Course notes for EE394V Restructured Electricity Markets: Market Power

Ross Baldick

Market power in the absence of transmission constraints

- This material is based on Part 4 of *Power System Economics*, by Steven Stoft.

Outline

(i) Defining market power,
(ii) Exercising market power,
(iii) Modeling market power,
(iv) Designing to reduce market power,
(v) Recovering fixed costs,
(vi) Predicting market power,
(vii) Monitoring market power,
(viii) Homework exercise.

2.1 Defining market power

(i) Different definitions,
(ii) Regulatory focus,
(iii) Economic focus,
(iv) Comments,
(v) Why is market power a concern?
(vi) Price and quantity measures,
(vii) Economic versus physical withholding,
(viii) Auction rules,
(ix) Market power on the demand side.

2.1.1 Different definitions

- Economics and regulatory definitions of market power typically differ in several ways.

Economics definition The ability to profitably alter prices away from the competitive price.

  - Concerned with deviation from competitive level, whether above or below competitive levels.
  - Does not qualify extent or duration of this ability.

Regulatory definitions Examples:

  - The ability to "withhold" (sell less than if behaving competitively).
  - The ability to increase prices for a significant period of time.

2.1.2 Regulatory focus

- Regulatory definitions often focus on a particular identified *action* or "exercise," such as withholding.
- Focus on a particular action may not identify all situations that satisfy the economic definition of market power and may not consider whether the action is profitable:
  - In the homework exercise, you were prohibited from physical withholding, but this does not prevent you from other actions!
- Regulatory agencies such as the Department of Justice have historically been concerned about the possibility of *collusion* (explicit agreements between suppliers to withhold) or of the effect of mergers, rather than with "unilateral" market power.
- Although collusion is a concern, we will not consider it in detail:
  - In the homework, I hope that you did not collude with other groups!
  - Regulatory history focusing on collusion means that regulatory analysis applied to electricity markets may not be able to identify unilateral market power.

2.1.3 Economic focus

- Economics definition focuses on the *outcome* of the effect on price and profit.
- Unilateral actions by a generator that result in this outcome:
  - offering energy at a price higher than marginal costs ("economic withholding"), or
  - not offering all of its capacity ("physical withholding") also resulting in higher prices.
- If this action would increase profit (because increase in prices (and decrease in production costs) compensates for decrease, if any, in sales) then the generator has market power.
- Market power on the supply side is called "monopoly power" or "oligopoly power."
- Other actions can also correspond to market power:
  - For example, a *buyer* of energy with flexibility in the amount consumed could purchase less than consistent with willingness-to-pay, depressing the price for all energy purchased, "monopsony power."

2.1.4 Comments

- Most firms have some market power in that some of the time they could profitably alter prices:
  - Economics definition counts this as market power.
  - Public policy issue is then whether market power occurs enough of the time and produces enough distortion of price from competitive levels (or other measure of market power) in a particular market to be "significant," according to some particular notion of significant, to warrant the cost of action to reduce market power.
  - Regulatory definition tries to capture this issue, but by not being explicit about the criterion for "significant," fails to be useful as a definition without further elaboration.
- We will develop quantitative measures of deleterious effects of market power.
- Public policy decision involves trading off the deleterious effects of market power with the cost of mitigating it to assess when the exercise of market power is significant enough to warrant action.

Comments, continued

- Profitability is part of definition:
  - otherwise, participants that choose to offer at price cap into the ERCOT up-balancing market (and who are never dispatched for any balancing up energy and never profit) would be defined as having exercised market power.
  - otherwise, a baseload nuclear plant would be defined as having market power, even if withholding production would be unprofitable.

Comments, continued

- Trying to increase or maximize profit is not in itself anti-social behavior:
  - Simply a model of "rational," self-interested market participant behavior that can be useful to predict or understand outcomes,
  - Does not always model behavior!
  - Data in model may be uncertain!
  - Effort to be rational may exceed benefits!
- Given the fundamental economic assumption that rational behavior entails trying to maximize profits, if a market participant "has" market power then it will "exercise" its market power:
  - economics does not typically distinguish between "having" and "exercising" (or "abusing") market power.

Comments, continued

- Regulators *do* distinguish between having and exercising market power, implying that market participants are not acting in their own self-interests (at least in "short-term"):
  - if short-term profit maximization would result in regulatory action or longer-term entry by competitors then market participants may forbear from maximizing their short-term profits in order to maximize longer-term profits.
- Typically difficult to model these effects.
- Assumption of short-term profit maximization provides upper bound on what might actually occur in practice, given actual forbearance.

2.1.5 Why is market power a concern?

- Inefficiency of production:
  - withholding of low variable operating cost generation may result in higher variable operating cost generation being used,
  - higher overall fuel bill must be paid for.
- Inefficiency of capital allocation:
  - higher prices may induce too much new construction.
- Inefficiency of allocation:
  - since demand may be lower because of withheld generation.
- Transfers of wealth from demand to generators.
- Quantitative measures of market power should relate either explicitly or implicitly to these deleterious effects.

2.1.6 Price and quantity measures

- To understand market power, we begin with the absence of it.
- We also ignore transmission constraints for now.
- Assume that each generator specifies an offer function that is equal to its marginal costs:
  - Price-taking (in the economics sense) or competitive offer,
  - as in offer-based economic dispatch example.
- Adding up the offers horizontally (taking the sum of the inverses of the offers) yields the competitive supply q^{c}.
- The inverse of the competitive supply function is the industry-wide marginal costs of production p^{c}.
- Also assume that each demand makes a bid that is equal to its willingness-to-pay.
  - That is, each market participant behaves competitively.
- Adding up the bids horizontally yields the competitive demand q^{d}.
- The result of offer-based economic dispatch is the same as finding the intersection of supply and demand.
- The intersection is specified by the competitive price $P^{\star}$ and quantity $Q^{\star}$.

