

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

Important Acknowledgement:

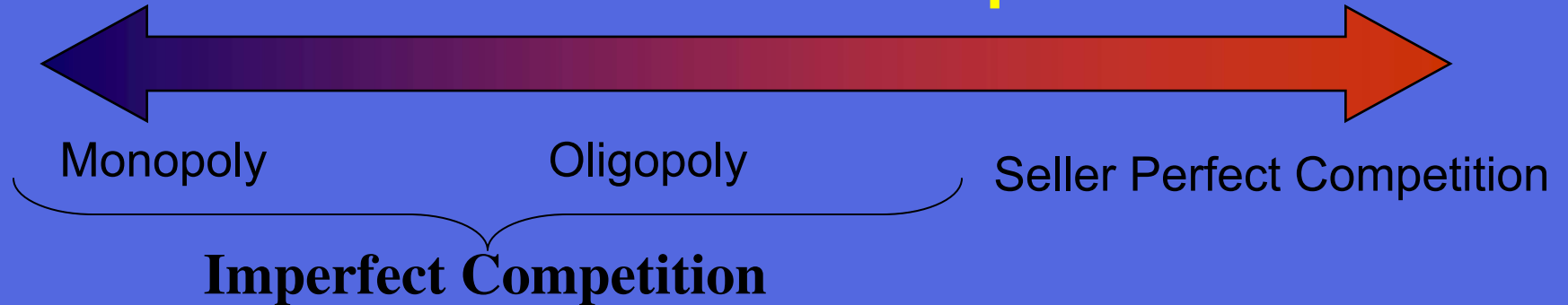
These slides are based on materials originally prepared by Daniel Kirschen (U of Manchester) with edits by Leigh Tesfatsion (Iowa State U).

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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, perfect competition, and imperfect competition were first touched on in K/S Chapter 2.
- ❑ However, in Chapter 4, K/S discuss and illustrate Economic Dispatch problems with some new complications – namely, “no-load costs,” “start-up costs,” and “scheduling (unit commitment)” constraints.
- ❑ Moreover, perfect/imperfect competition concepts are more explicitly developed for power market applications, with illustrative power market examples.

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 their own favor)
 - ◆ At least two sellers act strategically in an attempt to exercise their 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



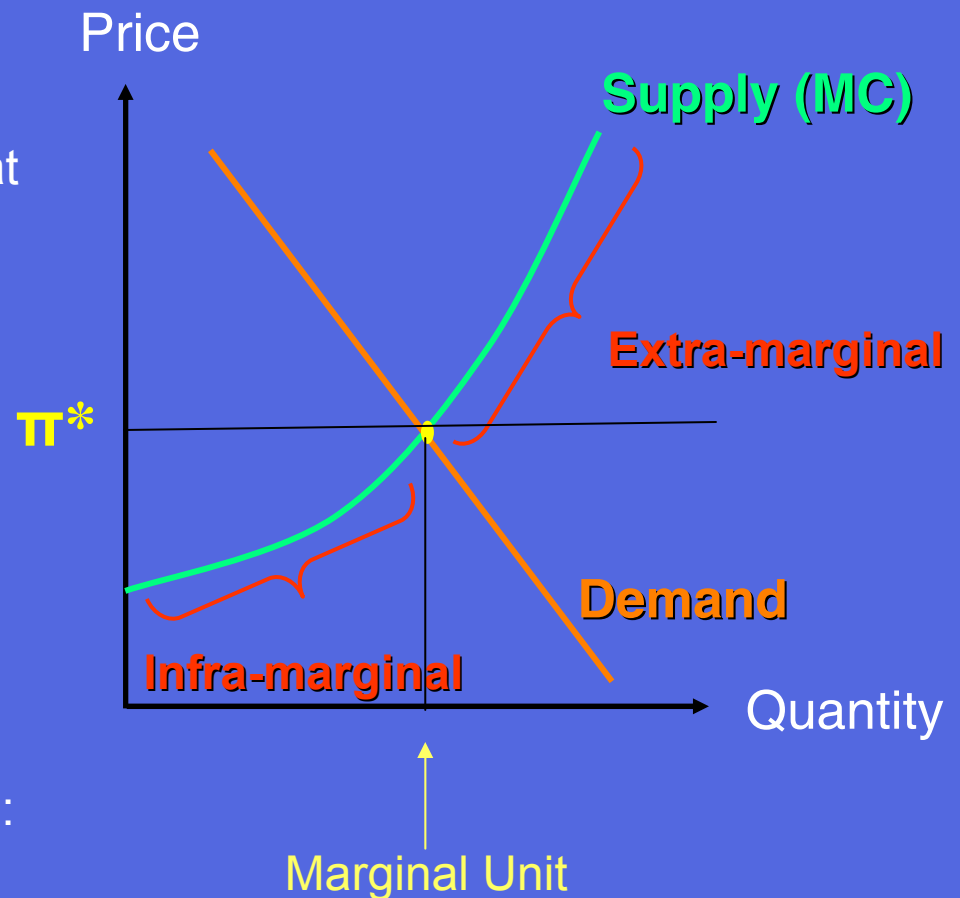
- **Monopsony:**
 - ◆ A single buyer (the *monopsonist*) can set the market price at will
 - ◆ Must be regulated to prevent exploitation of sellers
- **Oligopsony:**
 - ◆ At least two buyers have market power (ability to move the market price in their own favor)
 - ◆ At least two buyers act strategically to exercise their 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***

