MANCHESTER 1824

The University of Manchester

Participating in Markets for Electric Power (Kirschen/Strbac Chapter 4)

Important Acknowledgement:

These slides are based on materials originally prepared by Daniel Kirschen (U of Manchester) with edits by Leigh Tesfatsion (Iowa State U).

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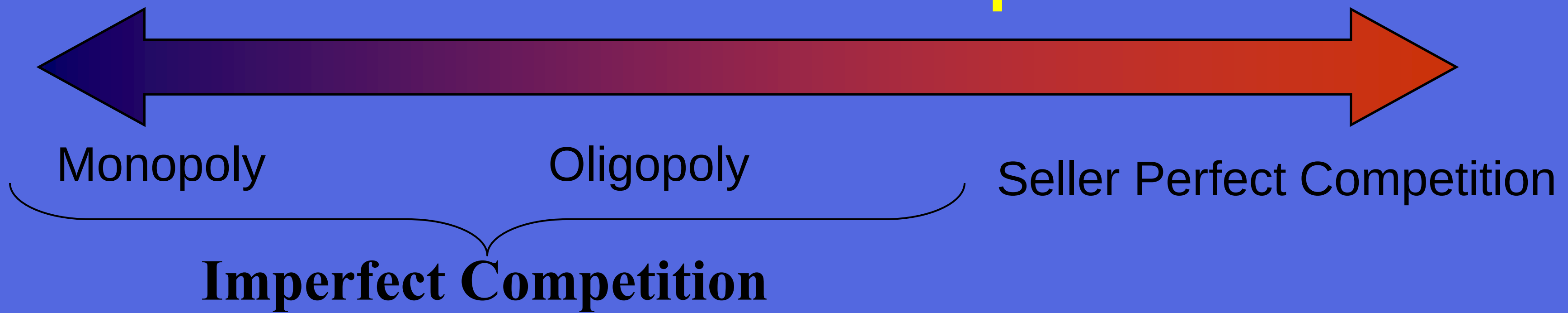
Remark on These K/S Chapter 4 Notes:

- **K/S Chapter 4 provides a deeper discussion of issues touched on in earlier K/S chapters and in other lecture materials.**
- For example, the basic Economic Dispatch problem (with balance and operating capacity constraints) has already been discussed at some length in the required notes on optimization from Section III of our course.
- Similarly, GenCo cost curves, perfection competition, and imperfect competition were first touched on in K/S Chapter 2.
- K/S Chapter 4 discusses and illustrates Economic Dispatch problems with “no-load costs,” “start-up costs,” and “scheduling (unit commitment)” constraints, but SCUC was covered in detail in Section IV of our course
- **NEW PART:** K/S Chapter 4 more explicitly develops perfect/imperfect competition concepts for power market applications, with illustrative power market examples. **We will stress this part of K/S Chapter 4.**

Market Structure: Seller's Perspective



- **Monopoly:**
  - A single seller (the ***monopolist***) can set the market price at will
  - Must be regulated to prevent exploitation of buyers
- **Oligopoly:**
  - At least two sellers have ***market power*** ***= ability to move the market price in a way that increases own net earnings***
  - At least two sellers act strategically in an attempt to exercise market power
- **Seller Perfect competition:**
  - No seller perceives any opportunity to exercise market power
  - Each seller acts as a "price taker" (takes the market price as given)

CAUTION: In general, market power can also be exercised by buyers!

Market Structure: Buyer's Perspective

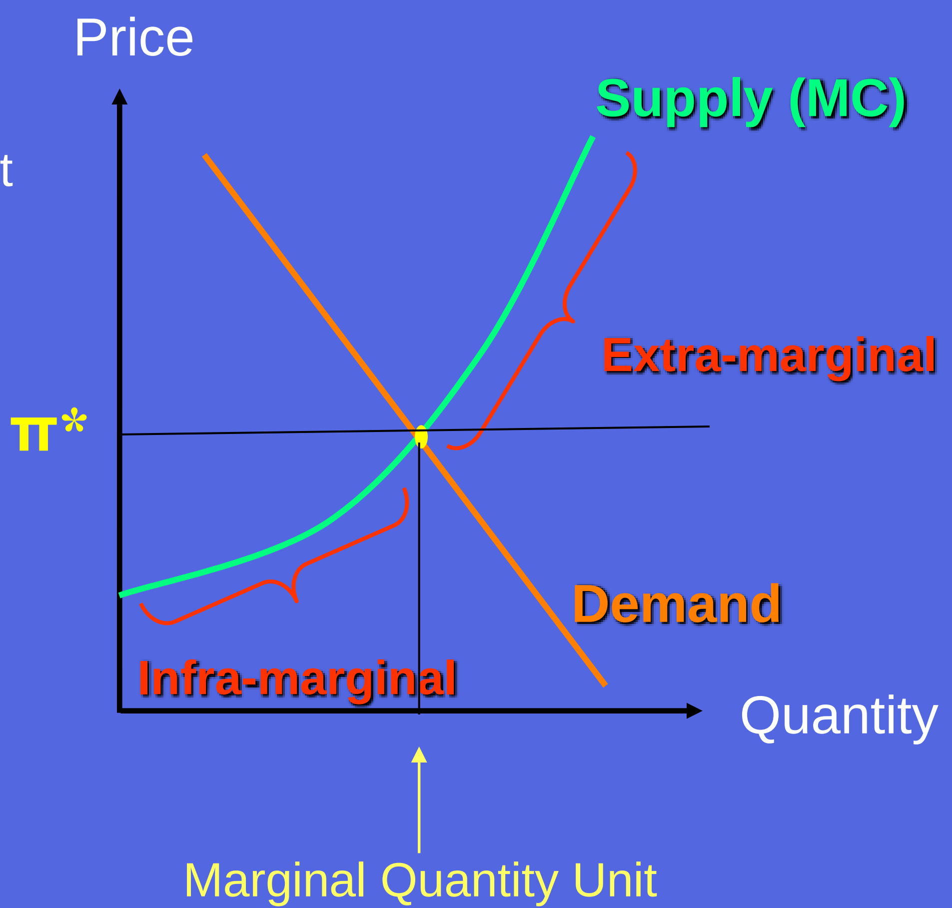
- **Monopsony:**
  - A single buyer (the ***monopsonist***) can set the market price at will
  - Must be regulated to prevent exploitation of sellers
- **Oligopsony:**
  - At least two buyers have market power (ability to move the market price in their own favor)
  - At least two buyers act strategically to exercise market power
- **Buyer Perfect competition:**
  - No buyer perceives any opportunity to exercise market power
  - Each buyer acts as a "price taker" (takes market price as given)

Perfect Competition

- All sellers act as price takers (seller perfect competition)
- All buyers act as price takers (buyer perfect competition)
- Several possible explanations for price-taking behavior:
  - ***Small in size*** (no ability to move the market price)
  - Afraid to manipulate market price for ***fear of encouraging entry*** of sellers/buyers into the market
  - Afraid to manipulate market price for ***fear of regulation***

Perfect Competition… Continued

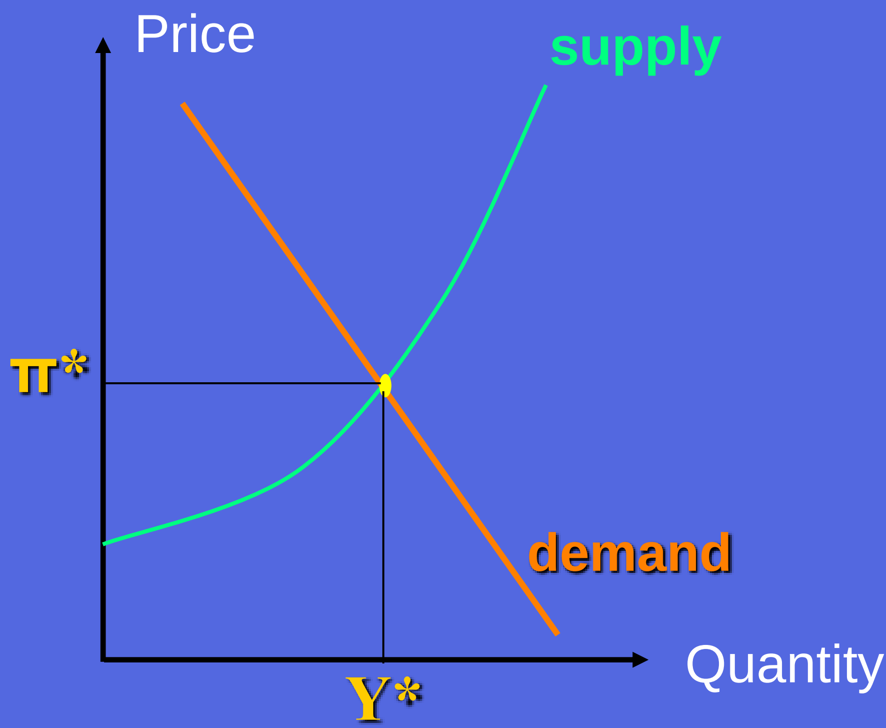
- Same D/S analysis applies to a centralized auction among buyers and sellers and to a bilateral trade between a single buyer and seller.
- (Market) price π* is set to achieve D=S, and every traded unit is sold at this same price.
- Marginal quantity unit:
  - "Last" unit sold at price π*
- Infra-marginal quantity units:
  - π* ≥ sale reservation price (marginal cost)
  - π* ≤ purchase reservation price (maximum willingness to pay)
- Extra-marginal quantity units (all other units):
  - Not traded except under special circumstances (e.g., must run units)