Price and quantity measures, continued

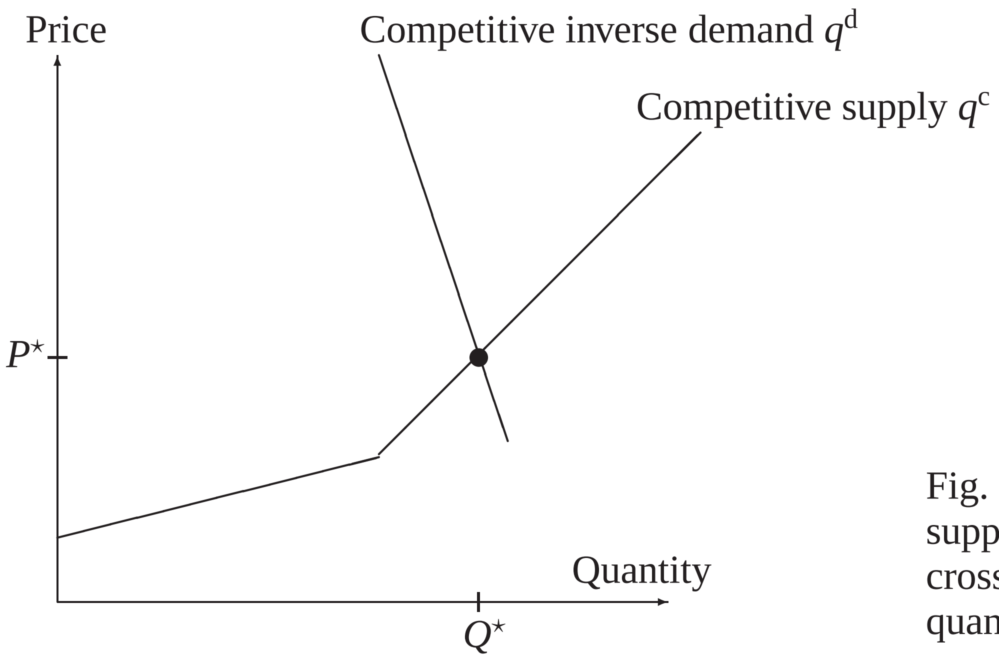

Fig. 2.1. Competitive supply and demand cross at price $P^{\star}$ and quantity $Q^{\star}$.

Price and quantity measures, continued

- Now suppose that a generator withholds by removing a quantity ΔQ_W of its potential production from the offer.
  - For simplicity, assume that all *other* offers remain based on marginal costs.
- The resulting supply curve q^e is shifted, in part, compared to the competitive supply q^c.
- This shift will increase the price and decrease the quantity where the supply and demand cross.
- Withholding of supply results in price P^e and quantity Q^e.

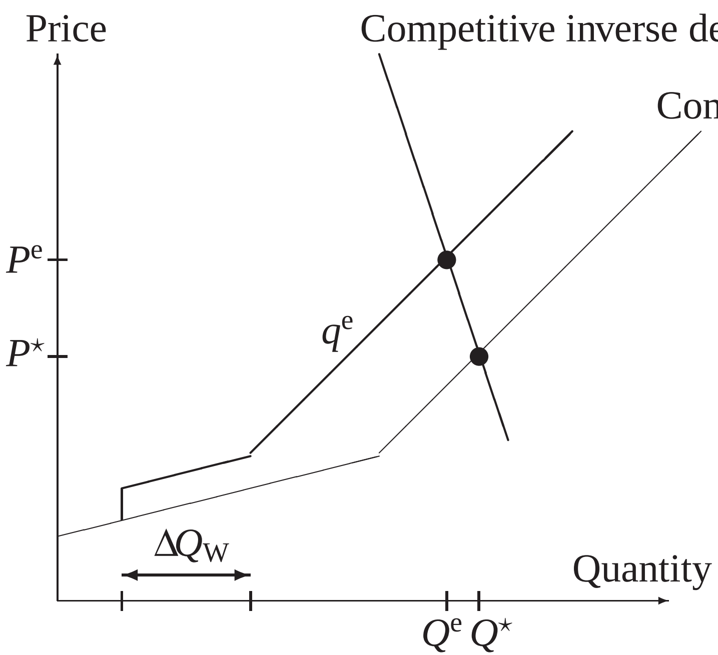

Fig. 2.2. Supply curve and demand cross at price P^{e} and quantity Q^{e}.

Price and quantity measures, continued

- Note that at the price P^{e}, the production $q^{\mathrm{e}}(P^{\mathrm{e}})$ is less than the corresponding "competitive" production $q^{\mathrm{c}}(P^{\mathrm{e}})$ at that price by the "quantity withheld" ΔQ_{W}.

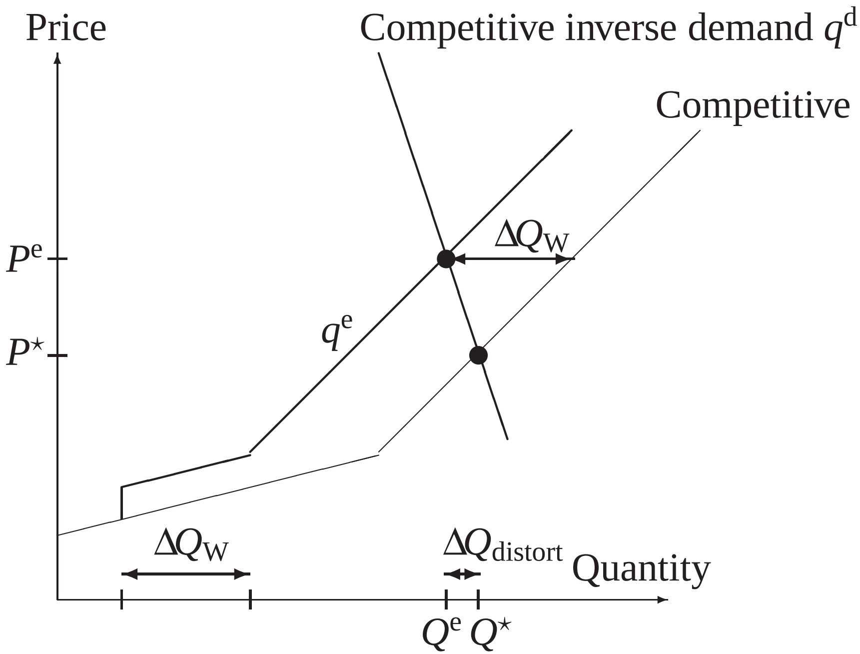

Fig. 2.3. At price P^{e}, production is less than competitive production by quantity withheld.

Price and quantity measures, continued

- The quantity withheld is typically larger than the "quantity distortion," $\Delta Q_{\text{distort}} = Q^{\star} - Q^{\text{e}}$, which measures the decrease in production compared to the competitive equilibrium.
  - The quantity distortion is less than the quantity withheld since the higher price under withholding causes more production by other generators and reduction of demand.
  - If the demand is "inelastic," that is, a constant quantity independent of price, then the quantity distortion would be zero.

Price and quantity measures, continued

- Analogous to the quantity distortion is the "price distortion," the increase in price above the competitive level, $\Delta P_{\text{distort}} = P^{\text{e}} - P^{\star}$.