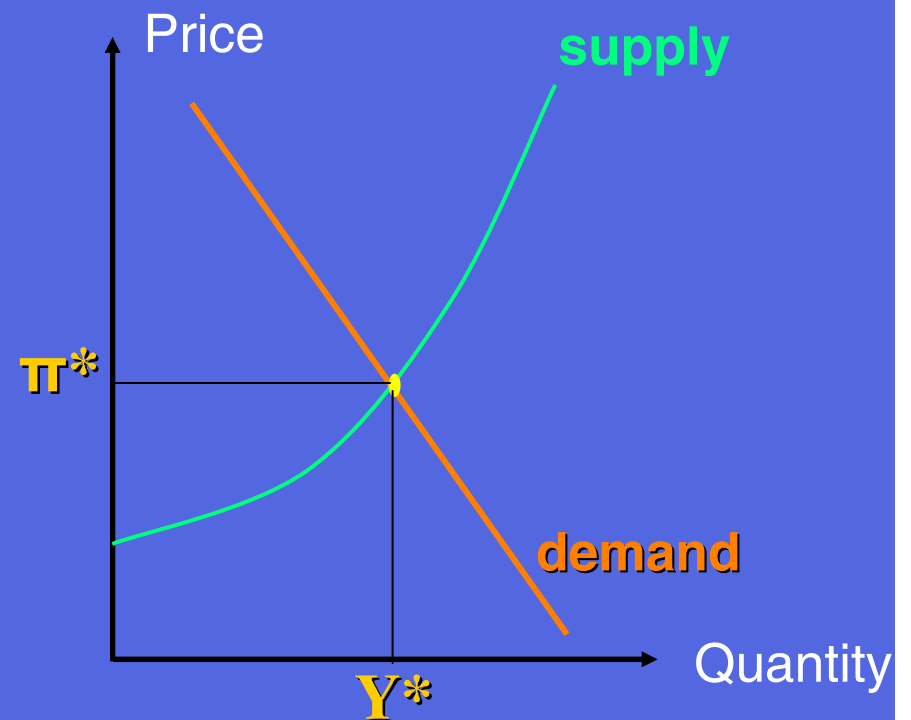
Perfect Competition... Continued

- 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 unit:
 - ◆ “Last” unit sold at price π^*
- Infra-marginal units:
 - ◆ $\pi^* \geq$ sale reservation price (marginal cost)
 - ◆ $\pi^* \leq$ purchase reservation price (maximum willingness to pay)
- Extra-marginal units (all other units):
 - ◆ Not traded except under special circumstances (e.g., minimum operating capacity constraints)



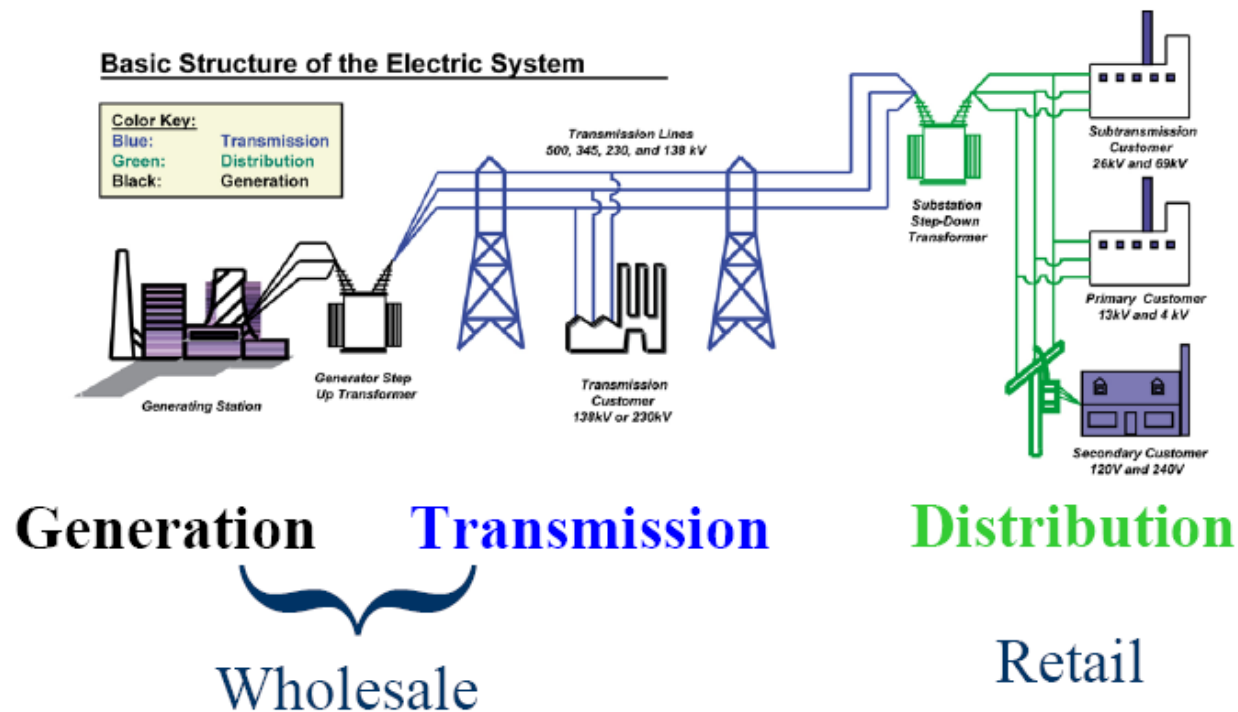
Demand Bids & Supply Offers under Perfect Competition

- **(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 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

$$\max_y \{ \underbrace{\pi \cdot y}_{\text{Revenue from selling } y} - \underbrace{c(y)}_{\text{Cost of producing } y} \}$$



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



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

Cost of producing y

Revenue from selling y

Independent of quantity produced because price taker

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 K/S (Chapter 2) that a GenCo is said to have **market power** if it can change the market price to increase its net revenues, where

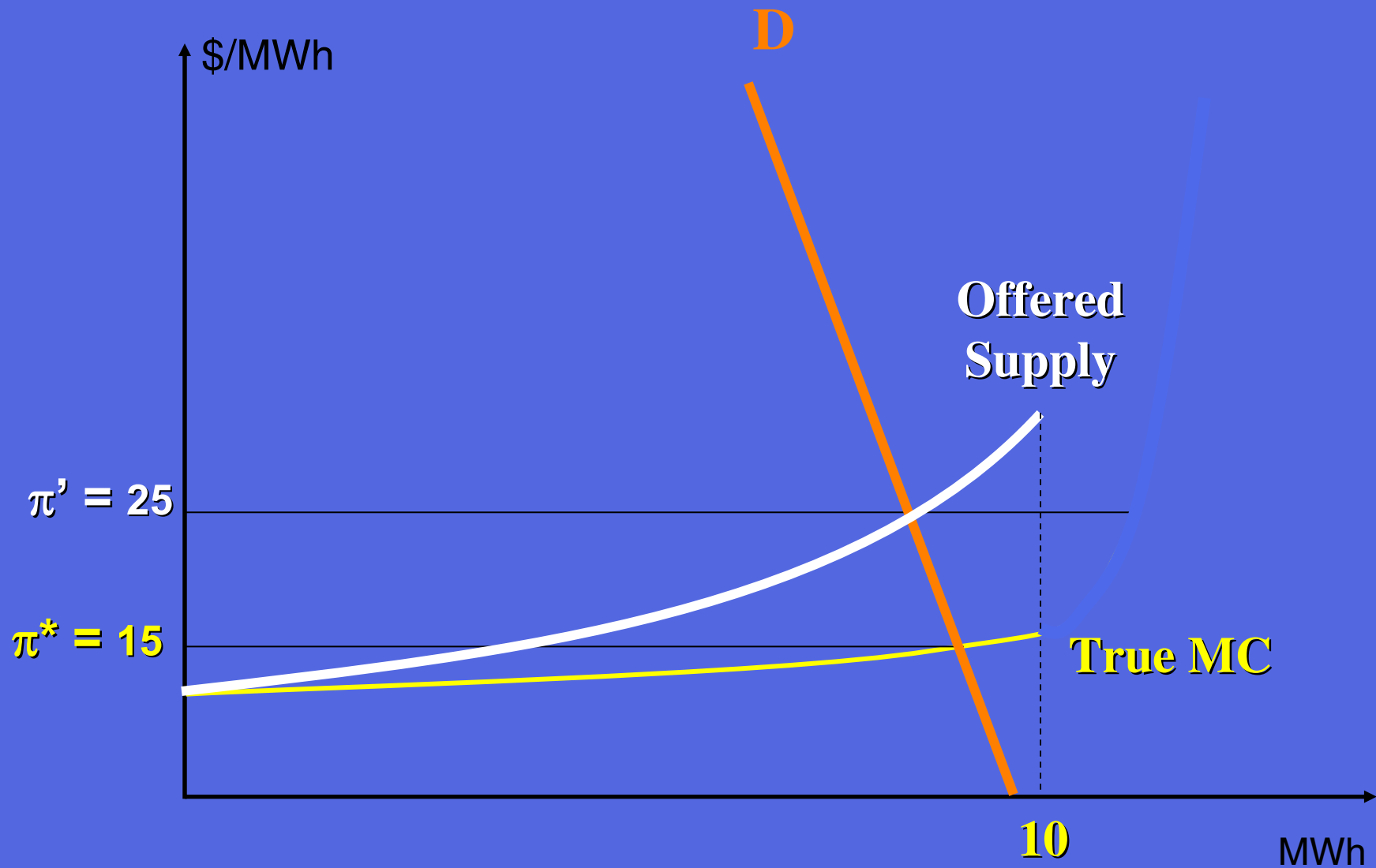
$$\text{Net Revenues} = [\text{Revenues} - \text{Avoidable Cost}]$$

