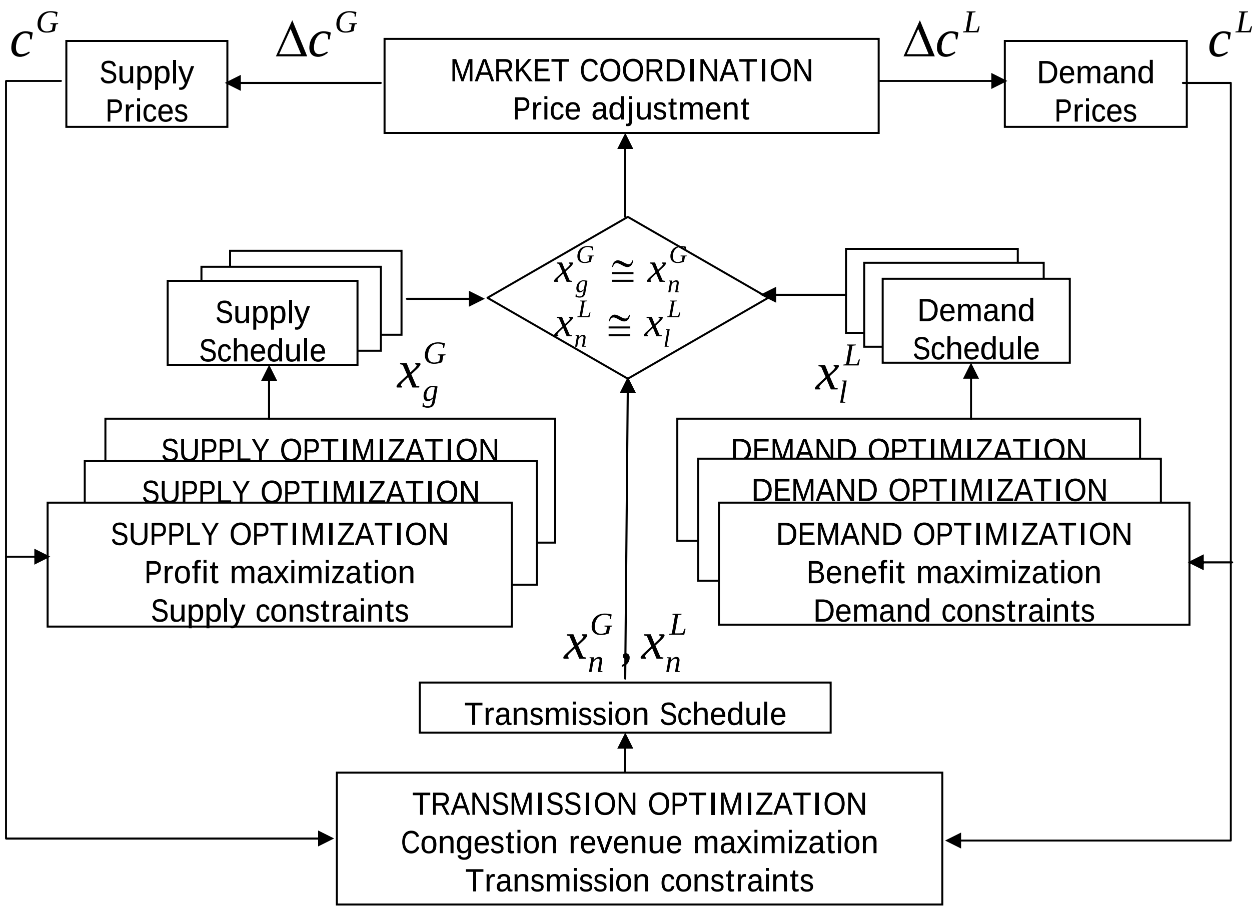
$$\varphi^L(c^L) = \max_{x^L} \left\{ f^L(x^L) - c^L \cdot x^L \middle| x^L \in X^L \right\}$$

Supply Profit + Network Profit + Demand Profit = Overall Market Profit

- *Invisible Hand*

  If individual profit for each supply, demand and transmission entity is maximal then the overall market profit is maximal. (A. Smith)