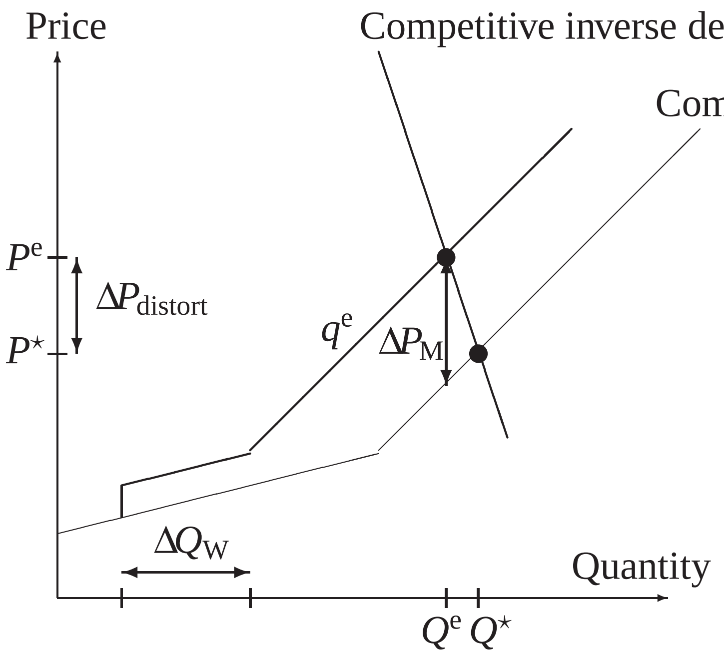

Fig. 2.4. Price distortion and industry mark-up.

Price and quantity measures, continued

- Another price-related measure is the "industry mark-up," the increase in price above marginal costs $\Delta P_{\mathrm{M}} = P^{\mathrm{e}} - p^{\mathrm{c}}(Q^{\mathrm{e}})$, where p^{c} is the industry-wide marginal costs of production evaluated at the actual production level Q^{e}:
  - price $p^{\mathrm{c}}(Q^{\mathrm{e}})$ corresponds to industry-wide efficient dispatch at the quantity Q^{e}.
  - The price mark-up is typically larger than the price distortion since the industry-wide marginal costs evaluated at the quantity Q^{e} is usually lower than the industry-wide marginal costs evaluated at the larger quantity $Q^{\star}$.
- We can also consider:
  - the mark-up compared to a firm's own marginal costs at the quantity it is actually producing, and
  - the average of these firm mark-ups over all firms.

Price and quantity measures, continued

- Summarizing these definitions, we have:
  - Quantity withheld, $\Delta Q_{\mathrm{W}} = q^{\mathrm{c}}(P^{\mathrm{e}}) - Q^{\mathrm{e}}$.
  - Quantity distortion, $\Delta Q_{\mathrm{distort}} = Q^{\star} - Q^{\mathrm{e}}$.
  - Price distortion, $\Delta P_{\mathrm{distort}} = P^{\mathrm{e}} - P^{\star}$.
  - Industry mark-up, $\Delta P_{\mathrm{M}} = P^{\mathrm{e}} - p^{\mathrm{c}}(Q^{\mathrm{e}})$.
- If any of $Q_{\mathrm{W}}, \Delta Q_{\mathrm{distort}}$, P_{distort}, or P_{M} are strictly positive then there is market power on the supply side in an electricity market.
- If demand is inelastic then there can be market power on the supply side with no quantity distortion.

2.1.7 Economic versus physical withholding

- Market power can be exercised by:
  - not offering all capacity to market (physical or quantity withholding), or
  - offering at a price higher than marginal costs (economic or financial withholding).
- The outcome of both is a quantity withheld.
- If capacity is known publicly then economic withholding is less detectable than physical withholding:
  - outcome of both can be similar,
  - in homework exercise, could have reached similar outcomes with physical withholding.

2.1.8 Auction rules

- As mentioned previously, electricity market auction pricing rules may deviate from setting the market clearing price:
  - Using the offer price of the last accepted offer, (that is, the marginal offer price) is not always the market clearing price.
  - The marginal offer price may be lower than the market clearing price if demand is curtailed or if a demand bid price would have set the market clearing price.
- If the price is below the market clearing price then there will not be adequate remuneration from the market and, in the longer term, investment will be inadequate:
  - ongoing concern about “resource adequacy” in ERCOT is indicative that prices may be below competitive prices on average.

Auction rules, continued

- “Thin” hockey stick offers (offer matches marginal costs until just below capacity, then offer price increases significantly) can be interpreted as an attempt to circumvent pricing rules that depress prices below the market clearing price:
  - Offer is reflecting “right-hand marginal costs” at full output.
  - So, should not be deemed market power unless price is actually above competitive price!
  - In absence of demand specifying willingness-to-pay, such thin hockey sticks still do not determine competitive price.
- “Thick” hockey stick offers (offer price is well above marginal costs for a sizeable proportion of capacity) is withholding.

2.1.9 *Market power on the demand side*

- Market power on the demand side is called “monopsony power” or “oligopsony power” and involves reducing price compared to the competitive price.
- Withholding demand tends to decrease the price.
- A typical example involves interruptible demand and the independent system operator (ISO) in its role as monopsony buyer of energy on behalf of demand.
- Suppose that interruptible demand agrees to interrupt for some side-payment by the ISO.
- The ISO may find that, by interrupting the demand, the market price is depressed enough to more than compensate for the side-payment to the interruptible demand.
- Although this action may save money for consumers, it can decrease welfare in the short-term (assuming offers and other bids were competitive), and it discourages investment compared to optimal level (also decreasing welfare in long-term).
- Initial proposals for ERCOT “emergency interruptible load” program involved such a side-payment.

2.2 Exercising market power

(i) Real-time market,
(ii) Forward markets,
(iii) Long-run reactions,
(iv) Marginal and non-marginal generators,
(v) Effects of market power,
(vi) What constitutes significant market power?

2.2.1 Real-time market

- Administered by the ISO, which sets "real-time prices:"
  - in ERCOT currently, called the "balancing market,"
  - in ERCOT nodal, will be called the "real-time" market.
- Arranges for *physical delivery* of power.
- Would be called the "spot market" in other commodities and the market price would be called the "spot price."

2.2.2 Forward markets

- In addition to the “real-time” market, there are “forward markets” and other “forward contracts:”
  - the day-ahead energy market is a short-term (one day ahead) forward market and is also administered by the ISO:
    - ERCOT does not currently have an ISO-administered day-ahead market for energy,
    - ERCOT will administer a day-ahead market for energy and ancillary services in ERCOT nodal, but we will not focus on ancillary services in this course,
    - ERCOT will also consider unit commitment decisions, but we will not focus on unit commitment in this course,
  - there are longer-term forward markets not administered by the ISO (see, for example, Intercontinental Exchange, www.theice.com),
  - two parties can forward contract “over-the-counter” between themselves for any contract term and with a variety of conditions:
    - month ahead, season ahead, year ahead, multiple years,
    - off-peak hours, on-peak hours, all hours in contract term.