- A GenCo can potentially exercise market power in two basic ways:
 - ◆ raise its offered sales price (**economic withholding**)
 - and/or*
 - ◆ reduce its offered sales quantity (**physical withholding**)

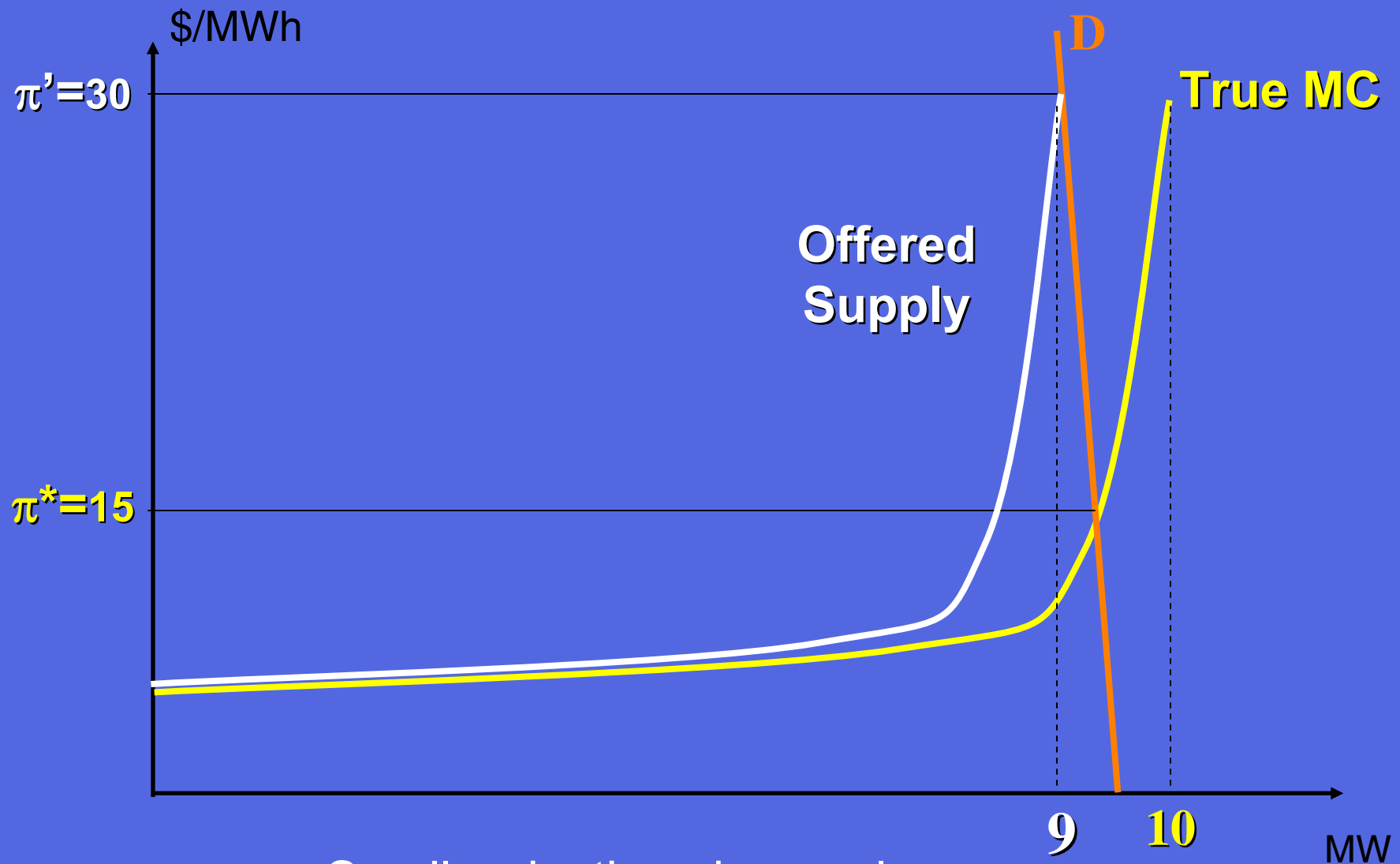
Example:

- 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 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 revenues will increase if and only if the price it receives per unit sold rises enough to compensate it for any decrease in the total quantity it sells.