Market Commodity Clearing
… and Coordination



Market Commodity Clearing

Market Equilibrium

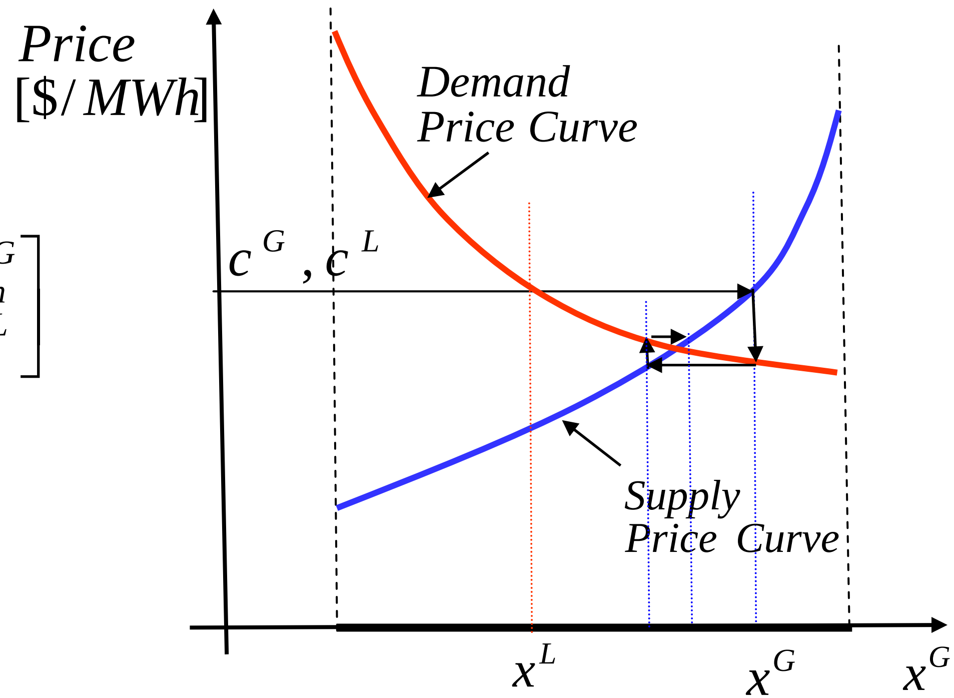
- Optimality Condition

$$\begin{bmatrix} x_g^G - x_n^G \\ x_n^L - x_l^L \end{bmatrix} = 0 \in \partial\varphi(c^G, c^L) = \partial\left\{\sum_G \varphi^G(c^G) + \sum_{G,L} \varphi^N(c^G, c^L) + \sum_L \varphi^L(c^L)\right\}$$

- Price Adjustment

$$\begin{bmatrix} \Delta c^G \\ \Delta c^L \end{bmatrix}_{k+1} = \begin{bmatrix} c^G \\ c^L \end{bmatrix}_{k+1} - \begin{bmatrix} c^G \\ c^L \end{bmatrix}_k = -\begin{bmatrix} \alpha^G \\ \alpha^L \end{bmatrix} \cdot \begin{bmatrix} x_g^G - x_n^G \\ x_n^L - x_l^L \end{bmatrix}$$