Forward markets, continued

- Forward markets "hedge" (or reduce) exposure to price volatility (variability) by arranging a trade at an agreed quantity and agreed fixed price for the contract term.
- Forward trade could, in principle, be made for "physical delivery," where seller intends to produce energy.
- However, forward markets in most commodities involve "financial commitment," where seller can make good on commitment by paying the difference between the spot (real-time) and the agreed price:
  – as in "contract for differences."

Forward markets, continued

- For example, a generator and demand can agree to trade 10 MW at \$50/MWh for all hours in a particular contract duration.
  - The generator makes a commitment to provide 10 MW at price \$50/MWh to the demand.
  - Contract insulates both parties (“hedges”) from real-time price for the agreed quantity.
  - For example, if the demand actually consumes 11 MW in real-time (and has no other forward contracts) then it pays \$50/MWh for the 10 MW agreed quantity and pays the real-time price for the other 1 MW.

Forward markets, continued

- The net payment from the various markets is due to the forward positions and the *deviations* from the forward positions.
- Again, using the example of the 10 MW forward trade:
  - if 11 MW was physically consumed by demand then:
    - 10 MW is paid by demand at the agreed forward price, while
    - the deviation $11 - 10 = 1$ MW is paid for at the real-time price.
  - If 9 MW was physically consumed by demand then:
    - 10 MW is paid by demand at the agreed forward price, while,
    - the deviation $9 - 10 = -1$ MW is "paid for" at the real-time price;
    - that is, 1 MW is sold back to the market at the real-time price.

Forward markets, continued

- If 15 MW was generated by the generator:
  - the 10 MW forward quantity is compensated at the agreed forward price, while
  - the deviation $15 - 10 = 5$ MW is compensated at the real-time price.
- If 0 MW was generated by the generator:
  - the 10 MW forward quantity is compensated at the agreed forward price, while
  - the deviation $0 - 10 = -10$ MW is "compensated" at the real-time price;
  - that is, the generator buys back 10 MW at the real-time price and so makes good on its forward commitment by paying the difference between the real-time and the forward price.
- Overall net payment (forward plus real-time) can be made less variable with forward contracts than without forward contracts.
- Forward markets and contracts are desirable since market prices vary and since most market participants prefer a more stable revenue stream.

Forward markets, continued

- As mentioned, the day-ahead market is an example of a forward market.
- The day-ahead prices are the forward contract prices.
- Day-ahead quantity is paid at the day-ahead price.
- Deviations from the day-ahead quantities are paid at the real-time price.

Forward markets, continued

- Participation in forward markets is voluntary.
- When would a demand purchase a forward contract?
  - If the forward contract price is lower than (or not much higher than) the expected market price.
- When would a generator sell a forward contract?
  - If the forward contract price is higher than (or not much lower than) the expected market price.
- This argument depends on market participants forming sensible probabilistic models of price outcomes.

Forward markets, continued

- Non-participation in forward markets ("physical withholding" from the forward market) is not (in itself) an exercise of market power:
  - if real-time prices are competitive then non-participation in the forward market could simply reflect risk preferences of market participants.
- However, forward prices can reflect expectations of market power in the real-time market.
- So, forward markets can suffer from market power.

2.2.3 Long-run reactions

- Suppose that a generator exercises market power today.
- What will happen in the longer-term?
    - (i) the demand-side may decrease its consumption by shifting to other energy sources, changing its industrial process, or becoming more energy efficient,
    - (ii) other suppliers may enter the market, or
    - (iii) the regulator (public utility commission) may respond.
- If exercising market power now is anticipated to affect these responses then this may affect the generator behavior, typically reducing price compared to "full" exercise of short-term market power:
    - (i) "long-run" demand price response,
    - (ii) "threat of entry," and
    - (iii) "regulatory threat."
- As mentioned, assumption of short-term profit maximization provides upper bound on what might actually occur in practice, given actual forbearance.

2.2.4 Marginal and non-marginal generators

- Although the offer price of the "marginal" generator typically is equal to the clearing price, the offers of non-marginal generators can determine *which* generator is marginal.
- That is, the offer that causes prices to be high may not be the offer that sets the price.
- In previous withholding example, the withheld quantity corresponds to an non-marginal offer.

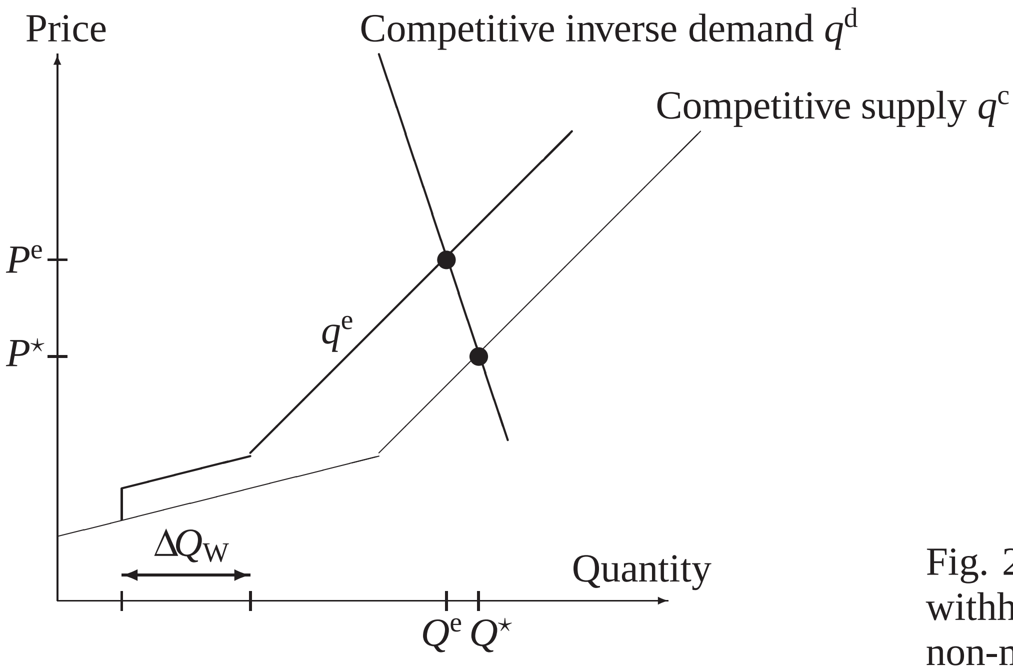

Fig. 2.5. Quantity withholding that is non-marginal.

2.2.5 Effects of market power

- Transfer of wealth from consumers to generators,
- Inefficient sharing of generation amongst generators, increasing fuel cost,
- Lower demand than socially optimal,
- If prices are too high in the long-term then this will encourage more entry than is socially optimal.
  – Conversely, lack of entry despite tight supply is evidence that prices are too low!