Option 1: Economic withholding can increase market price

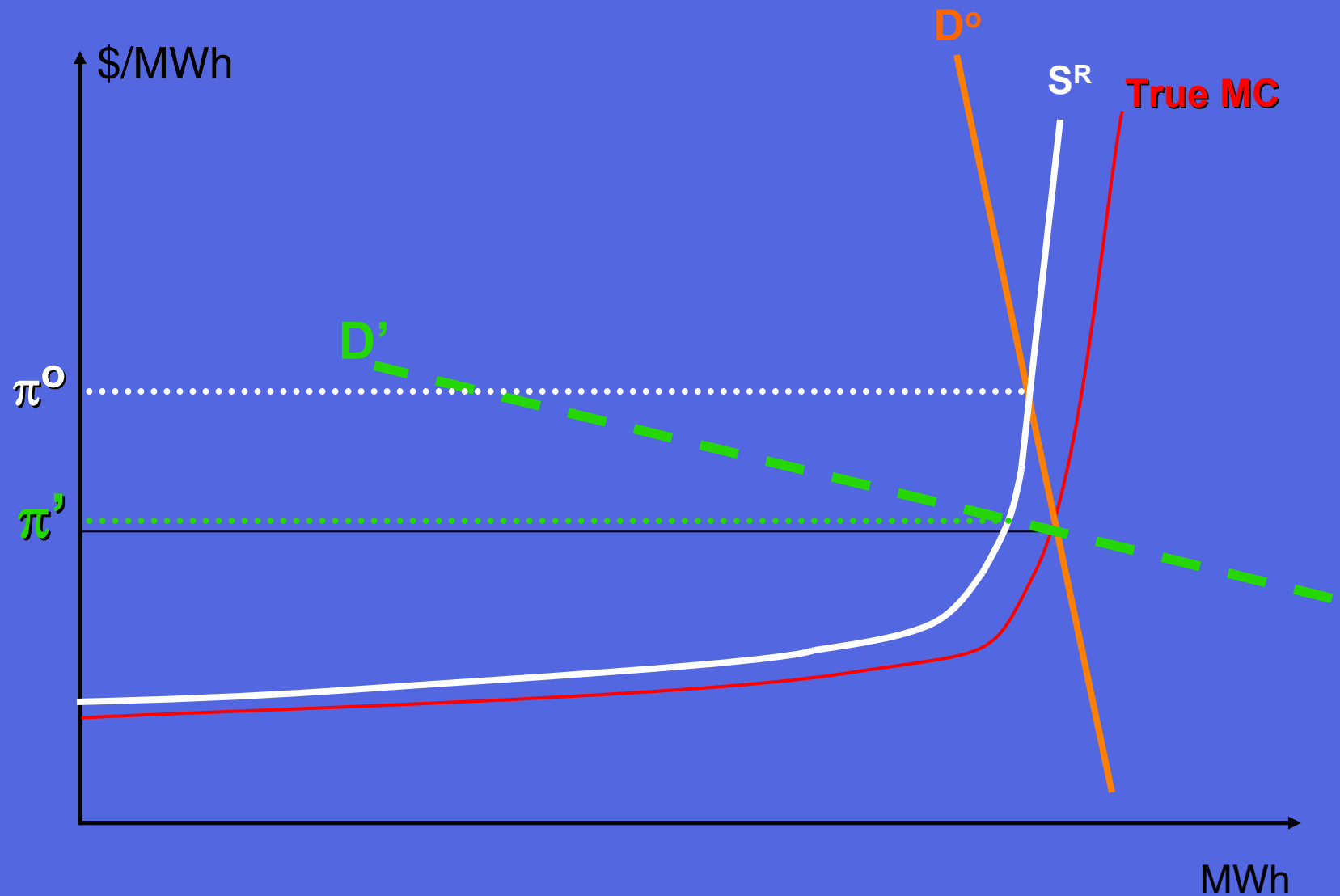


Option 2: Physical withholding can increase market price



→ 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:**

- ◆ Tariffs (regulated retail prices)
 - ◆ Need for reliable communication of prices from wholesale to retail
 - ◆ Need for 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

- **ALL** GenCos benefit from the exercise of market power by any **ONE** GenCo.
- Unilaterally reducing offered output or increasing offered price to increase net revenues **is legal**.
- Explicit deliberate communication among GenCos to raise prices **is not legal**.
- Market power interferes with the efficient dispatch of generating resources
- Strategic supply offers can result in
 - ◆ Marginal units no longer priced at true MC
 - ◆ More expensive generation dispatched prior to cheaper generation

Game Theory and Nash Equilibrium (Cf. Course Section II.B)

- 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 revenues earned 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 $\{a_i^* \mid i=1, \dots, N\}$ for GenCos $i=1, \dots, N$ 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 Revenue for GenCo i

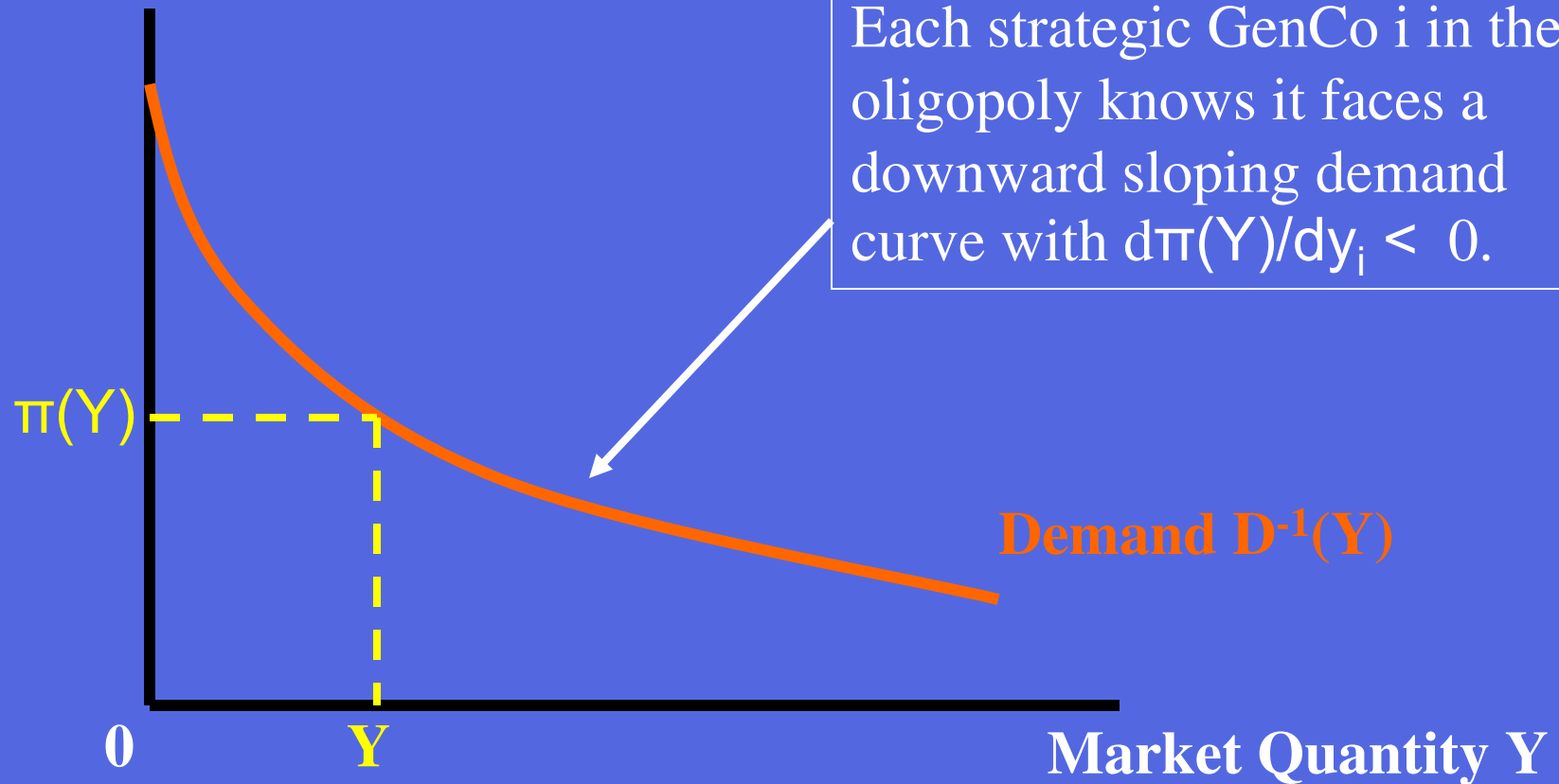
Notation “-i” means “for all but i”