- Supply/demand low



Market Commodity Clearing

Supply Optimization

- Profit Maximization Objective

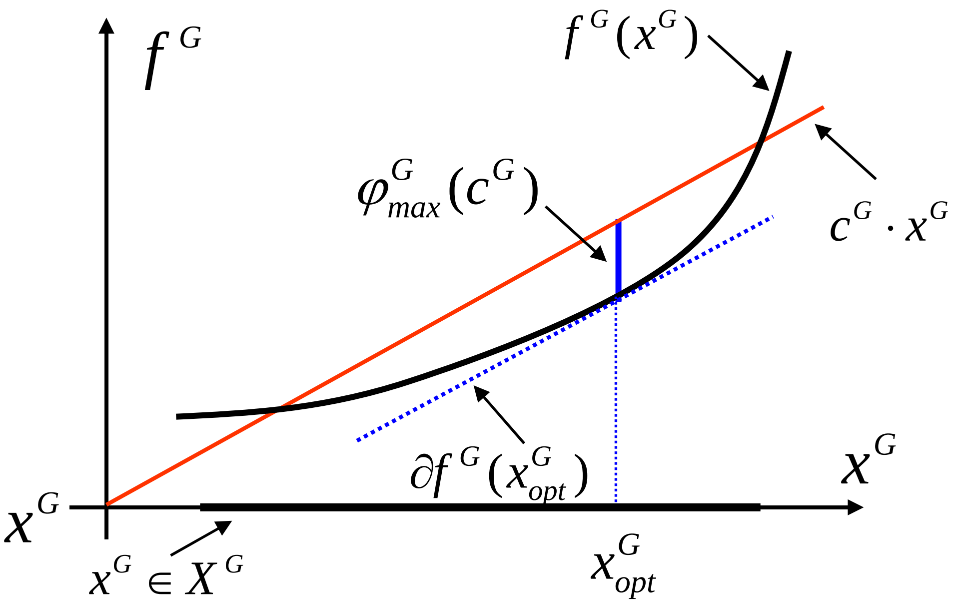
$$\varphi^G(c^G) = \max_{x^G}\left\{c^G \cdot x^G - f^G(x^G) \,\middle|\, x^G \in X^G\right\}$$

- Supply Technology Set X^G

  Power output limits
  Ramping limits
  Inter-temporal constraints

- Optimality Condition

$$c^G \in \partial f^G(x^G)$$



Market Commodity Clearing
Demand Optimization

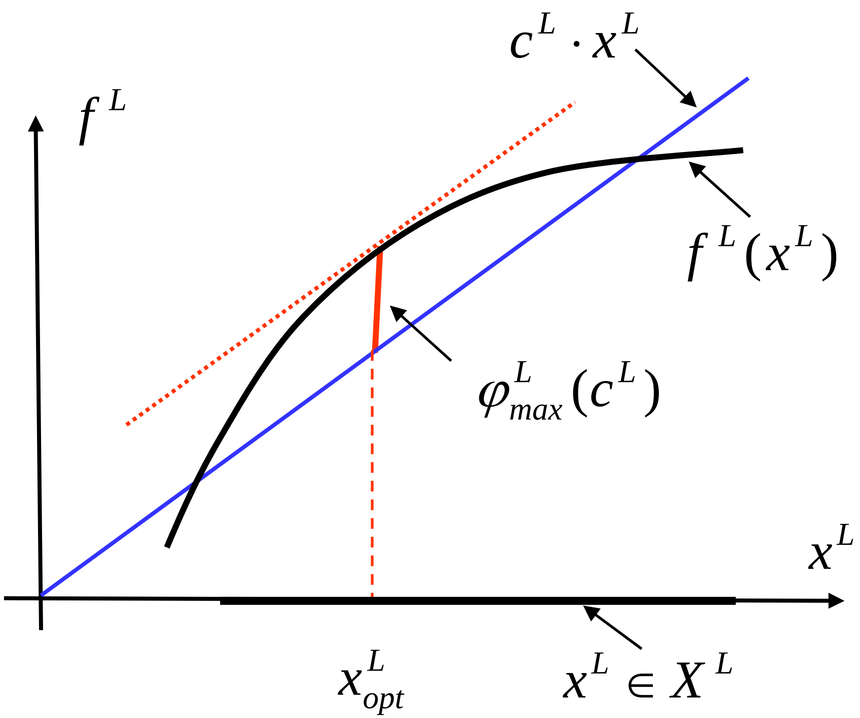
- Benefit Maximization Objective

$$\varphi^L(c^L) = \max_{x^L}\left\{ f^L(x^L) - c^L \cdot x^L \,\middle|\, x^L \in X^L \right\}$$

- Demand Technology Set X^L
  - *Consumption limits*
  - *Ramping limits*
  - *Inter-temporal constraints*

- Optimality Condition

$$-c^L \in \partial(-f^L(x^L))$$



Market Commodity Clearing

Transmission Network Optimization

- Maximization of Congestion Revenue

$$\varphi^N(c^G,c^L)=\max_{x^G,x^L}\left\{c^L\cdot x^L-c^G\cdot x^G \,\middle|\, (x^G,x^L)\in X^N\right\}$$