2.2.6 *What constitutes significant market power?*

- Fleeting high prices may not translate to significant increases in average:
  - Forward markets protect against risk of being "caught out" by occasional high prices, at least for hedged quantity.
- Appropriate to use average measures over time to assess significance of market power (and decide whether the cost of reducing market power is worth the benefit):
  - wealth transfer,
  - inefficiency,
  - profits.
- Random variations in demand due to weather cause variations:
  - The size of "natural" variations due to demand provide a useful gauge of what is significant.
  - For example, if yearly weather variation causes a variation in a measure (for example, profit) on the order of 2% then it is probably fruitless to try to reduce withholding to having a less than 2% effect on profits.
- Ultimately requires public policy input as to "significant."

2.3 Modeling market power

(i) Profit maximization for a monopoly,
(ii) Cournot model of oligopoly,
(iii) Herfindahl-Hirschman index,
(iv) Other issues.

2.3.1 Profit maximization for a monopoly

- An extreme case is where there is only one generator, a "monopoly."
- Fundamental economic assumption is that market participant wishes to maximize its profits (as in homework assignment).
- The monopolist chooses its production quantity Q in each particular pricing interval to maximize its profits.
- Market rules typically require specification of offer:
  - generator may not be able to literally specify quantity Q, but
  - by understanding demand response to price (or the inverse of this function, the "inverse demand" p^{d}) can specify offer that results in a quantity Q.
  - Since monopolist is the only generator, "market clearing" condition requires that demand equals Q.
- Note that the monopolist is "taking" whatever price clears the market (so is a "price-taker" in electricity market sense) but is *not* behaving competitively and is *not* a price-taker in the economics sense!

Profit maximization for a monopoly, continued

- The "short-run" profit (per hour) in any pricing interval is:

$$\pi_{\text{monopoly}}(Q) = p^{\text{d}}(Q)Q - c(Q),$$

- where c are the total variable operating costs of the generator.
- Ignoring capacity constraints, to find quantity Q^{m} that maximizes profit for monopoly, set derivative of profit equal to zero:

$$\begin{aligned} 0 &= \frac{\partial \pi_{\text{monopoly}}}{\partial Q}(Q^{\text{m}}), \\ &= \frac{\partial p^{\text{d}}}{\partial Q}(Q^{\text{m}})Q^{\text{m}} + p^{\text{d}}(Q^{\text{m}}) - \frac{\partial c}{\partial Q}(Q^{\text{m}}), \end{aligned}$$

- the term $\frac{\partial p^{\text{d}}}{\partial Q}(Q^{\text{m}})Q^{\text{m}} + p^{\text{d}}(Q^{\text{m}})$ is called the "marginal revenue:"
  - note term due to effect of quantity Q on price.
- $\frac{\partial c}{\partial Q}$ is the marginal costs, which we will abbreviate as c'.
- Profit maximization occurs when marginal revenue equals marginal costs.

Profit maximization for a monopoly, continued

- Equating marginal revenue and marginal costs are the first-order necessary conditions for profit maximization.
- Sufficient conditions for profit to be maximum are that: derivative of profit is zero (that is, first-order conditions are satisfied); costs are convex; and $p^{\mathrm{d}}(Q)Q$ is concave in Q.
- We will usually assume that convexity/concavity aspects of sufficient conditions hold.

Profit maximization for a monopoly, continued

- Re-arranging the first-order necessary conditions, we obtain:

$$
\begin{aligned}
p^{\mathrm{d}}(Q^{\mathrm{m}}) - c'(Q^{\mathrm{m}}) &= -\frac{\partial p^{\mathrm{d}}}{\partial Q}(Q^{\mathrm{m}})Q^{\mathrm{m}}, \\
\frac{p^{\mathrm{d}}(Q^{\mathrm{m}}) - c'(Q^{\mathrm{m}})}{p^{\mathrm{d}}(Q^{\mathrm{m}})} &= -\frac{\partial p^{\mathrm{d}}}{\partial Q}(Q^{\mathrm{m}})\frac{Q^{\mathrm{m}}}{p^{\mathrm{d}}(Q^{\mathrm{m}})}, \\
&= 1/e,
\end{aligned}
$$

- where $e = -\frac{p^{\mathrm{d}}(Q^{\mathrm{m}})}{Q^{\mathrm{m}}} \Big/ \frac{\partial p^{\mathrm{d}}}{\partial Q}(Q^{\mathrm{m}})$ is the "price elasticity" evaluated at the market clearing conditions.
- The ratio $L = \frac{p^{\mathrm{d}}(Q^{\mathrm{m}}) - c'(Q)}{p^{\mathrm{d}}(Q^{\mathrm{m}})}$, the ratio of the mark-up of market price above marginal costs divided by the market price, is called the "Lerner index" or "price-cost margin."
- The Lerner index ranges from zero to one.

Profit maximization for a monopoly, continued

- If we invert p^{d} to obtain the "demand function" q^{d} and set $P^{\mathrm{m}} = p^{\mathrm{d}}(Q^{\mathrm{m}})$, we can re-write e as:

$$e = -\frac{\partial q^{\mathrm{d}}}{\partial P}(P^{\mathrm{m}})\frac{P^{\mathrm{m}}}{q^{\mathrm{d}}(P^{\mathrm{m}})}.$$

- Price elasticity is the change in quantity per change in price, normalized by the price and quantity to make a dimensionless ratio.
- Noting that the derivative is approximately equal to the ratio of a small change in the function value Δq^{d} divided by a small change in the argument ΔP, we can interpret the elasticity as:

$$e \approx -\frac{\Delta q^{\mathrm{d}}}{q^{\mathrm{d}}(P^{\mathrm{m}})} \Big/ \frac{\Delta P}{P^{\mathrm{m}}},$$

  the fractional change in demand per fractional change in price.
- In principle, the elasticity can range from zero to infinity.

Profit maximization for a monopoly, continued

- Summarizing, for a monopoly, Lerner index $L = 1/e$.
- Suppose that $e > 1$ and consider the effect on Lerner index and price if e decreases, with everything else staying the same.
  - As e decreases towards 1, the Lerner index and prices increase.
  - In principle, prices and profits become unbounded as e approaches 1 from above.
- If $e < 1$ then there is no solution to setting the derivative of profit equal to zero:
  - for a given $e < 1$, profit increases without bound as Q decreases towards zero and P increases towards infinity.
- Note that a demand that is independent of price has zero elasticity:
  - meeting a fixed demand independent of price is problematic from a market power perspective!