Demand Bids & Supply Offers under Perfect Competition

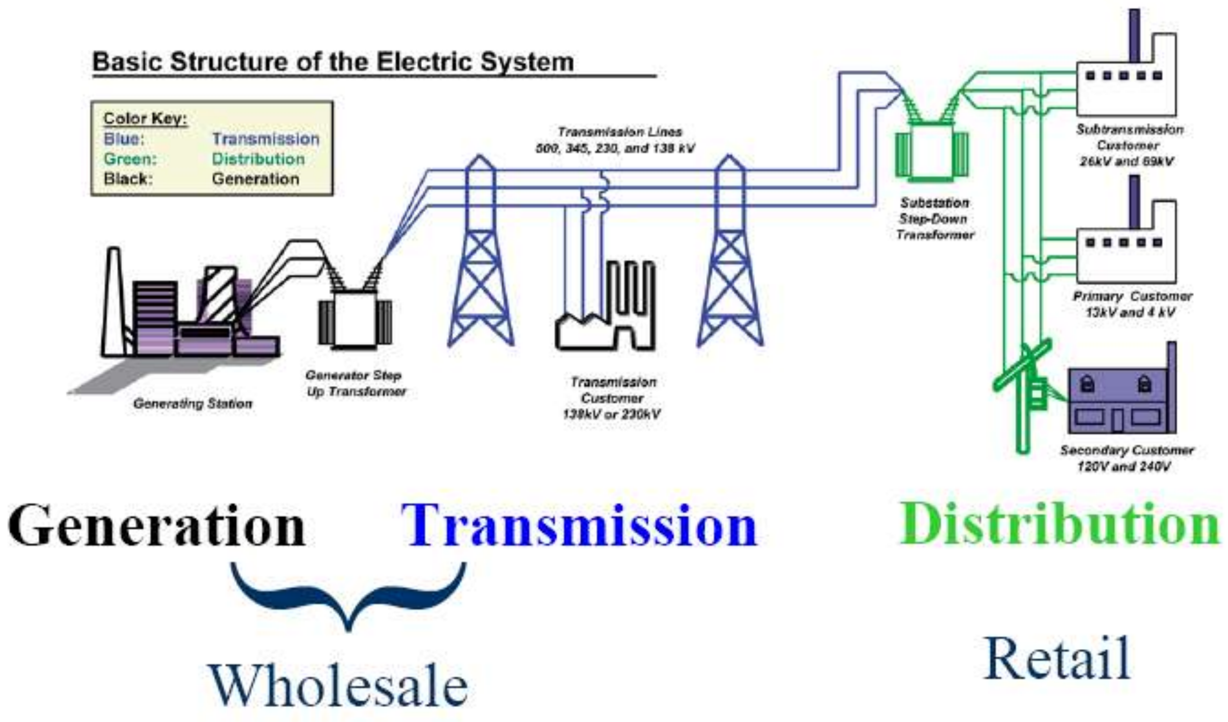
- **(Market) clearing price π* taken as given by all buyers and sellers !**
- Only role of demand bids and supply offers is to determine amount Y* of inframarginal units to be traded.
- Sellers/buyers have no incentive to withhold inframarginal units.
- Sellers/buyers have no incentive to bid/offer extramarginal units in the absence of "must run" (minimum operating capacity) constraints.
- Buyers (sellers) might still have some reason to misrepresent their true reservation prices to ensure dispatch.

  (In what circumstances?)



Generation Company (GenCo) Perspective

Source: http://www.nerc.com/page.php?cid=1|15



Perfect Competition: The GenCo's Perspective

Short-Run GenCo Optimization Ignoring Capacity Constraints

$y:$ Output of the GenCo

$$\max_{y} \{\underbrace{\pi . y}_{\text{Revenue from selling } y} - \underbrace{c(y)}_{\text{Avoidable Costs at } y}\}$$

Avoidable Costs at y

Revenue from selling y

$$\frac{d\{\pi . y - c(y)\}}{dy} = 0$$

Independent of quantity produced because price taker

$$\pi = \frac{dc(y)}{dy}$$

Adjust production y until the marginal cost of production is equal to the price π. Check to ensure revenues cover avoidable costs at this point. If so, produce; otherwise shut down.

Imperfect Competition: The GenCo's Perspective

- Recall from Section II a GenCo has ***market power*** if it can change the market price to increase its net earnings, where

  Net Earnings = [Revenues – Avoidable Costs]

- GenCo can exercise market power in two basic ways:
  - raise its offered sales price (***economic withholding***)

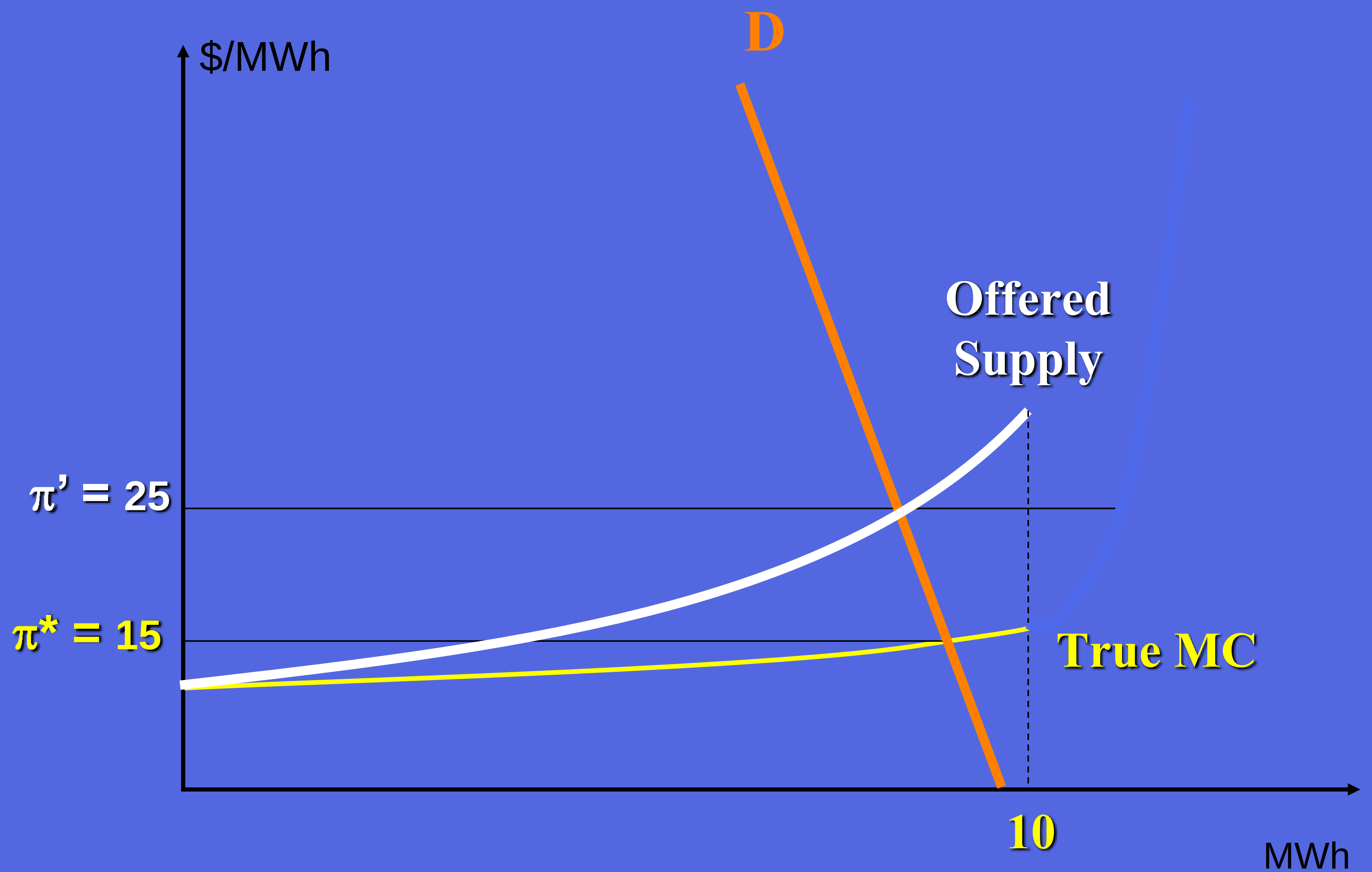
  and/or

  - reduce its offered sales quantity (***physical withholding***)