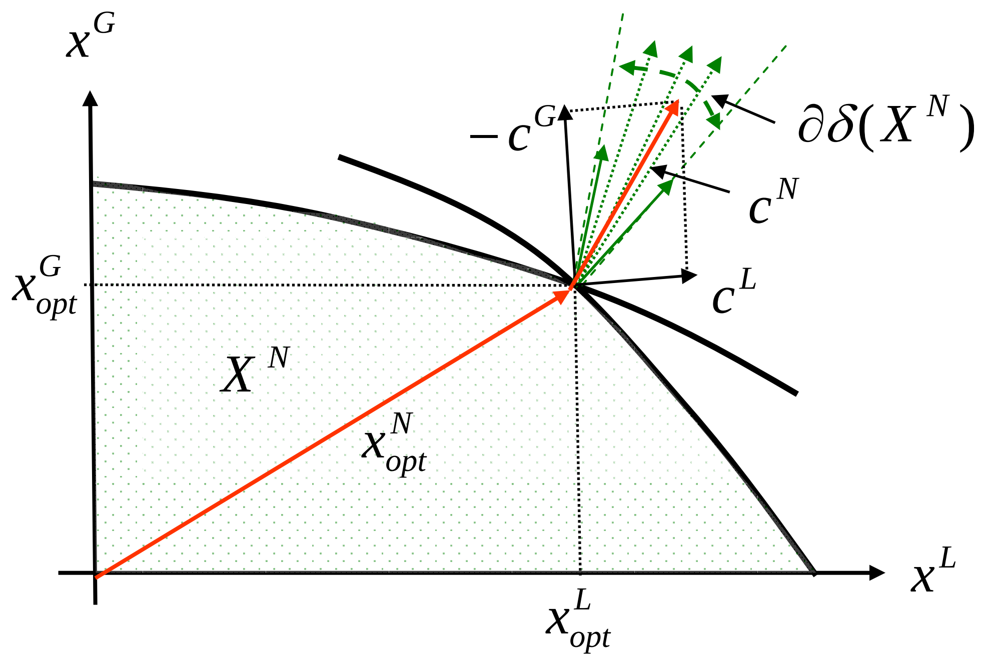
$$=\max_{x^G,x^L}\left\{c^L\cdot x^L-c^G\cdot x^G-\delta(X^N)\right\} \quad \delta(X^N)=\begin{cases}0 & (x^G,x^L)\in X^N\\ \infty & (x^G,x^L)\notin X^N\end{cases}$$

- Optimality Condition

$$(-c^G,c^L)\in\partial\delta(X^N)$$

- Congestion Revenue

$$\varphi^N_{\max}=c^L\cdot x^L_{opt}-c^G\cdot x^G_{opt}\geq 0$$

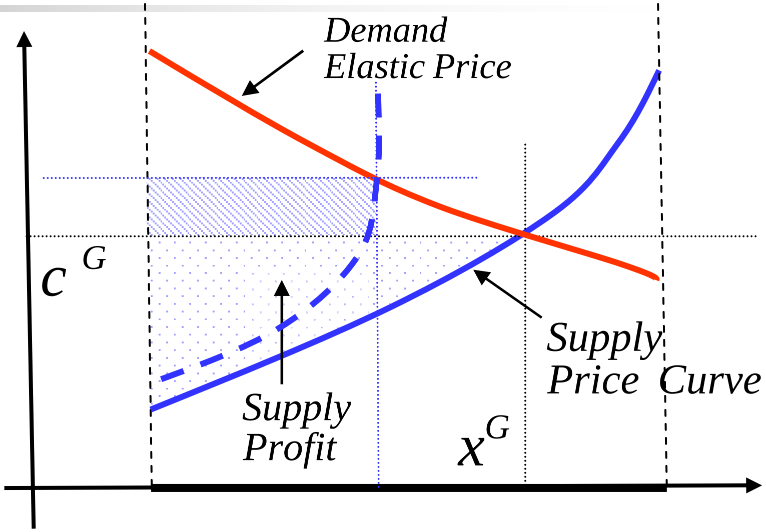


Market Commodity Pricing
Market Power Existence

- Supply Monopoly

$$\max_{x^G}\left\{c^G(x^G)\cdot x^G - f^G(x^G)\,\middle|\, x^G \in X^G\right\}$$