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

Cournot Oligopoly: The Market Perspective

(Compare K/S Chapter 2, Section 2.5.2.1)

Market Price π



Strategic GenCo's First-Order Necessary Conditions (FONC) for optimization in a Cournot Oligopoly

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

y_i : Production of GenCo i

$$Y = y_1 + \dots + y_n$$

= the total industry output

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

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

GenCo i assumes other GenCos will maintain current output levels.

Also, note that

$$d\pi(Y)/dy_i = d\pi(Y)/dY$$

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

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

$$\pi(Y) \left\{ 1 + \frac{y_i}{Y} \frac{Y}{dY} \frac{d\pi(Y)}{\pi(Y)} \right\} = \frac{dc(y_i)}{dy_i} \quad \text{FONC from previous page}$$

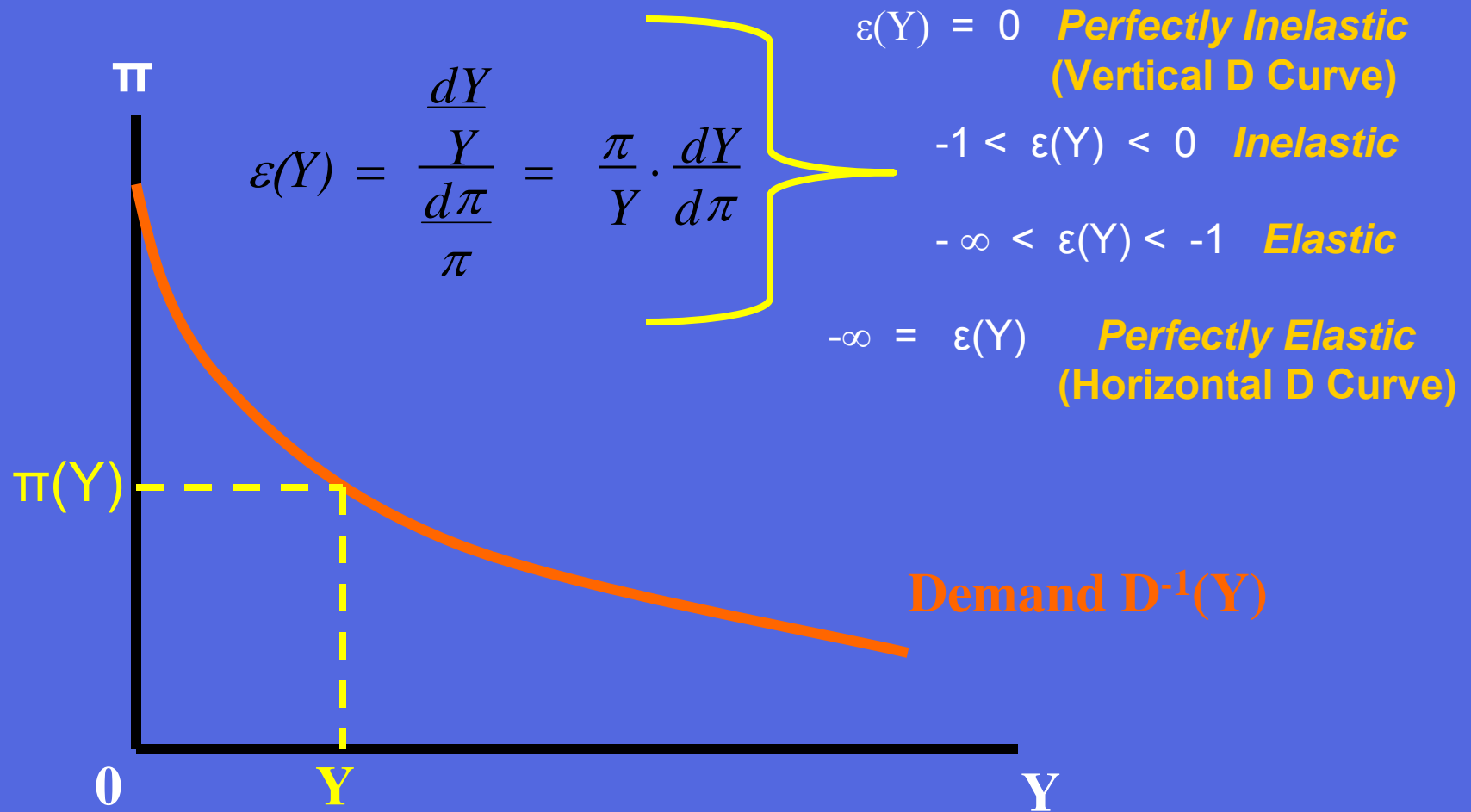
$$\varepsilon(Y) = \frac{\frac{dY}{Y}}{\frac{d\pi}{\pi}} = \frac{\pi}{Y} \cdot \frac{dY}{d\pi} \quad \text{Price-elasticity of demand (< 0)}$$

$$s_i = \frac{y_i}{Y} \quad \text{Market share of GenCo } i \text{ (< 1)}$$

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

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

Remark on Price-Elasticity of Demand



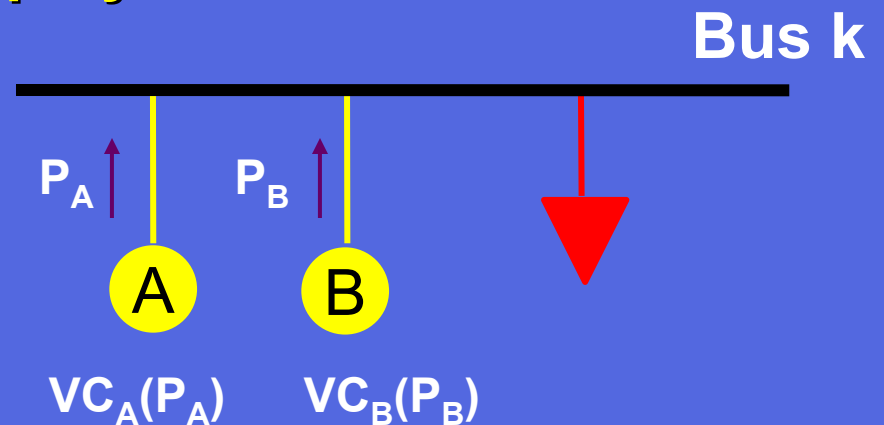
Strategic GenCo's FONC for Optimization in a Cournot Oligopoly ... Continued.