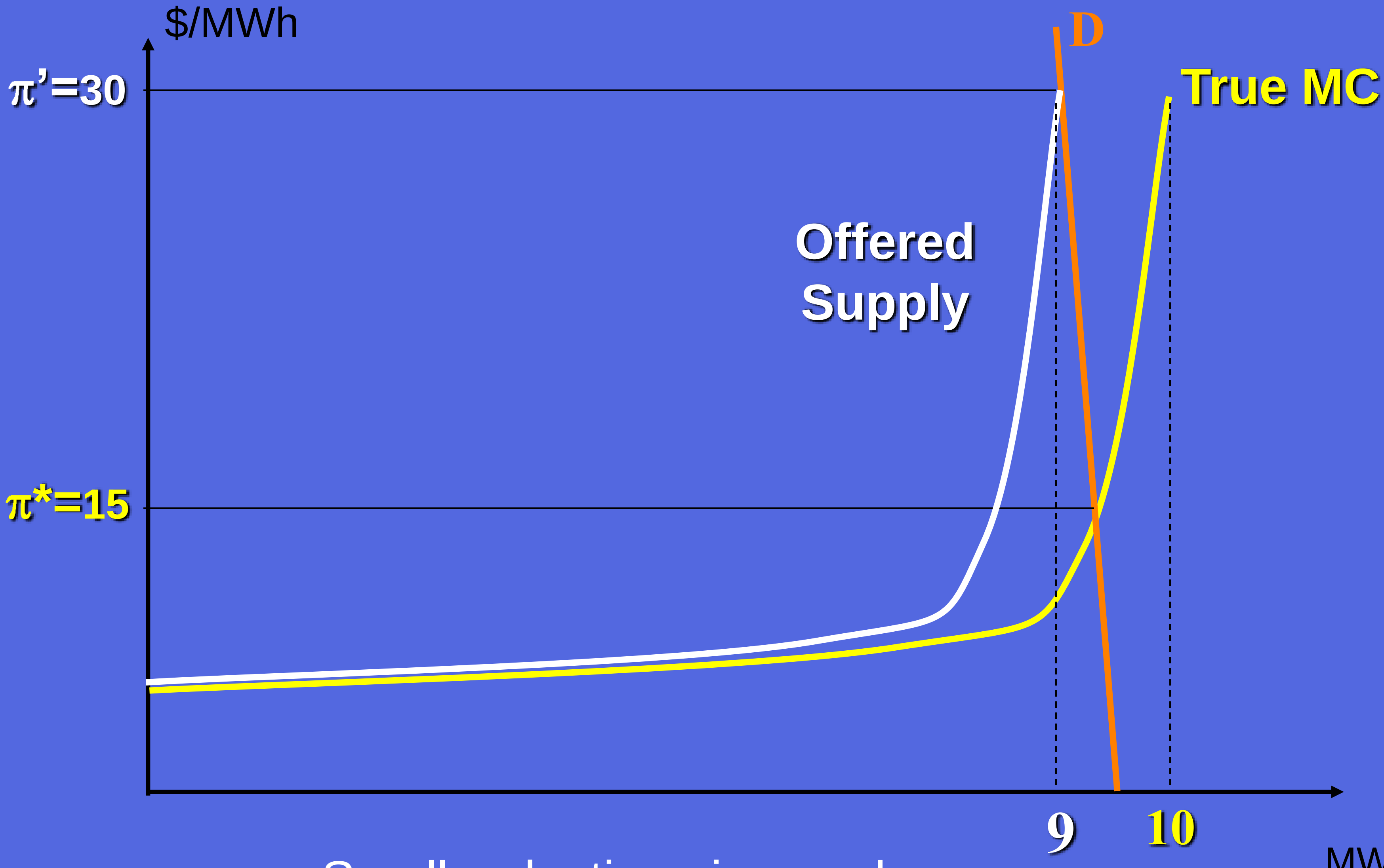
Example:

- A GenCo has the capacity to produce 10 MWs, and the current market price is $15/MWh
  - **Option 1: Economic Withholding** Offer to sell some units for a price higher than $15 and hope this will increase the market price
  - **Option 2: Physical Withholding** Offer to sell only 9 MWs and hope the market price rises enough to compensate for the loss of sales volume
- Whether option 1 or option 2 would in fact turn out to be advantageous for the GenCo depends on its market power.
- The GenCo's net earnings will increase if and only if the price it receives per unit sold rises enough to compensate for any decrease in the total quantity it sells.

Option 1: Economic withholding can increase market price

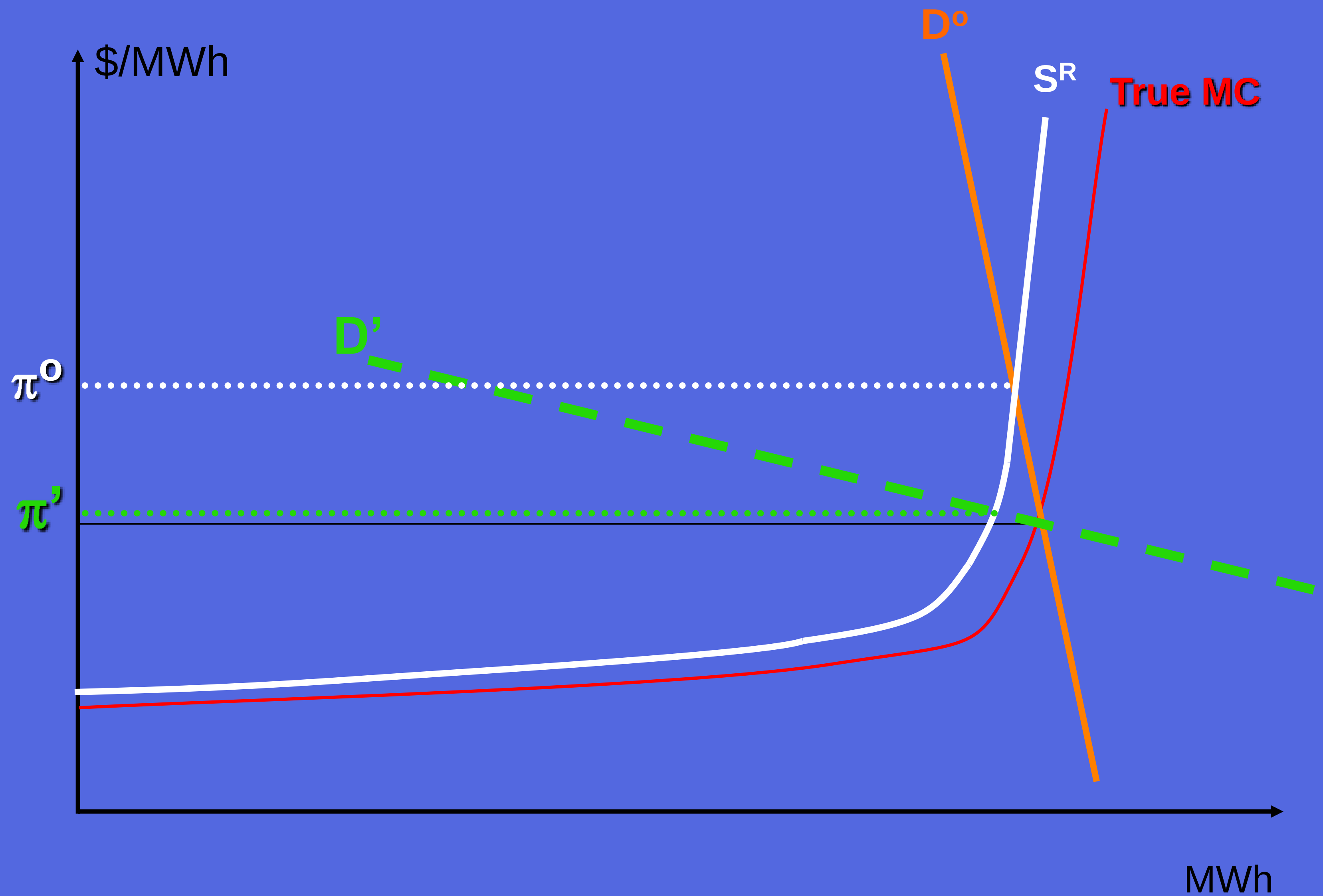


Option 2: Physical withholding can increase market price



Small reductions in supply can cause large changes in the market price π

Increasing price-elasticity of demand reduces ability of strategic GenCos to exercise market power: *Example*



Increasing the price-elasticity of demand

◆ Obstacles:

- Regulated retail prices
- Need for reliable communication of prices from wholesale to retail
- Need for retail storage (heat, intermediate products, dirty clothes)

◆ Even relatively small amounts of "fixed demand" (i.e., demand totally unresponsive to price) can result in substantial seller market power.