Profit maximization for a monopoly, continued

- In most electricity markets today, even with some demand response, the price elasticity of demand is lower than 1:
  - retail residential customers do not (yet) see the real-time price directly, and
  - other demands have only limited price-responsiveness.
- Zarnikau reports elasticities in ERCOT for industrial customers that are 10^{-3} or smaller!
  - See "Industrial customer response to wholesale prices in the restructured Texas electricity market," Jay Zarnikau *et al.*, *Energy*, 32(9):1715–1723, September 2007.
- Observed outcome in electricity markets of (relatively) low prices and low price elasticity are not consistent with our basic model!
- What are we missing in our basic model?
  - Regulatory action: hard to model,
  - more competitors: oligopoly instead of monopoly,
  - many other issues!

2.3.2 Cournot model of oligopoly

- How would we model an oligopoly consisting of generators $i = 1, \ldots, n$?
- We assume that they each act "unilaterally" to maximize their own profit and ignore explicit collusion:
  - this unilateral behavior is sometimes called "tacit collusion;" however, this phrase appears to be used differently by different people.
- Although we assume unilateral actions, an action by one participant will affect the price and therefore the profits of all participants:
  - we seek to model the result of *all* of their individual unilateral decisions, considering the interaction between their decisions.

Cournot model of oligopoly, continued

- Models of interaction require specification of how each participant perceives the effect of the other participants in the market.
  - The Cournot model posits that each participant i assumes that each other participant $j \neq i$ commits to a fixed output level Q_j.
  - Each other participant j somehow specifies its offer so that the quantity Q_j is produced independent of the market price (not literally possible in electricity market with "offer caps" and under some market rules).
- One way to think of this situation is that player i is going to maximize its profits as though it is a monopolist facing the "residual demand" defined by $\left(\text{demand} - \sum_{j \neq i} Q_j\right)$.
- Models of interaction also require specification of the information available to market participants:
  - the basic Cournot model posits that each participant has complete knowledge about other participants and demand,
  - true in the homework exercise, but not (exactly) true in reality because of uncertainty about supply of others and demand.

Cournot model of oligopoly, continued

- Apply these assumptions symmetrically and find consistent profit maximizing choices:
  - Have n variables to choose, $Q_1, \ldots, Q_n$, and n profit functions to maximize, so under appropriate assumptions there will be a unique solution,
  - Capacity constraints and other issues can cause there to be multiple solutions or no solutions.
- A consistent set of profit maximizing choices is called a (pure strategy) *Nash equilibrium*.
- Later will discuss Nash equilibrium in more detail and generalize.

Cournot model of oligopoly, continued

- The market clearing condition is now that demand equals $\sum_j Q_j$, so that the market price will be $p^{\mathrm{d}}(\sum_j Q_j)$.
- The "short-run" profit (per hour) in any pricing interval for generator i is:

$$\pi_i(Q_i, Q_{-i}) = p^{\mathrm{d}}(\sum_j Q_j)Q_i - c_i(Q_i),$$

- where Q_{-i} is a vector consisting of the quantities of the other generators, $Q_j, j \neq i$, and
- c_i are the variable operating costs of generator i.
- Note that π_i depends on Q_i and $Q_j, j \neq i$.

Cournot model of oligopoly, continued

- To find the quantity Q_i^{e} that maximizes profit π_i for generator i, under the assumption that the quantities Q_j, $j \neq i$, are fixed at values Q_j^{e}, $j \neq i$, set derivative of π_i with respect to Q_i equal to zero:

$$\begin{aligned} 0 &= \frac{\partial \pi_i}{\partial Q_i}(Q_i^{\mathrm{e}}, Q_{-i}^{\mathrm{e}}), \\ &= \frac{\partial p^{\mathrm{d}}}{\partial Q}\Big(\sum_j Q_j^{\mathrm{e}}\Big) Q_i^{\mathrm{e}} + p^{\mathrm{d}}\Big(\sum_j Q_j^{\mathrm{e}}\Big) - \frac{\partial c_i}{\partial Q_i}(Q_i^{\mathrm{e}}), \end{aligned}$$

- where Q_{-i}^{e} is a vector consisting of the quantities Q_j^{e}, $j \neq i$, and
- $\dfrac{\partial c_i}{\partial Q_i}$ is the marginal costs of generator i, which we will again abbreviate as c_i'.
- These are the first-order necessary conditions for profit maximization for generator i:
  - analogous conditions also hold for Q_j^{e}, $j \neq i$,
  - need to solve all conditions simultaneously.

Cournot model of oligopoly, continued

- We will assume that the convexity/concavity aspects of the sufficient conditions hold in order for the first-order necessary conditions to characterize profit maximization for each generator i.
- Re-arranging, we obtain:

$$\begin{aligned}
p^{\mathrm{d}}(\sum_j Q_j^{\mathrm{e}}) - c_i'(Q_i^{\mathrm{e}}) &= -\frac{\partial p^{\mathrm{d}}}{\partial Q}(\sum_j Q_j^{\mathrm{e}})Q_i^{\mathrm{e}}, \\
\frac{p^{\mathrm{d}}(\sum_j Q_j^{\mathrm{e}}) - c_i'(Q_i^{\mathrm{e}})}{p^{\mathrm{d}}(\sum_j Q_j^{\mathrm{e}})} &= -\frac{\partial p^{\mathrm{d}}}{\partial Q}(\sum_j Q_j^{\mathrm{e}})\frac{Q_i^{\mathrm{e}}}{p^{\mathrm{d}}(\sum_j Q_j^{\mathrm{e}})}, \\
&= \frac{1}{e}\frac{Q_i^{\mathrm{e}}}{\sum_j Q_j^{\mathrm{e}}},
\end{aligned}$$

using the previous definition of elasticity $e = -\frac{p^{\mathrm{d}}(\sum_j Q_j^{\mathrm{e}})}{\sum_j Q_j^{\mathrm{e}}} / \frac{\partial p^{\mathrm{d}}}{\partial Q}(\sum_j Q_j^{\mathrm{e}})$, evaluated at the market clearing quantity $\sum_j Q_j^{\mathrm{e}}$.

Cournot model of oligopoly, continued

- The ratio $L_i = \frac{p^{\mathrm{d}}(\sum_j Q_j^{\mathrm{e}}) - c_i'(Q_i^{\mathrm{e}})}{p^{\mathrm{d}}(\sum_j Q_j^{\mathrm{e}})}$ is the Lerner index or price-cost margin for firm i.
- Defining $s_i = Q_i^{\mathrm{e}} / \sum_j Q_j^{\mathrm{e}}$, the market share, the Cournot model predicts $L_i = s_i/e$:
  - generators with larger market share will have higher price-cost margin,
  - in the limit for generators with market share approaching zero, the price will equal their marginal costs.