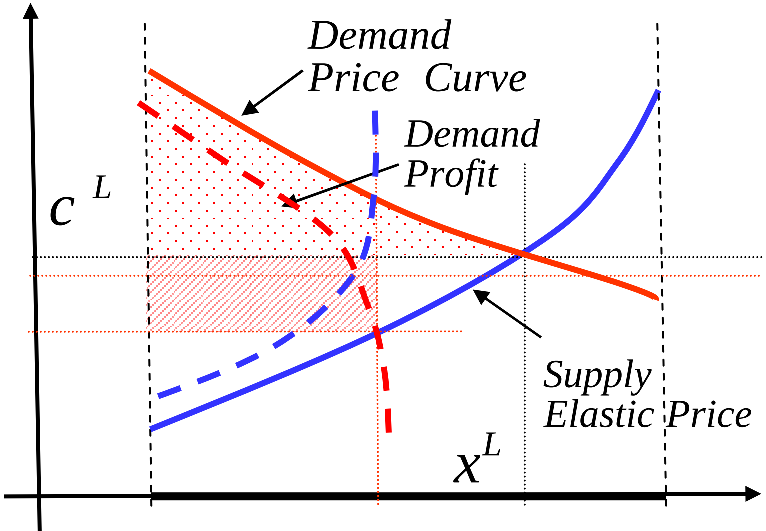
$$c^G(x^G) + x^G\cdot\frac{dc^G(x^G)}{dx^G} = \frac{df^G(x^G)}{dx^G}$$



- Demand Monopsony

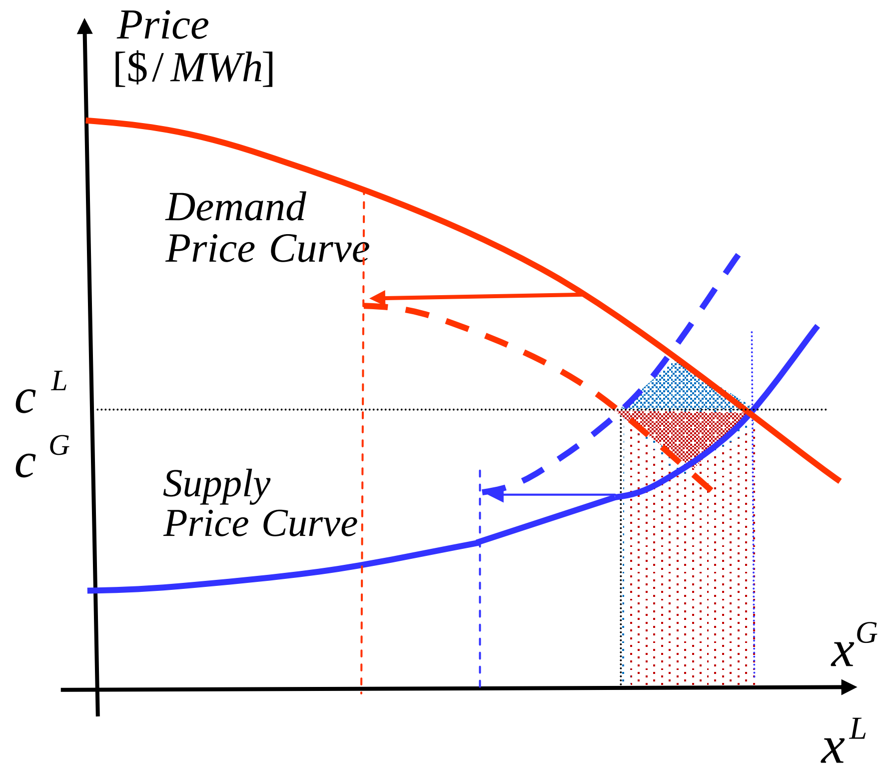
$$\max_{x^L}\left\{f^L(x^L) - c^L(x^L)\cdot x^L\,\middle|\, x^L \in X^L\right\}$$