◆ But an increase in the price-elasticity of demand does tend to reduce average market price

- Not necessarily in the best interests of GenCos (even if price volatility is reduced)
- Impetus will need to come from somewhere else

Further Comments on GenCo Market Power

- Under a uniform price rule, ***ALL*** GenCos benefit from the exercise of market power by any ***ONE*** GenCo.
- Unilaterally reducing offered output or increasing offered price to increase net earnings ***is legal under Dept of Justice rules***
- Explicit deliberate communication among GenCos to raise prices is ***not legal under Dept of Justice rules***.
- Market power can interfere with the efficient dispatch of generating resources:
  - Marginal quantity units no longer priced at true MC
  - More expensive generation dispatched prior to cheaper generation

Game Theory and Nash Equilibrium (Cf. Course Section V.A)

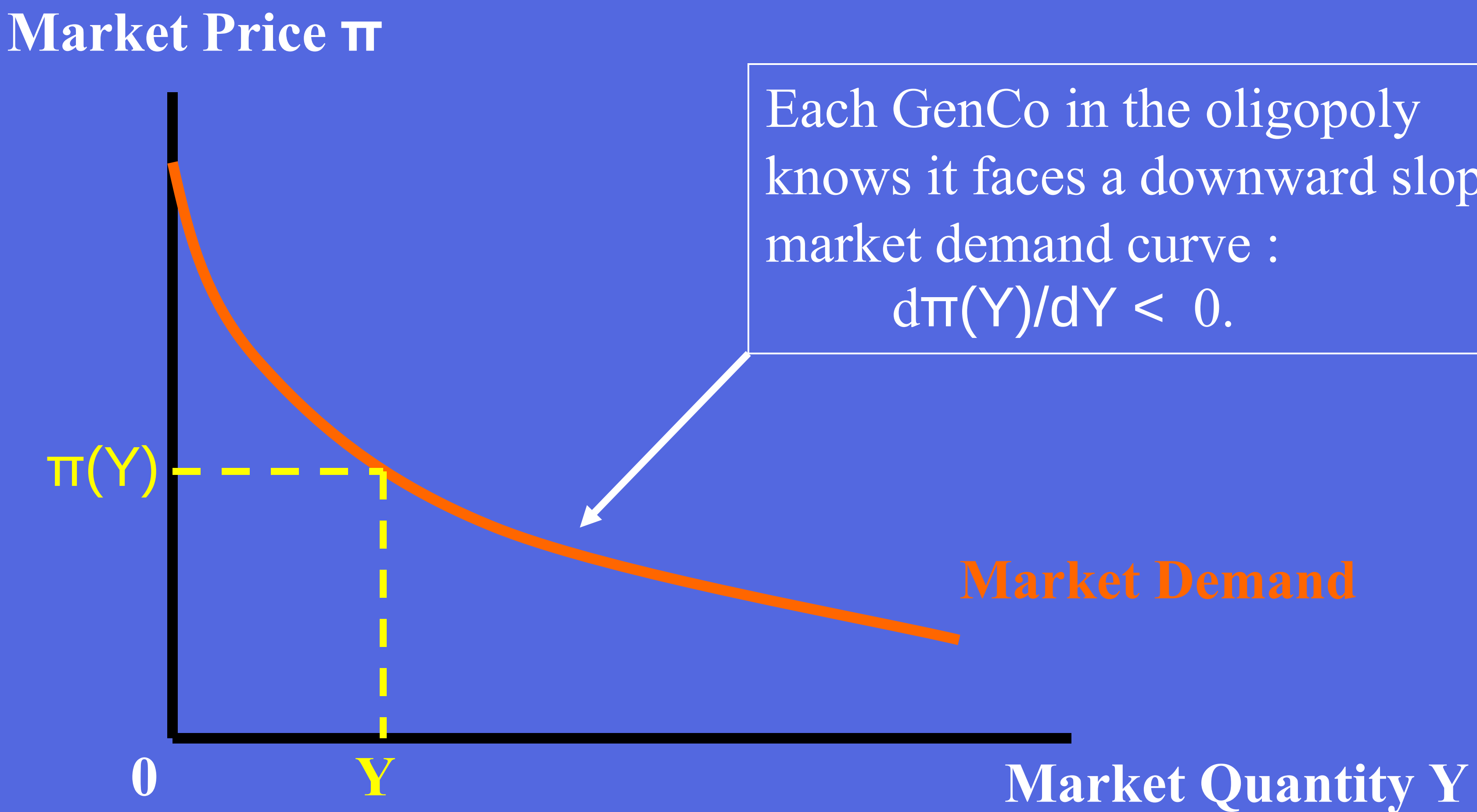
- Each GenCo must consider the possible actions of others when selecting its supply offer (strategy)
- Classical optimisation theory is insufficient
- ***N-Player Non-Cooperative Game Among GenCos:***
  - Each GenCo competes against the remaining N-1 GenCos
  - Net earnings attained by each GenCo depend on the supply offer choices of some or all of the other N-1 GenCos
- ***Nash Equilibrium for the Above Game:***
  - A set of supply offers $\{a^*_i \mid i=1,\ldots,N\}$ for GenCos i=1,…,N such that no GenCo i sees any reason to deviate from its supply offer given the other GenCos $j \neq i$ do not deviate from their supply offers:

Net Earnings for GenCo i

Notation "-i" means "for all but i"

$$\Omega^i(a^*_i, a^*_{-i}) \geq \Omega^i(a_i, a^*_{-i}) \quad \forall i, a_i$$

Cournot Oligopoly (GenCo Quantity Competition)
(Compare K/S Chapter 2, Section 2.5.2.1)



Each GenCo in the oligopoly knows it faces a downward sloping market demand curve :

$$d\pi(Y)/dY < 0.$$

GenCo's First-Order Necessary Conditions for net earnings optimization in a Cournot Oligopoly

$$\max_{y_i} \{ y_i \cdot \pi(Y) - c(y_i) \}$$

$$\frac{d}{dy_i} \{ y_i \cdot \pi(Y) - c(y_i) \} = 0$$

$$\pi(Y) + y_i \frac{d\pi(Y)}{dy_i} = \frac{dc(y_i)}{dy_i}$$

$$\pi(Y) \left\{ 1 + \frac{y_i}{Y} \frac{Y}{dY} \frac{d\pi(Y)}{\pi(Y)} \right\} = \frac{dc(y_i)}{dy_i}$$

$C(y_i)$ = avoidable cost function

y_i : Production of GenCo i

$Y = y_1 + \ldots + y_n$

= the total industry output

GenCo i assumes other GenCos will maintain current output levels.

Here we use identity $d\pi(Y)/dy_i = d\pi(Y)/dY$ (because $dY/dy_i = 1$).

GenCo's FONC for Optimization in a Cournot Oligopoly … Continued

$$\pi(Y)\left\{1+\frac{y_i}{Y}\frac{Y}{dY}\frac{d\pi(Y)}{\pi(Y)}\right\}=\frac{dc(y_i)}{dy_i}$$

FONC from previous page

$$\varepsilon(Y)=\frac{\frac{dY}{Y}}{\frac{d\pi}{\pi}}=\frac{\pi}{Y}\frac{dY}{d\pi}$$

Price-elasticity of demand (≤ 0)

$$s_i=\frac{y_i}{Y}$$

Market share of GenCo i ($0 \leq S_i \leq 1$)

$$\pi(Y)\left\{1-\frac{s_i}{|\varepsilon(Y)|}\right\}=\frac{dc(y_i)}{dy_i}$$

Optimal y_i^* for GenCo i is at a point where net earnings are ***maximized***. For optimality with positive y_i^* , this term must lie between 0 and 1 so that $\pi(Y) \geq 0$ and $\pi(Y) \geq$ marginal cost. This requires $0 \leq s_i /|\varepsilon(Y)| \leq 1$