Cournot model of oligopoly, continued

- What are the implications for the homework exercise?
- The part of the demand curve in the homework exercise that is "vertical" has zero elasticity:
  - The Cournot model suggests that profit maximizers will try to increase the price-cost margin and therefore increase the price whenever the supply curve intersects the vertical part of the curve.
- The part of the demand curve in the homework exercise that is "horizontal" has infinite elasticity and fixed price:
  - The Cournot model suggests that profit maximizers will try to increase the quantity sold to try to equate marginal costs with the price whenever the supply curve intersects the horizonal part of the curve.
- Putting these together, the Cournot model suggests that the equilibrium will be at the "corner" where all demand is served, but with price equal to the willingness-to-pay of the demand (or the price cap).

Cournot model of oligopoly, continued

- This "corner solution" would be difficult to exactly sustain in practice:
  - even slightly too much total production would drive prices towards zero.
- Nevertheless, the Cournot model would suggest that market participants would adjust their quantities to bring the clearing quantity and price close to the corner.
- This conclusion is independent of demand:
  - inconsistent with the results of the homework for low demand, and
  - inconsistent with observations of real markets for low demand.
- In homework and real markets, offers are specified as functions:
  - competing firms do not specify quantity,
  - offers allow for different production quantities at different prices.
- Also many other differences between Cournot model and reality.
- So, not surprising that our Cournot analysis does not predict outcome perfectly!

2.3.3 Herfindahl-Hirschman index

- The generation-weighted average price-cost margin is:

$$\begin{aligned} L &= \sum_i s_i L_i, \\ &= \sum_j (s_j)^2/e, \text{ using the Cournot model.} \end{aligned}$$

- The expression $\sum_j (s_j)^2$ is called the Herfindahl-Hirschman index (HHI) and is between 0 and 1:
  - for a large number of small firms, $\sum_j (s_j)^2 \approx 0$,
  - for a monopolist, $\sum_j (s_j)^2 = 1$.
- The HHI measures "market concentration" in that the smaller the number of firms and the larger their market share, the higher the HHI, and the higher the price-cost margin.
- Note that the s_i are based on "market share" defined to mean the ratio of production by generator i to total production:
  - some versions of "HHI" use measures of capacity, which has no theoretical relation to mark-up.

Herfindahl-Hirschman index, continued

- The HHI is used by several regulatory agencies to estimate the effect of *mergers* on market power.
- Percentages are often used by regulatory agencies instead of decimals for market share, yielding an index between 0 and 10,000.
- It is also used as a measure of market power exercised by market participants unilaterally.
- The only rigorous justification for using HHI is in the context of the Cournot model using market shares.
- Relationship of HHI to mark-up also requires knowledge of elasticity:
  - Price elasticity in electricity market is much smaller than in other markets.
  - So, levels of HHI that might correspond to “acceptable” levels of markets power in other markets may not be acceptable in electricity markets.
  - Nevertheless, such levels borrowed from other industries are routinely used in regulation of electricity markets!

2.3.4 Other issues

- The Cournot model focuses on generator costs, market share, and price elasticity.
- There are a number of other issues that we have not (yet) represented:

1. Forward contracts and retail obligations of retailers affiliated with generators,
2. Uncertainty of demand (and residual demand) and requirements to keep offers fixed over multiple pricing intervals,
3. Long-run consequences of exercising market power,
4. Repetition of similar market situations day after day,
5. Transmission capacity constraints,
6. Details about form of generator offer,
7. Generator capacity constraints,
8. Generator start-up and min-load costs and minimum up- and down-times,
9. Ancillary services.

- We will discuss some, but not all, of these in subsequent lectures.

2.4 Designing to reduce market power

(i) Market share and demand elasticity,
(ii) Why are prices so low?
(iii) Forward contracts and retail obligations,
(iv) Demand uncertainty,
(v) Fixed offers over multiple intervals,
(vi) Introducing elasticity of demand into ancillary services.

2.4.1 Market share and demand elasticity

- We identified market share and demand elasticity in the Cournot model as contributing to determining price:
  - price increases with increasing market shares,
  - price decreases with increasing demand elasticity.
- Compared to, for example, microprocessor production or home improvement retailing, market shares are relatively low in most electricity markets:
  - Intel's market share is around 75%,
  - largest supplier in ERCOT, Luminant, has market share around 20% to 30%.

Market share and demand elasticity, continued

- Demand elasticity is very low in electricity markets:
  - Part of the reason is that very few customers are exposed to real-time prices for energy (advanced metering is being deployed to change this, but also requires changes in regulatory policy),
  - Part of the reason is that demand for ancillary services by ISO may be represented in the market as being inelastic.
- Exposing more customers to real-time energy prices (requires metering infrastructure and political will) can be expected to increase the price elasticity of demand, but exposes customers to price volatility.
- Exposure to volatility of real-time prices can be hedged by forward contracts.
- Representing elasticity of demand for ancillary services by the ISO into market can increase residual demand elasticity in the energy market (see later).

2.4.2 *Why are prices so low in actual markets?*

- Since elasticity in current markets is so low, the Cournot model is not consistent with observations.
- Recalling some of the several issues not yet represented in model:

  (i) Forward contracts and retail obligations of retailers “affiliated” with generators (having same parent company or owner),

  (ii) Uncertainty of demand and requirements to keep offers fixed over multiple pricing intervals,

  (iii) The form of the offer function.

2.4.3 Forward contracts and retail obligations

- Consider a generator affiliated with a company that also has retail load obligations at a fixed price.
- That is, appropriate profit function involves cost of generation and sale at wholesale and retail.
- Integration of generator and retailer serves to decrease market power:
  - Similar analysis applies to any generator that has sold a forward contract.
- Example will illustrate why the retail obligation reduces market power.

Forward contracts and retail obligations, continued

- Suppose there are five generators each with capacity 10,000 MW and each with marginal cost \$20/MWh.
- Four (of the five) generators have retail obligations, with peak demand of around 12,500 MW each.
- The other generator is unaffiliated.
- Total demand is characterized by:
  - a demand parameter Q_0 that varies over time and with weather, and
  - responsiveness to price.
- In particular, demand is:

$$q^{\mathrm{d}}(P) = Q_0 - (P - 20)Q_0/10,000.$$

- The corresponding inverse demand is:

$$p^{\mathrm{d}}(Q) = 10,020 - 10,000Q/Q_0.$$

- Note that Q_0 specifies the demand that would be consumed if price equalled \$20/MWh.
- For each \$1/MWh increase in price, demand decreases by $Q_0/10,000$.

Forward contracts and retail obligations, continued

- Suppose that each of the four retailers is obliged to serve one quarter of the total demand:
  - retail obligations at fixed retail price.
- Suppose that total demand is at or below 40,000 MW.
  - Since each retailer owns 10,000 MW of generation with marginal cost \$20/MWh, each retailer would pay no more than \$20/MWh to purchase energy to meet its retail obligation.
  - Since the unaffiliated generator will not sell at a loss, it will sell for no less than \$20/MWh.
  - Even if no energy is actually bought and sold, we can observe that the market clearing price would be \$20/MWh.
- Suppose that total demand is higher than 40,000 MW.
  - Again, the unaffiliated generator will sell at a price of at least \$20/MWh.
  - If the unaffiliated generator sells at a price higher than \$20/MWh then each retailer will use its own generation for 10,000 MW of its demand.
  - The unaffiliated generator supplies the balance, Q_5, of the demand that is above 40,000 MW, yielding price $p^{\mathrm{d}}(40,000+Q_5)$.