- 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 $y^* = (y^*_1, \dots, y^*_N)$ if the expectations of **each** GenCo 1, ..., N are **fulfilled** at y^* .

Cournot Power Market Oligopoly: 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 a particular Bus k of a transmission grid during a particular hour h.
- In the particular functional forms given below, coefficient units [e.g., MW, \$/MWh, $\$/(\text{MW})^2\text{h}$] are suppressed for ease of notation, **but it is important to remember these coefficients are not unit free!!!**

Cournot Power Market Oligopoly: Example ... Cont'd

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

- ◆ $VC_A(P_A) = 35 \cdot P_A$ (\$/h)
- ◆ $VC_B(P_B) = 45 \cdot P_B$ (\$/h)

and the market demand function is given by

- ◆ $\pi(P) = 100 - 1 \cdot P$ (\$/MWh)

Suppose also that fixed demand (load) is $L=25$, and the Economic Dispatch solution is

- ◆ $P_A^* = 15$ (MW) and $P_B^* = 10$ (MW)
- ◆ $[P_A^* + P_B^*] = L = 25$ (MW)

Then

- ◆ $\pi(L) = 100 - 1 \cdot L = 75$ (\$/MWh)
- ◆ $Rev_A(P_A^*) = 75 \cdot 15 = 1125$ (\$/h); $VC_A(P_A^*) = 35 \cdot 15 = 525$ (\$/h)
- ◆ $Rev_B(P_B^*) = 75 \cdot 10 = 750$ (\$/h); $VC_B(P_B^*) = 45 \cdot 10 = 450$ (\$/h)
- ◆ Net Revenue of A = $NetRev_A(P_A^*) = [Rev_A(P_A^*) - VC_A(P_A^*)] = 600$ (\$/h)
- ◆ Net Revenue of B = $NetRev_B(P_B^*) = [Rev_B(P_B^*) - VC_B(P_B^*)] = 300$ (\$/h)

Cournot Power Market Oligopoly: Example ... Cont'd

Summary:

For $P_A=15$ MW and $P_B = 10$ MW, we have:

Fixed Demand (Load) L

Net Revenue of A

25	600
300	75

Net Revenue of B

Market Price $\pi(L)$

Cournot Power Market Oligopoly: Example ...Continued

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

Demand	NetRev A
NetRev B	Price

Cournot Power Market Oligopoly: Example ...Cont'd

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	NetRev A
NetRev B	Price

- Price decreases as supply increases
- NetRev of each GenCo affected by other
- Complex relationship between supplies and net revenues

Let's play the Cournot oligopoly as a game!

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	NetRev A
NetRev B	Price

Let's play the Cournot oligopoly as a game!

Supplies $P_A=15$ $P_A=20$ $P_A=25$ $P_A=30$

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

Nash Equilibrium solution!

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

Demand	NetRev A
NetRev B	Price

Cournot Power Market Oligopoly: Example 1 ... Continued

Fixed Demand (Load) L

Net Revenue of A

$P_A = 25$

$P_B = 15$	40	625
	225	60

$$VC_A = 35 \cdot P_A \text{ \$/h}$$

$$VC_B = 45 \cdot P_B \text{ \$/h}$$

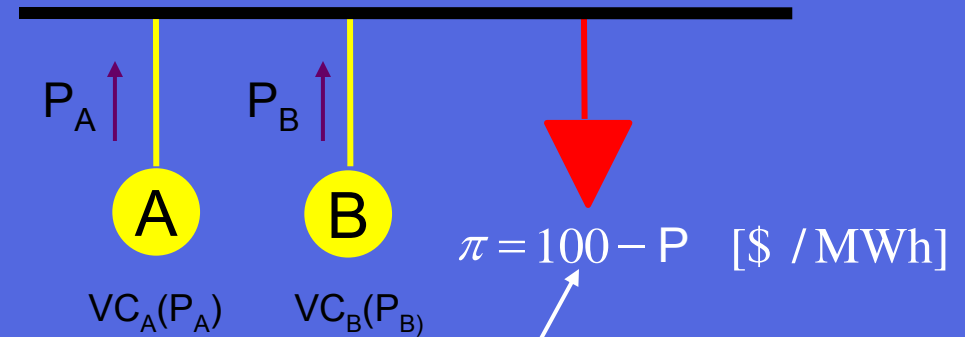
Net Revenue of B

Price $\pi(L)$

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

Bertrand Oligopoly: Example

- Variable Cost Functions:
 - ♦ $VC_A = 35 \cdot P_A$ \$/h
 - ♦ $VC_B = 45 \cdot P_B$ \$/h
- Price offer by GenCo A?
- Price offer by GenCo B?
- Market price?
- Quantity traded?



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

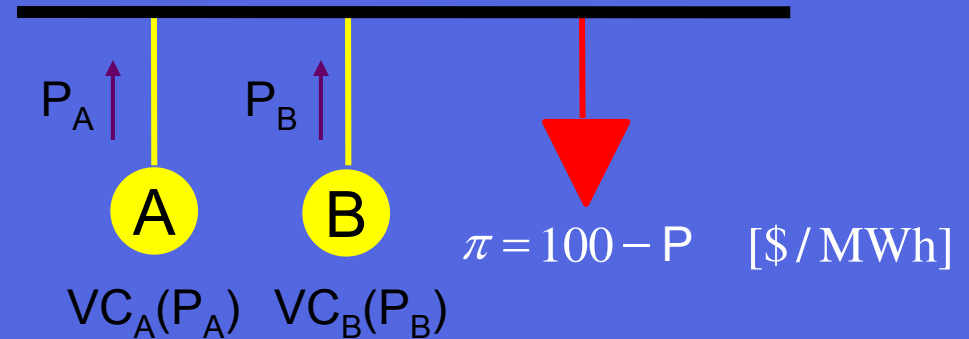
Bertrand Oligopoly: Example ... Continued

- Variable Cost Functions:

- ◆ $VC_A = 35 \cdot P_A$ \$/h

- ◆ $VC_B = 45 \cdot P_B$ \$/h

- Marginal cost of A: 35 \$/MWh
- Marginal cost of B: 45 \$/MWh
- A will offer a price just below 45 \$/MWh
- B cannot offer a price below 45 \$/MWh because it would lose money on every MWh
- Market price: just below 45 \$/MWh
- Demand: 55 MW
- $P_A = 55$ MW
- $P_B = 0$