Remark on Price-Elasticity of Demand

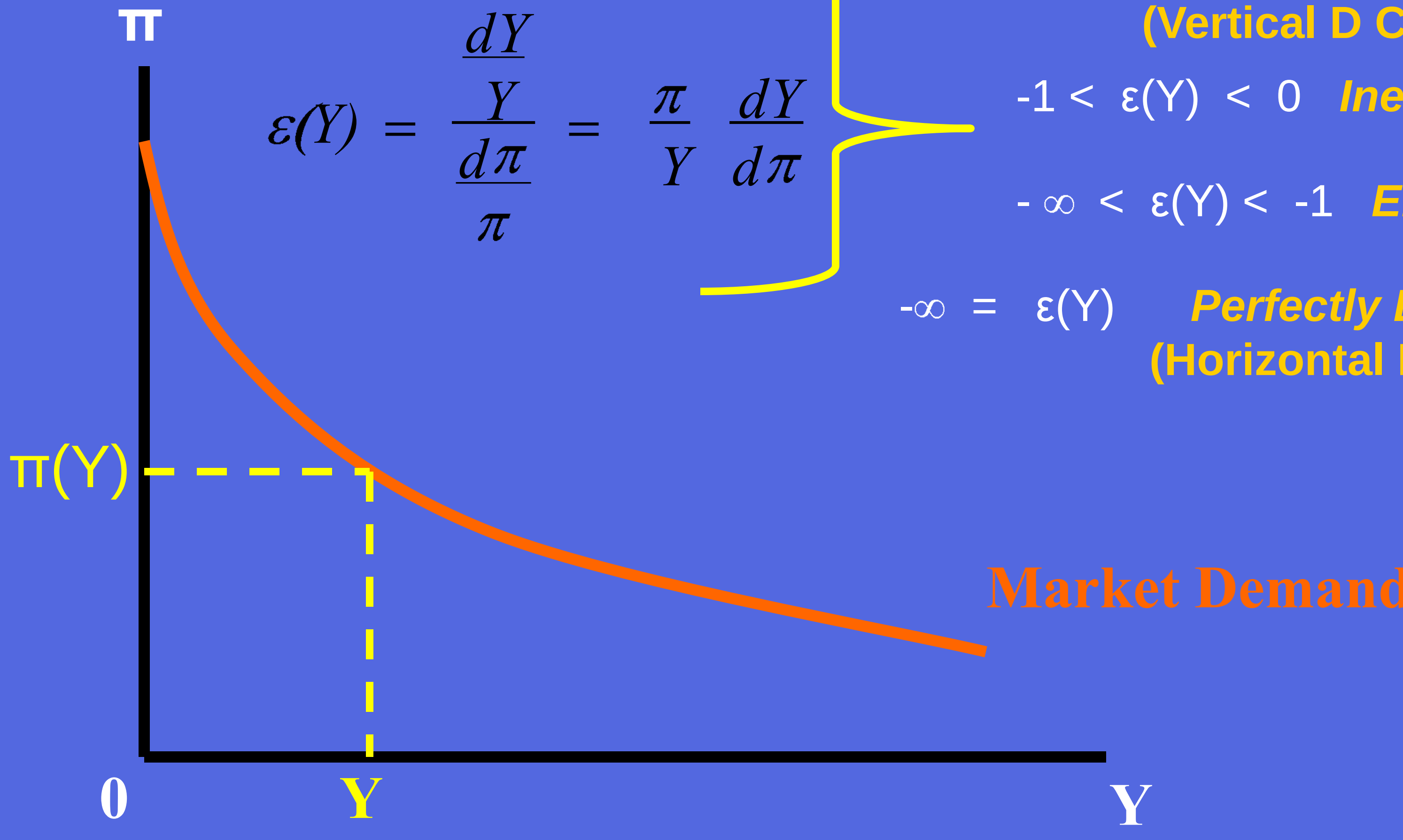
$$\varepsilon(Y) = \frac{\frac{dY}{Y}}{\frac{d\pi}{\pi}} = \frac{\pi}{Y}\frac{dY}{d\pi}$$

$\varepsilon(Y) = 0$ ***Perfectly Inelastic*** **(Vertical D Curve)**

$-1 < \varepsilon(Y) < 0$ ***Inelastic***

$-\infty < \varepsilon(Y) < -1$ ***Elastic***

$-\infty = \varepsilon(Y)$ ***Perfectly Elastic*** **(Horizontal D Curve)**



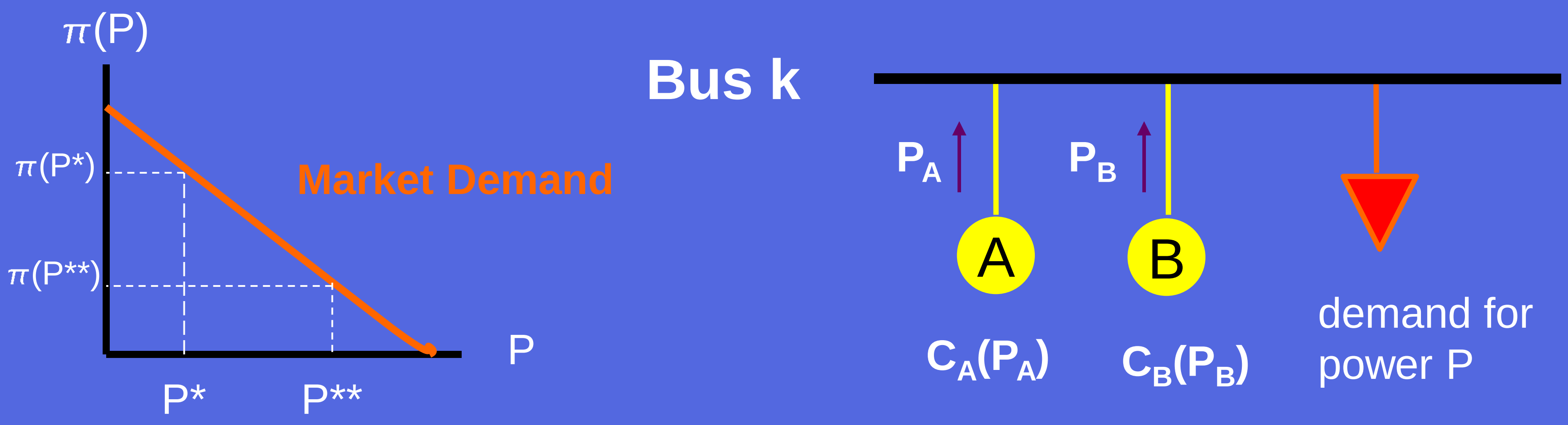
GenCo's FONC for Optimization in a Cournot Oligopoly … Continued.

- Consider the following FONC for GenCo i:

$$\pi(Y)\left\{1-\frac{s_i}{|\varepsilon(Y)|}\right\}=\frac{dc(y_i)}{dy_i}$$

- Let the total output Y be replaced by [$y_i + h(y^e_{-i})$] = Sum of y_i plus *expected* outputs for all OTHER GenCos.
- Then optimal y_i choice for GenCo i can be expressed as a function $y_i^* = f(y^e_{-i})$ of the *expected* output of other GenCos.
- A ***Nash equilibrium*** is obtained at $y^* = (y^*_1,\ldots,y^*_N)$ if the expectations of *each* GenCo 1,…,N are *fulfilled* at y*.

Cournot Oligopoly: Power Market Example (K/S 4.3.3.3)



- Suppose two GenCos A and B must decide how much power P_A and P_B to produce and deliver to Bus k during hour H
- Market Demand P is then determined as $P = P_A + P_B$ at market price $\pi(P)$
- NOTE: In the particular functional forms below, coefficient units [e.g., MW, \$/MWh, \$/(MW)^{2}h] are suppressed for ease of notation, **but it is important to remember these coefficients are not unit free!!!**

Cournot Oligopoly: Power Market Example … Cont'd

Suppose the avoidable cost functions for A and B are given as follows:

- $C_A (P_A) = 35 \cdot P_A$ (\$/h)
- $C_B (P_B) = 45 \cdot P_B$ (\$/h)

and the (inverse) market demand function is given by

- $\pi(P) = 100 – P$ (\$/MWh)

Suppose the Economic Dispatch solution is

- $P^*_A = 15$ (MW) and $P^*_B = 10$ (MW)