$$\frac{df^L(x^L)}{dx^L} = c^L(x^L) + x^L\cdot\frac{dc^L(x^L)}{dx^L}$$



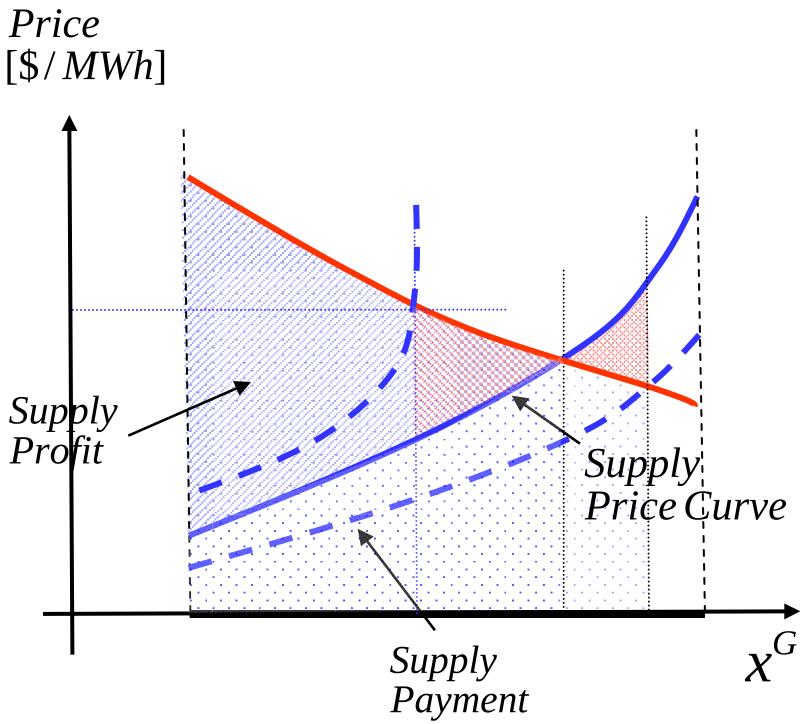
Market Commodity Pricing
Vickrey Payments and Charges

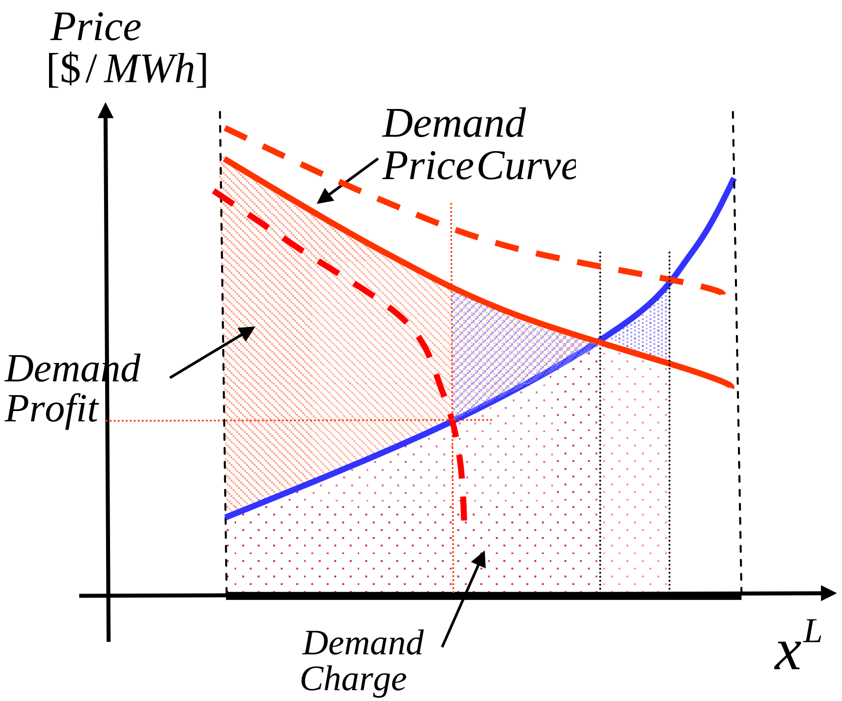
- Vickrey Payments
  - Suppliers paid all created profit
- Vickrey Charges
  - Consumers charges only for incurred costs
- Budget Deficit
  - Both supply and demand entities contribute to budget deficit