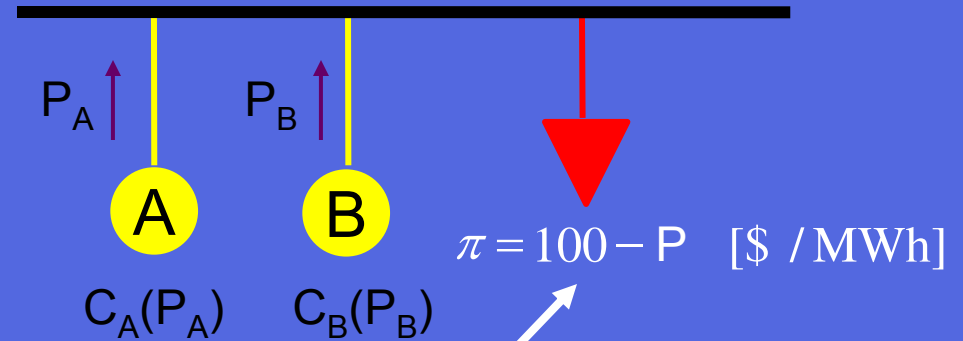
Bertrand Oligopoly: Example 2

- Variable Cost Functions

- ◆ $VC_A = 35 \cdot P_A$ \$/h

- ◆ $VC_B = 35 \cdot P_B$ \$/h

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



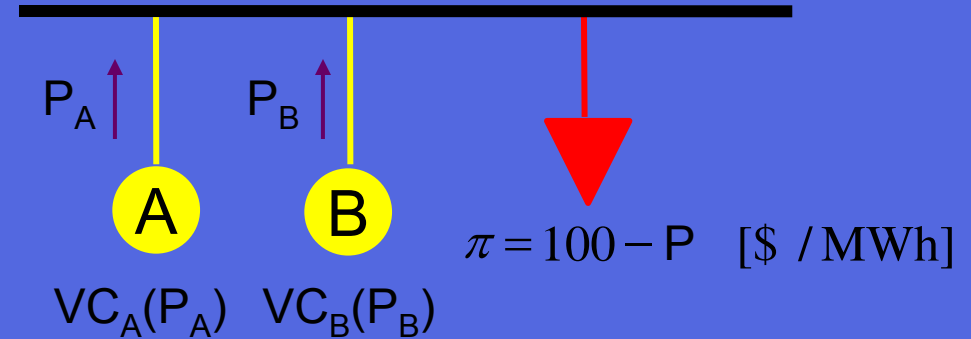
Inverse demand curve assumed known by GenCo A and GenCo B.

Bertrand Oligopoly: Example 2 ... Continued

- Variable Cost Functions:

- $VC_A = 35 \cdot P_A$ \$/h

- $VC_B = 35 \cdot P_B$ \$/h



- GenCo A cannot offer a price below 35 \$/MWh because it would lose 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: Offer prices at their common marginal cost
- Non-identical GenCos: Cheaper GenCo gets the whole market
- Not a realistic model of imperfect competition !

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

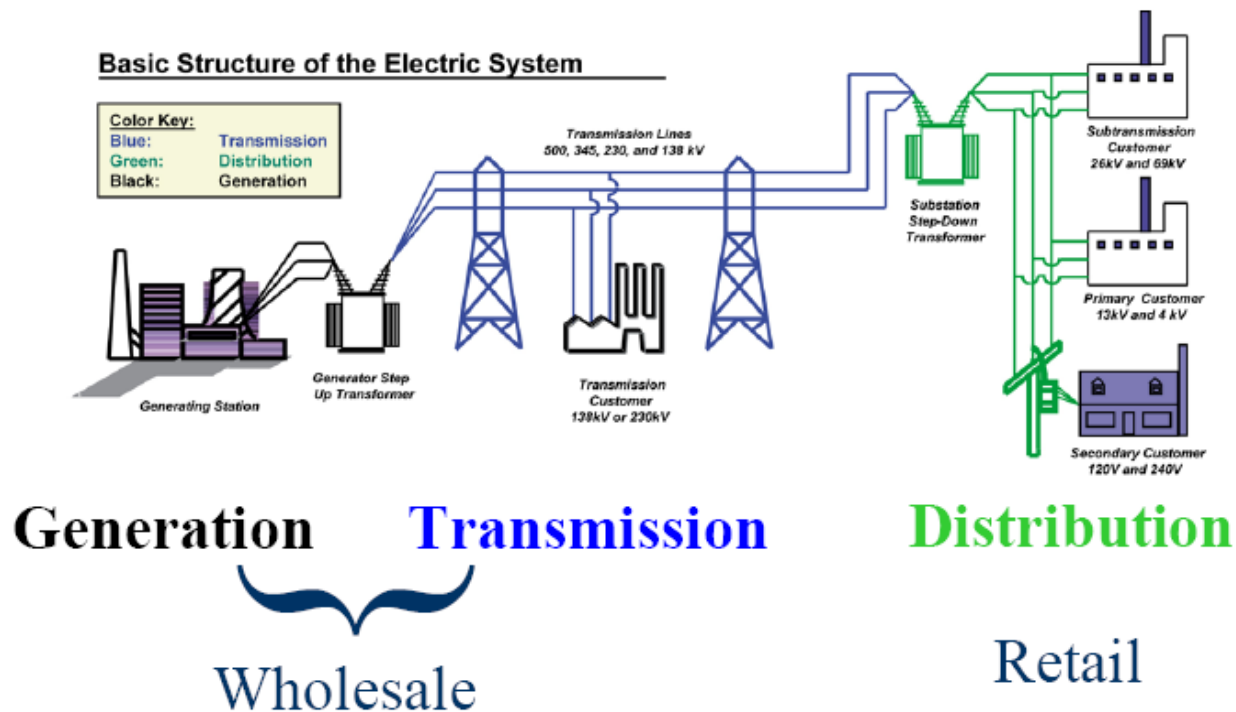
- Supply function equilibria
 - ◆ GenCo supply offers take form of upward sloping supply schedules (give minimum acceptable sale price for each successive unit offered)
- Agent-based modeling
 - ◆ Can represent more complex interactions among strategic power market traders with learning capabilities
- Maximization of net revenues not the only possible objective
 - ◆ Maximize market share
 - ◆ Avoid regulatory intervention

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!)
 - ◆ GenCo's perspective
 - ◆ Market operator's perspective
 - ◆ Market designer's perspective
 - ◆ Regulator's perspective