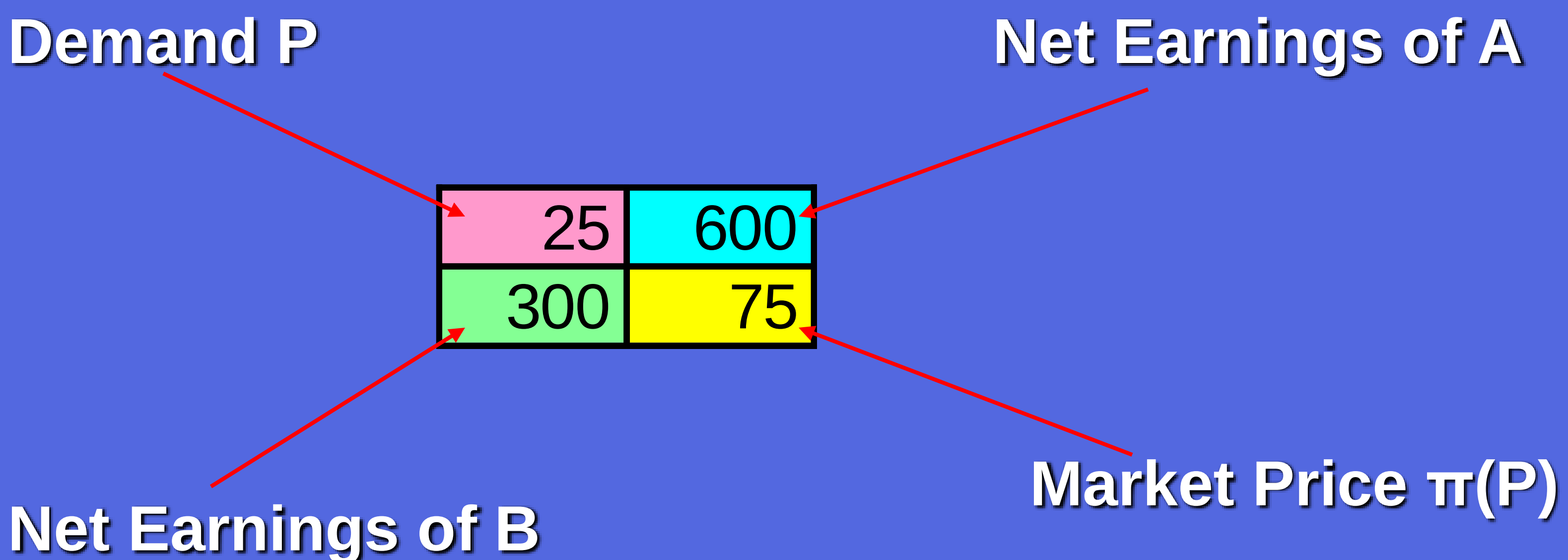
Then outcomes are as follows:

- Market Demand is $[P^*_A + P^*_B] = P^* = 25$ (MW)
- Market Price $= \pi(P^*) = 100 – P^* = 75$ (\$/MWh)
- $Revenue_A(P^*_A) = 75 \cdot 15 = 1125$ (\$/h) ; $C_A (P^*_A) = 35 \cdot 15 = 525$ (\$/h)
- $Revenue_B(P^*_B) = 75 \cdot 10 = 750$ (\$/h); $C_B (P^*_B) = 45 \cdot 10 = 450$ (\$/h)
- Net Earnings A $= NetEarn_A(P^*_A) = [Revenue_A(P^*_A) - C_A (P^*_A)] = 600$ (\$/h)
- Net Earnings B $= NetEarn_B(P^*_B) = [Revenue_B(P^*_B) - C_B (P^*_B)] = 300$ (\$/h)

Cournot Oligopoly: Power Market Example … Cont'd

Summary:

For P_A=15 MW & P_B = 10 MW, outcomes are as follows:



Cournot Oligopoly: Power Market Example …Cont'd

	$P_A=15$		$P_A=20$		$P_A=25$		$P_A=30$	
$P_B=10$	25	600	30	700	35	750	40	750
	300	75	250	70	200	65	150	60
$P_B=15$	30	525	35	600	40	625	45	600
	375	70	300	65	225	60	150	55
$P_B=20$	35	450	40	500	45	500	50	450
	400	65	300	60	200	55	100	50
$P_B=25$	40	375	45	400	50	375	55	300
	375	60	250	55	125	50	0	45

Demand	NetEarn A
NetEarnB	Price

Cournot Oligopoly: Power Market Example …Cont'd

Supply Offers	P_A=15		P_A=20		P_A=25		P_A=30	
P_B=10	25	600	30	700	35	750	40	750
	300	75	250	70	200	65	150	60
P_B=15	30	525	35	600	40	625	45	600
	375	70	300	65	225	60	150	55
P_B=20	35	450	40	500	45	500	50	450
	400	65	300	60	200	55	100	50
P_B=25	40	375	45	400	50	375	55	300
	375	60	250	55	125	50	0	45

Demand	NetEarn A
NetEarn B	Price

- Price decreases as $P=P_A+P_B$ increases
- NetEarn of each GenCo affected by other
- Complex relationship between supply offers $\{P_A, P_B\}$ and net earnings of A and B

Let's play the Cournot oligopoly as a game!

Supply Offers	$P_A=15$		$P_A=20$		$P_A=25$		$P_A=30$	
$P_B=10$	25	600	30	700	35	750	40	750
	300	75	250	70	200	65	150	60
$P_B=15$	30	525	35	600	40	625	45	600
	375	70	300	65	225	60	150	55
$P_B=20$	35	450	40	500	45	500	50	450
	400	65	300	60	200	55	100	50
$P_B=25$	40	375	45	400	50	375	55	300
	375	60	250	55	125	50	0	45

Demand	NetEarn A
NetEarn B	Price

If you are GenCo A, what supply offer P_A would you submit?

Cournot oligopoly as a game … "Optimal Solution(s)?

Supplies	P_A=15		P_A=20		P_A=25		P_A=30	
P_B=10	25	600	30	700	35	750	40	750
	300	75	250	70	200	65	150	60
P_B=15	30	525	35	600	40	625	45	600
	375	70	300	65	225	60	150	55
P_B=20	35	450	40	500	45	500	50	450
	400	65	300	60	200	55	100	50
P_B=25	40	375	45	400	50	375	55	300
	375	60	250	55	125	50	0	45

Demand	NetEarn A
NetEarn B	Price

Nash Equilibrium Solution!

Given GenCo B chooses $\mathbf{P_B}$=15, GenCo A's best production choice is $\mathbf{P_A}$=25. And given GenCo A chooses $\mathbf{P_A}$=25, GenCo B's best production choice is $\mathbf{P_B}$=15.

Cournot Oligopoly: Power Market Example … Continued

Demand P

Net Earnings of A

P_A=25

P_B=15		
	40	625
	225	60

Net Earnings of B

Price π(P)

$$C_A = 35 \;.\; P_A \;\$/h$$
$$C_B = 45 \;.\; P_B \;\$/h$$

- At the Nash equilibrium (15,25), the GenCos achieve a sales price 60 higher than their marginal costs (35 and 45).
- The cheaper GenCo A does not grab the whole market.
- The GenCos balance price and quantity in an attempt to make their net earnings as high as possible.
- **But the Nash equilibrium (15,25) is Pareto dominated by (10,20) !**

Cournot oligopoly as a game … "Optimal Solution(s)?

Supplies	P_A=15		P_A=20		P_A=25		P_A=30	
P_B=10	25	600	30	700	35	750	40	750
	300	75	250	70	200	65	150	60
P_B=15	30	525	35	600	40	625	45	600
	375	70	300	65	225	60	150	55
P_B=20	35	450	40	500	45	500	50	450
	400	65	300	60	200	55	100	50
P_B=25	40	375	45	400	50	375	55	300
	375	60	250	55	125	50	0	45

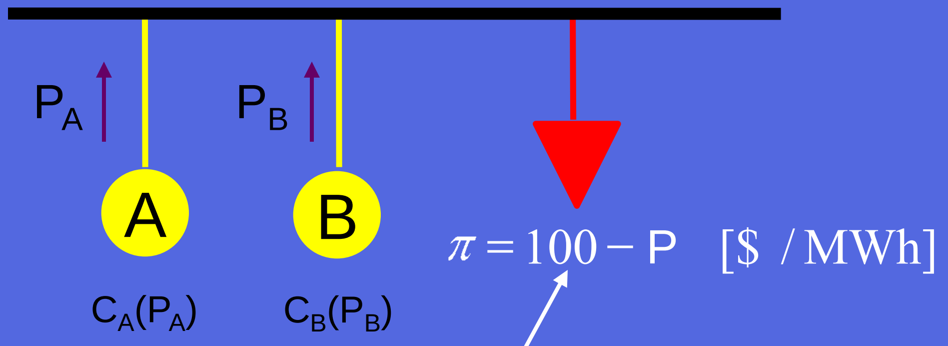
But (10,20) Pareto dominates (15,25)

Demand	NetEarn A
NetEarn B	Price

(15,25) is a Nash Equilibrium Solution

Bertrand Oligopoly (Price Competition): Power Market Example 1

- Avoidable Cost Functions:
  - $C_A = 35 \cdot P_A$ $/h
  - $C_B = 45 \cdot P_B$ $/h

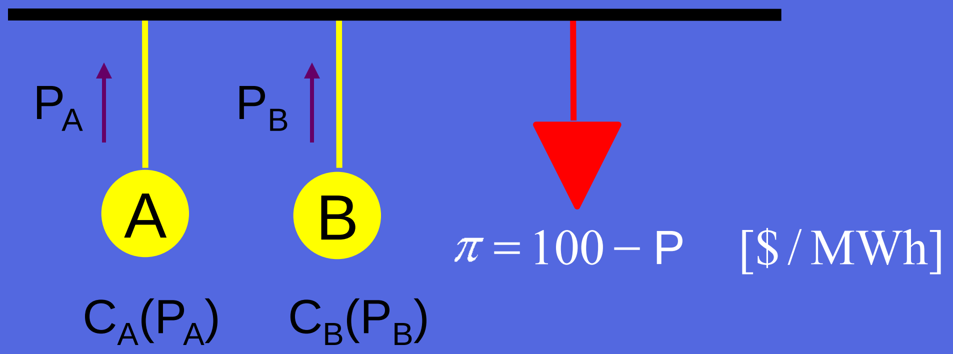


- Price offer by GenCo A?
- Price offer by GenCo B?
- Market price?
- Quantity traded?