Market Commodity Pricing
Incentive Compatibility

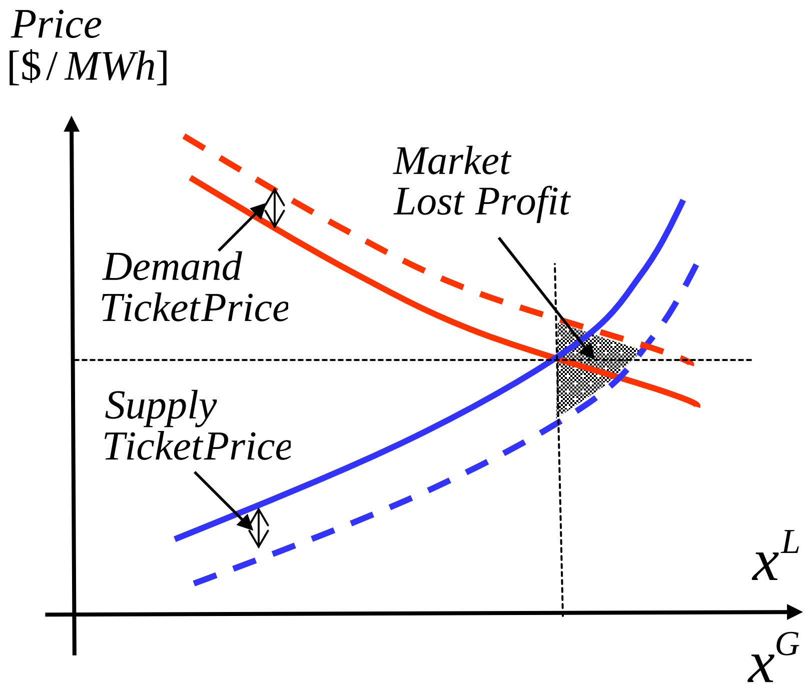
- Supply Incentive Compatibility
- Demand Incentive Compatibility





Market Commodity Pricing
Participation Tickets

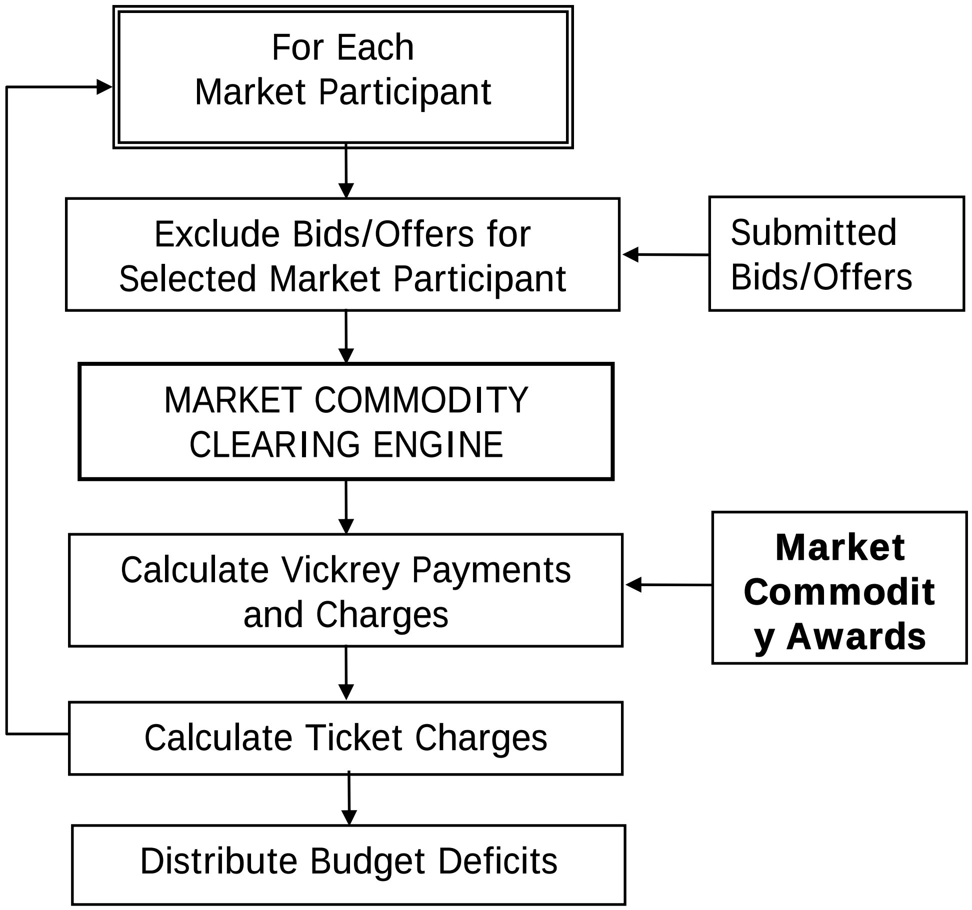
- Supply Ticket Prices
  - Added to offers to sell
- Demand Ticket Prices
  - Subtracted from bids to buy
- Budget Balance
  - Deficit reduced
  - Remaining deficit distributed to price takers
- Economic Efficiency
  - Slightly degraded