Retail Customer's Perspective

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

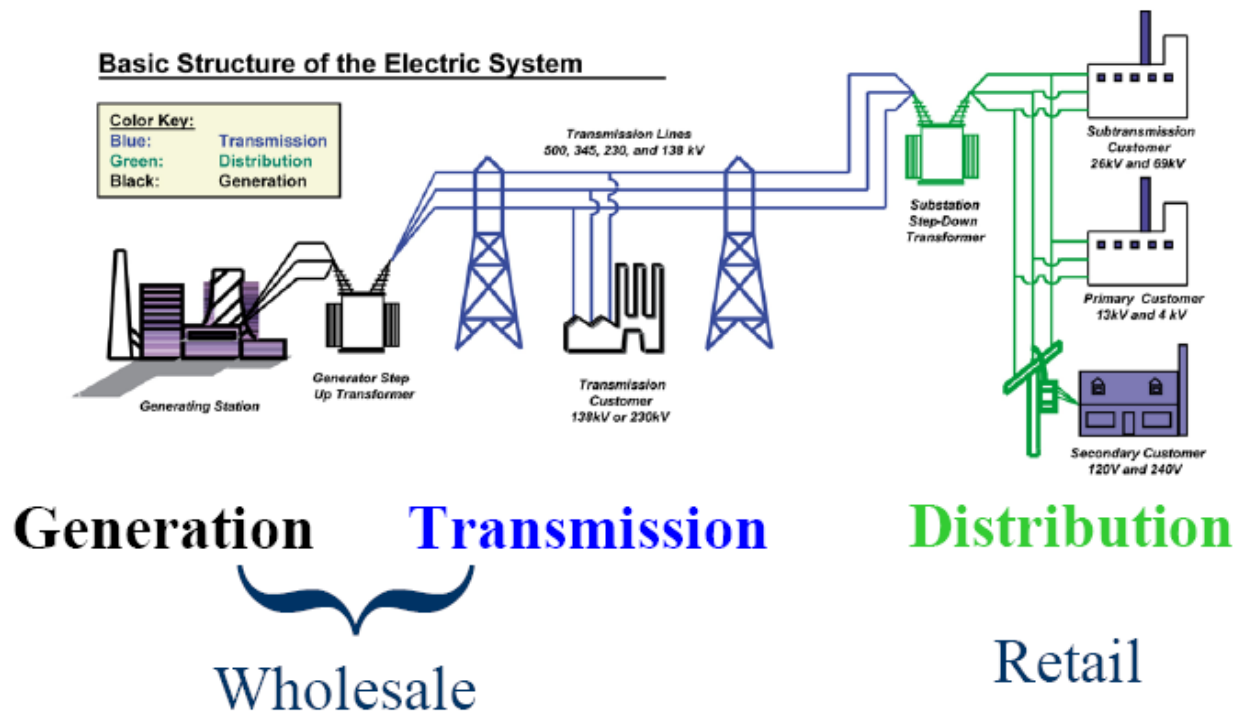


U.S. Retail Customer's Perspective

- **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
- Regional monopoly: traditional top-down forecasting
- Retail competition: bottom-up forecasting
 - ◆ Difficult problem: customer base changes
 - ◆ Much less accurate than traditional load forecasting

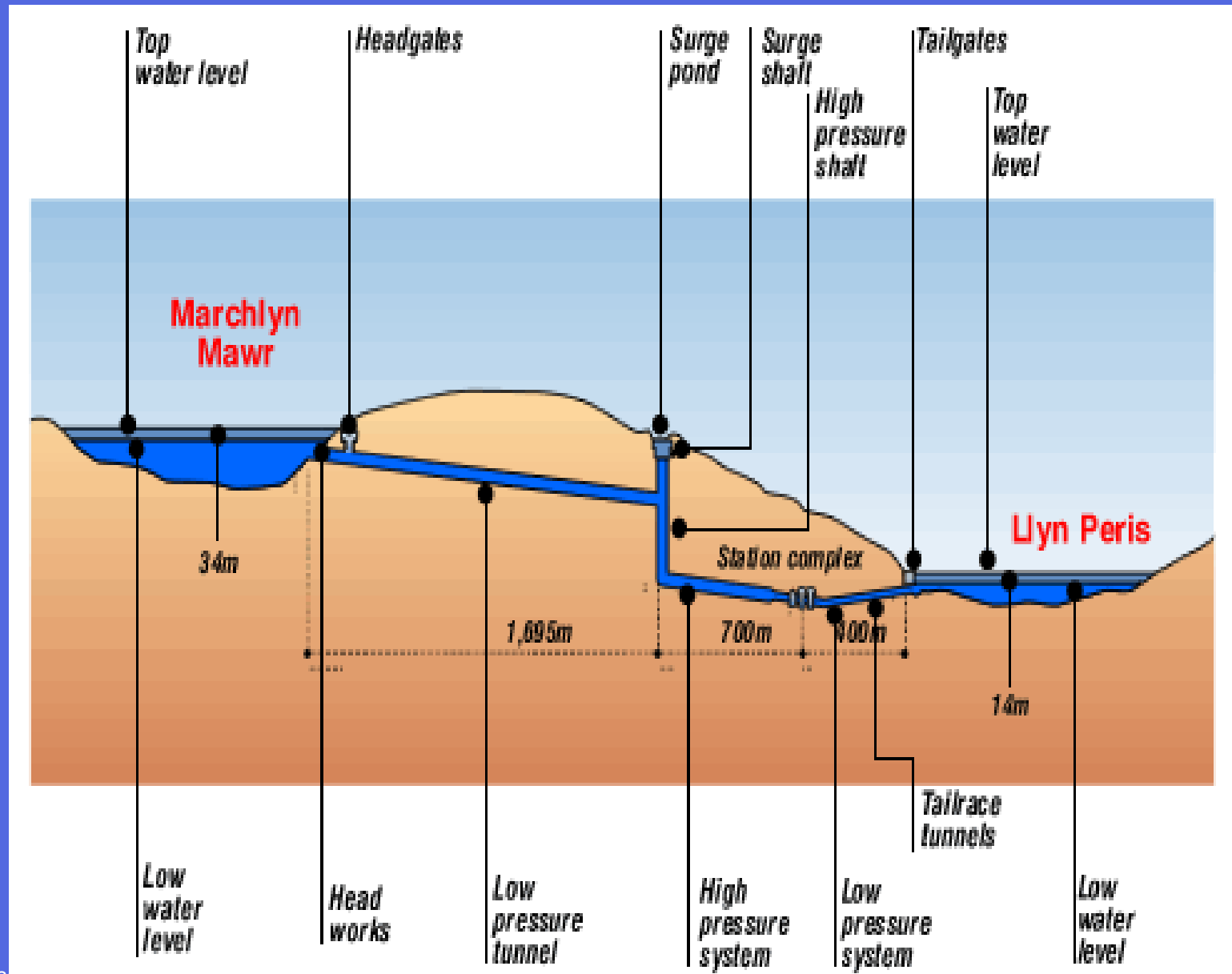
The Hybrid Participant's Perspective

- Small but growing number of wholesale power market participants can buy 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 light demand
 - ◆ Produce and sell energy by releasing this water down through turbines during periods of heavy demand

Pumped-Storage Hydro Plants ... Continued

- Energy cycle in a pumped-storage hydro plant is only about 75% efficient
(energy used to pump water up > energy sold)
- Difference between high price and low price periods must be large enough to cover the cost of the lost energy
- Profit through pure energy buy/sell activity is unlikely to be large enough to cover the fixed cost of investments.
- 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