Market demand curve assumed known by GenCo A and GenCo B.

If you were GenCo A, what would you report as your supply offer?

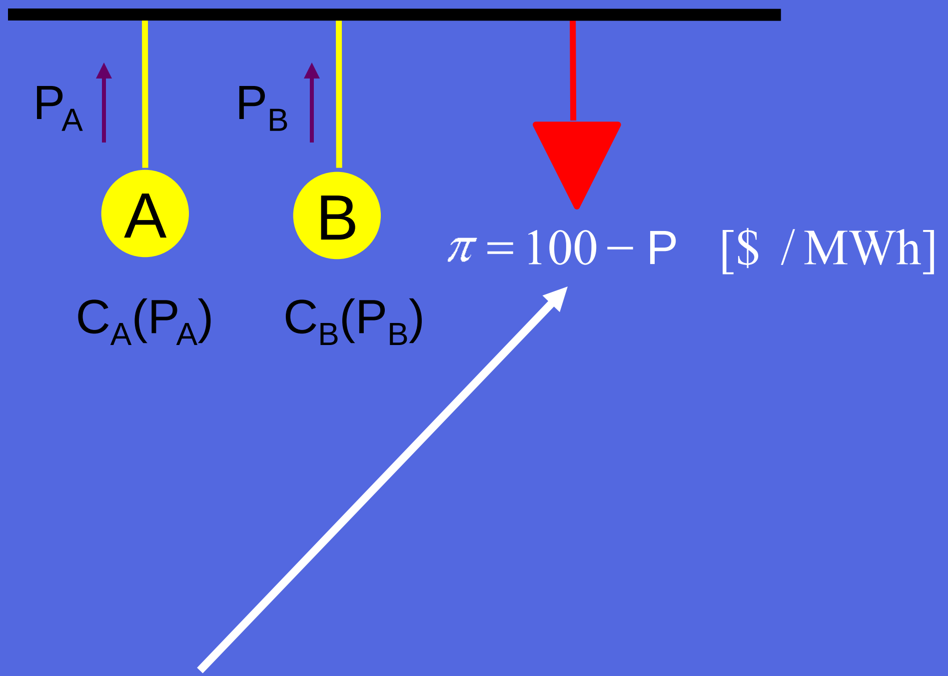
Bertrand Oligopoly: Power Market Example 1



- **Ex 1:** Avoidable Cost Functions:
  - $C_A = \mathbf{35} \cdot P_A$ $/h
  - $C_B = \mathbf{45} \cdot P_B$ $/h
- Marginal cost of A: 35 $/MWh
- Marginal cost of B: 45 $/MWh
- A will offer a price slightly below 45 $/MWh
- B cannot offer a price below 45 $/MWh because it would loose money on every MWh produced
- **Market price solution π :** slightly below 45 $/MWh
- **Market quantity solution P:** slightly above 55 MW
- **P_A solution** = slightly above 55 MW
- **P_B solution** = 0
- **GenCo A net earnings** = Approximately [45 x 55 - 35 x 55] = 550 $/h
- **GenCo B net earnings** = $ 0

Bertrand Oligopoly: Power Market Example 2

- **Ex 2:** Avoidable Cost Functions
  - $C_A = 35 \cdot P_A$ \$/h
  - $C_B = 35 \cdot P_B$ \$/h

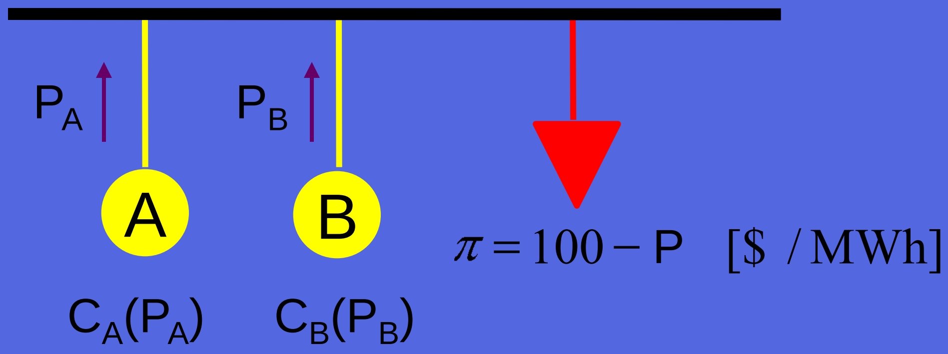


- Price offer by A?
- Price offer by B?
- Market price?
- Quantity traded?

Market demand curve assumed known by GenCo A and GenCo B.

Bertrand Oligopoly: Example 2 … Continued

- **Ex 2:** Avoidable Cost Functions:
  - $C_A = 35 \cdot P_A$ $/h
  - $C_B = 35 \cdot P_B$ $/h



- GenCo A cannot offer a price below 35 $/MWh because it would loose money on every MWh
- GenCo A cannot offer a price above 35 $/MWh because GenCo B would bid lower and grab the entire market
- Similarly for GenCo B in relation to GenCo A
- Market price: 35 $/MWh   Total Quantity Traded: 65 MW

BERTRAND OLIGOPOLY SOLUTION SUMMARY:

- Identical GenCos: Both offer a price at their common marginal cost
- Non-identical GenCos: Cheaper GenCo gets the whole market
- “Not a realistic model of imperfect competition for power markets.” (K/S)

Other Imperfect Competition Approaches to Modeling GenCo Behavior in Wholesale Power Markets

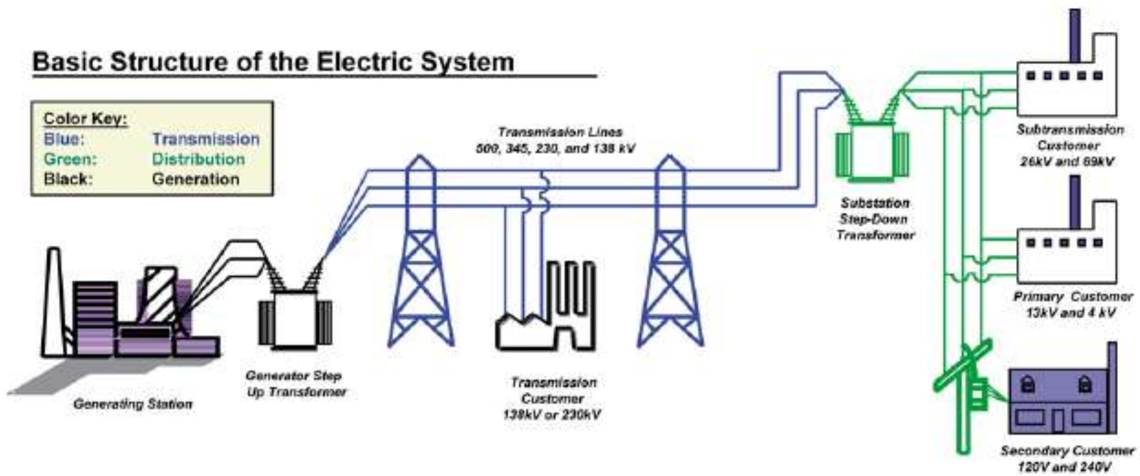
- Supply function equilibria
  - GenCo supply offers take form of upward sloping supply schedules ($\geqslant$ minimum acceptable sale price for each successive unit offered)
- Agent-based modeling (strategically learning traders)
  - Can represent more complex interactions among strategic power market traders with learning capabilities
- Maximization of own net earnings not only possible objective
  - Maximize market share
  - Avoid regulatory intervention
  - Collude on max of ***joint*** net earnings (with side payments)

Imperfect Competition Models for Wholesale Power Markets: A Summing Up

- Electricity markets do not deliver perfect competition
- Some factors facilitate the exercise of market power:
  - Low price elasticity of demand
  - Large market shares
  - Fluctuating demand with peak demand hours
  - Operation close to maximum capacity
- Study of imperfect competition in electricity markets is a hot research topic (must move beyond Cournot/Bertrand!)
  - Market trader (buyer/seller) perspective (high net earnings)
  - Market operator perspective (SR efficient & reliable operations)
  - Market designer perspective (LR market efficiency & reliability)
  - Regulator perspective (social welfare)