Market Commodity Pricing
Budget Deficit Distribution

- Supply and Demand Price Takers
  - Do not submit bid and offer prices; no market power
  - Self-committed, self-scheduled and self-dispatched market commodities
  - Price non-sensitive market participants
  - Out-of-market entities
- Price Taker Charges
  - Pro-rata distribution of market budget deficit after each market run; always balanced budget
  - If price takers market share is significant than participation tickets are not needed

Market Commodity Pricing
Pricing Engine



Electricity Market Design
Summary of Results

- Efficient Auction Design
  - Economic efficiency for overall electricity market using competitive trading platform
  - Separate market commodity clearing and market commodity pricing
- Market Commodity Clearing
  - Decomposition into atomic supply/demand/transmission optimization sub-problems
  - Supply and demand optimizations are convexified MIP models
  - Transmission optimization is convexified MIP model with linear objective and AC power flow equations
  - Optimization software can be utilized on multi-processor platforms

Electricity Market Design

Summary of Results cont…

- Market Commodity Pricing
  - Continuous and discrete commodity pricing
  - Incentive compatible strategies
  - Voluntary participation with free market exit
  - Budget balance at every market run

Market profit reduction
•Due to market participation tickets

?

1. Economic Efficiency
- Maximize total market profit

Market power does not exist
•Due to Vickrey payments/charges

2. Incentive Compatibility
•Truthful submissions

Guarantied profitability
•Due to Vickrey payments/charges

3. Volunteer Participation
•Non-negative market outcomes

Market budget balanced
•Due to deficit distribution

4. Market Balance
•Commodity and budget balance

Electricity Market Design
Next Steps

- Prototype MIP Decomposition Engine
  - Specify into details MIP models for supply, demand and transmission optimization problems
  - Develop Fenchel coordination mechanism
  - Evaluate performances and solution quality
- Prototype Pricing Engine
  - Calculate Vickrey payments and charges
  - Distribute budget deficit
  - Evaluate data volumes and calculation performances
- Proof the Concept of Auction Design

Electricity Market Design
References

- William Vickrey: *Counterspeculation, Auctions, and Competitive Sealed Tenders*, Journal of Finance, March 1961
- Hukukane Nikaido: *Convex Structures and Economic Theory*, Academic Press, 1968
- Tyrrell Rockafellar: *Convex Analysis*, Princeton, 1970
- Kazuo Murota: *Discrete Convex Analysis*, SIAM, 2003
- Leonid Hurwicz at al: *Designing Economic Mechanisms*, Cambridge University Press, 2006
- Noam Nisan at al: *Algorithmic Game Theory*, Cambridge University Press, 2007

Electricity Market Design
Discussion

THANK YOU!