Retail Customer's Perspective

Source: http://www.nerc.com/page.php?cid=1|15



Generation **Transmission** **Distribution**

Wholesale

Retail

U.S. Retail Customer's Perspective

- ***Retail customers*** = Industrial, commercial, and residential customers

- Some large retail customers buy directly from wholesale power markets

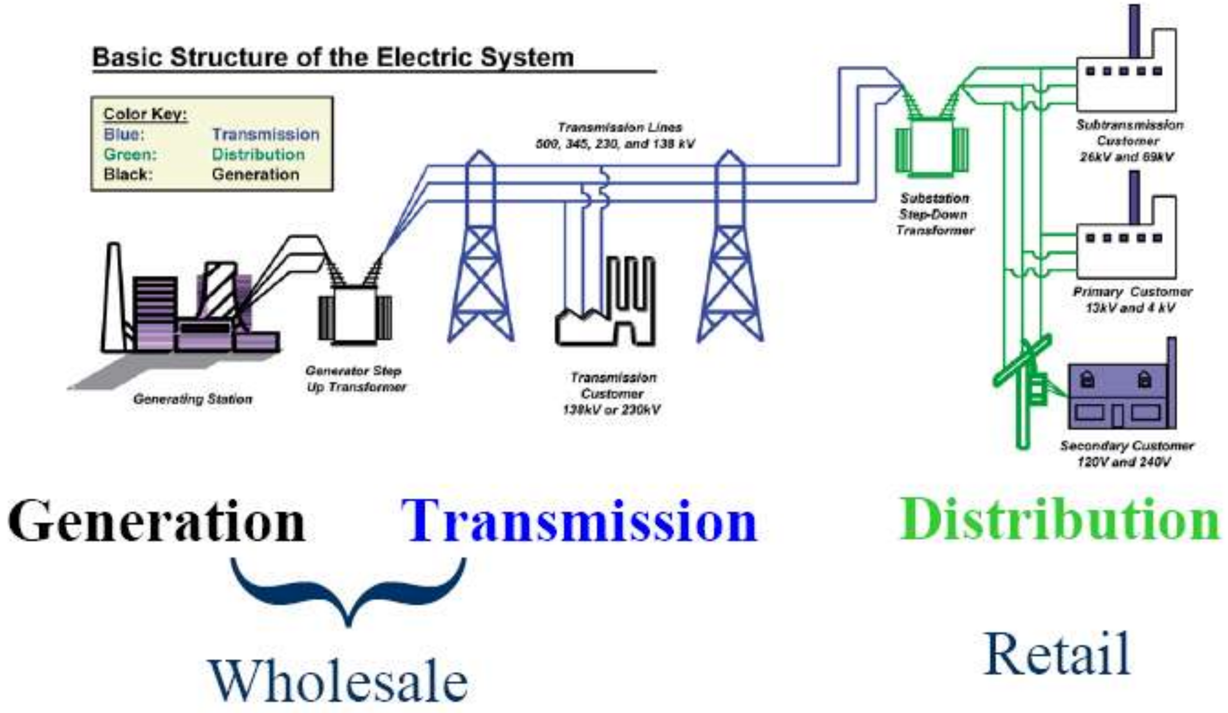
- Most retail customers buy from an intermediary, who in turn buys electric power in the wholesale power market.

- K/S (Chapter 1.2) refer to these intermediaries as ***Retailers.*** In U.S., often called ***Load-Serving Entities (LSEs).***

- Price risk for retail customers typically limited through regulation of the prices (rates) they can be charged.

Load-Serving Entity (Retailer) Perspective

Source: http://www.nerc.com/page.php?cid=1|15



The LSE (Retailer) Perspective

- Buy energy in bulk in the wholesale power market
  - Spot market (volatile prices, price risk, settlement of imbalances)
  - Contracts (secure firmer price/quantity terms)
- Sell energy “downstream” to retail customers, mostly at a regulated flat rate only infrequently changed
- Must forecast the load of its customers
- If LSE is a retail monopoly with large customer base:
  - Traditional top-down forecasting (aggregation reduces error)
- If LSE faces retail competition (customers can choose among many different competing retailers):
  - Demand more difficult to forecast (possibly unstable customer base)

The Hybrid Participant's Perspective

- Some wholesale power market participants can buy and/or sell energy at will
- Choice depends on circumstances (buy low, sell high)
- ***Pumped-storage hydro plants*** are the most common type of hybrid participant
    - Buy and consume energy to pump water up into reservoirs during periods of low demand (low market price)
    - Produce and sell energy by releasing this water down through turbines during periods of high demand (high market price)

Pumped-Storage Hydro Plants … Continued

- Energy cycle in a pumped-storage hydro plant is about 75% efficient

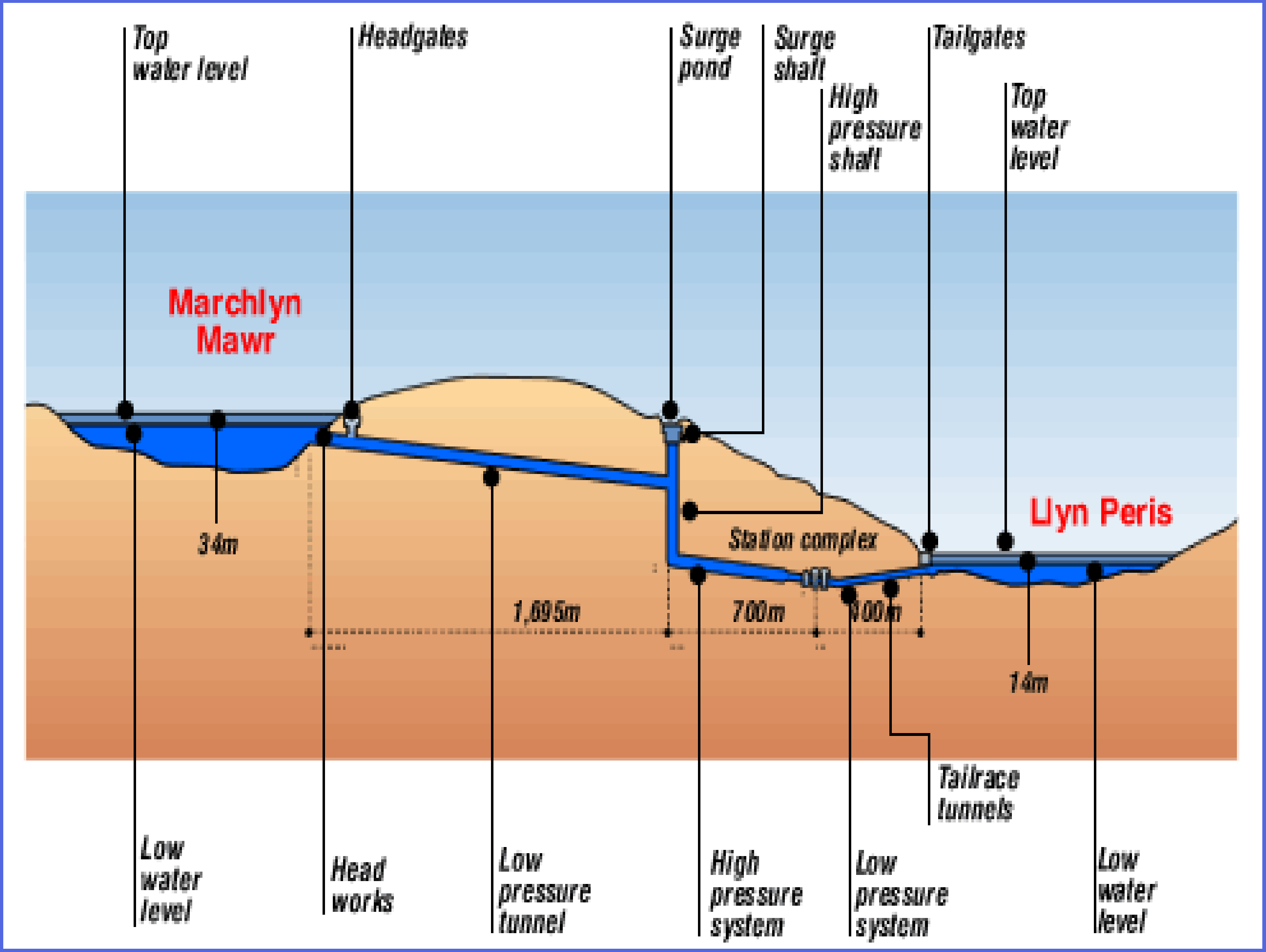
(energy used to pump water up > energy available for sale thru release)

- Difference between high price and low price periods must be large enough to cover the cost of the lost energy

- Net Earnings through ***standard energy*** buy/sell activity are unlikely to be large enough to cover fixed investment costs.

- But pumped-storage hydro plants can also make money through the provision to market operators of "ancillary services" in the form of ***reserve energy***.

Example: Pumped-Storage Hydro Plant



Pumped-Storage Hydro Plant Example … Continued