Forward contracts and retail obligations, continued

- The unaffiliated generator chooses a quantity Q_5^{e} to maximize its profit:

$$\begin{aligned}\pi_5(Q_5) &= p^{\mathrm{d}}(40,000+Q_5)Q_5 - 20Q_5,\\ &= (10,020-10,000(40,000+Q_5)/Q_0)Q_5 - 20Q_5,\\ &= -10,000(Q_5)^2/Q_0 + (10,000 - 4\times 10^8/Q_0)Q_5.\end{aligned}$$

- Differentiating profit π_5 and setting equal to zero, we obtain:

$$\begin{aligned}0 &= -20,000Q_5^{\mathrm{e}}/Q_0 + (10,000 - 4\times 10^8/Q_0),\\ Q_0 &= 40,000 + 2Q_5^{\mathrm{e}}.\end{aligned}$$

- Repeating the inverse demand function:

$$p^{\mathrm{d}}(40,000+Q_5^{\mathrm{e}}) = 10,020 - 10,000(40,000+Q_5^{\mathrm{e}})/Q_0.$$

- Eliminating Q_0 between the last two equations and noting that the equilibrium demand is $D^{\mathrm{e}} = 40,000 + Q_5^{\mathrm{e}}$ results in the relationship between equilibrium price P^{e} and demand for $D^{\mathrm{e}} \geq 40,000$:

$$P^{\mathrm{e}} = 5,020 - 2\times 10^8/(2D^{\mathrm{e}} - 40,000).$$

Forward contracts and retail obligations, continued

- The equilibrium price is shown in figure 4-4.1 on page 349 of Stoft:
  - price is \$20/MWh for total demand up to 40,000 MW = 40 GW,
  - price increases with demand for demand higher than 40 GW.
- Note that market power is mostly exercised on-peak because retail obligations (or contracts covering most but not all of the peak demand) mean that only during on-peak conditions does increased price translate into increased profit.

Forward contracts and retail obligations, continued

- To see how the retail obligations have helped to keep prices down, suppose that there are again five generators, each with 10,000 MW of capacity, but without any affiliated retailers and without any forward contracts between generators and demand.
- Applying the Cournot model, we have:

$$p^{\mathrm{d}}(\sum_j Q_j^{\mathrm{e}}) - c_i'(Q_i^{\mathrm{e}}) = -\frac{\partial p^{\mathrm{d}}}{\partial Q}(\sum_j Q_j^{\mathrm{e}})Q_i^{\mathrm{e}}.$$

- Since the generators are all the same, with marginal cost \$20/MWh, the solution to the model will have a symmetric solution:

$$\sum_j Q_j^{\mathrm{e}} = 5Q_i^{\mathrm{e}}, \forall i.$$

Forward contracts and retail obligations, continued

- The demand model yields:

$$\begin{aligned} q^{\mathrm{d}}(P) &= Q_0 - (P-20)Q_0/10,000, \\ p^{\mathrm{d}}(Q) &= 10,020 - 10,000Q/Q_0, \\ \frac{\partial p^{\mathrm{d}}}{\partial Q}(Q) &= -10,000/Q_0. \end{aligned}$$

- Solving simultaneously for the resulting price P^{e}, we obtain:

$$\begin{aligned} P^{\mathrm{e}} - 20 &= (-10,000/Q_0)Q_i^{\mathrm{e}}, \\ &= (-10,000/5Q_0)(Q_0 - (P^{\mathrm{e}}-20)Q_0/10,000). \end{aligned}$$

- Solving, we find that the price is P^{e} =\$1,686/MWh for all demand levels, much higher than before:
  - This is illustrated in figure 4-4.1 of Stoft on page 349.
  - Market power is exercised all the time in this case!
  - Relatively worse “off-peak” than in homework exercise and compared to reality.

Forward contracts and retail obligations, continued

- Even in the absence of retail obligation, unaffiliated generators and retailers can still be expected to agree to some forward contracts:
  - create similar incentives to retail load obligations,
  - forward contracts hedge exposure to adverse prices,
    - high prices are bad for demand and good for generators,
    - low prices are good for demand and bad for generators,
  - forward contracts facilitate financing of new generators since bankers will typically require that the developer has a contract before lending money to the developer.
- What price should a generator ask for a forward contract?
  - the low price that is characteristic of the case of retail load obligations?
  - the high price that is characteristic of the absence of load obligations?

Forward contracts and retail obligations, continued

- Full analysis of the situation when contract prices are *endogenous* requires model of *interaction* between forward and real-time markets.
- There have been several papers discussing interaction:
  - Allaz, B. and Vila, J. L. “Cournot competition, forward markets and efficiency,” *Journal of Economic Theory*, 53(1):1–16, 1993.
  - Bushnell, J. “Oligopoly equilibria in electricity contract markets,” *Journal of Regulatory Economics*, 2007.
- Bushnell examines, for example, a Cournot model with a forward and real-time market and n “symmetric” participants.
- He finds that the Lerner index with a forward and real-time market is the same as the Lerner index in a market with *only* a real-time market, but having n^2 symmetric participants.
- That is, the effect of the possibility of signing forward contracts is to mitigate market power by increasing the *effective* number of competitors:
  - generators sign forward contracts at a price less than the price reflecting full exercise of market power,
  - even though the generators could choose not to sign contracts!

Forward contracts and retail obligations, continued

- Results in literature have only partial generality, but forward contracting (and retail obligations) have role in mitigating market power compared to case of no contracting.
- Since contracting is also desired by market participants to hedge risk and to facilitate financing of new construction, it is important to design markets to allow for contracting (that is, not actively make contracting difficult) in order to reap the benefits of both the risk mitigation and market power mitigation:
  - California market from 1998 to 2000 had limited forward contracting, which significantly contributed to the "California crisis."
  - Will discuss in context of empirical studies of California.
- Group homework does not include forward contracts nor retail obligations:
  - need to find additional reasons for why market power is exercised more on-peak than off-peak in homework.

2.4.4 Demand uncertainty

- The basic Cournot model assumes that:
  - (i) quantity can be specified by generator i to be the profit-maximizing value Q_i^e, and
  - (ii) demand function is fixed and known when offer is made.
- The first issue is not problematic, even if market rules require an offer function to be specified, assuming that the demand is fixed and known.

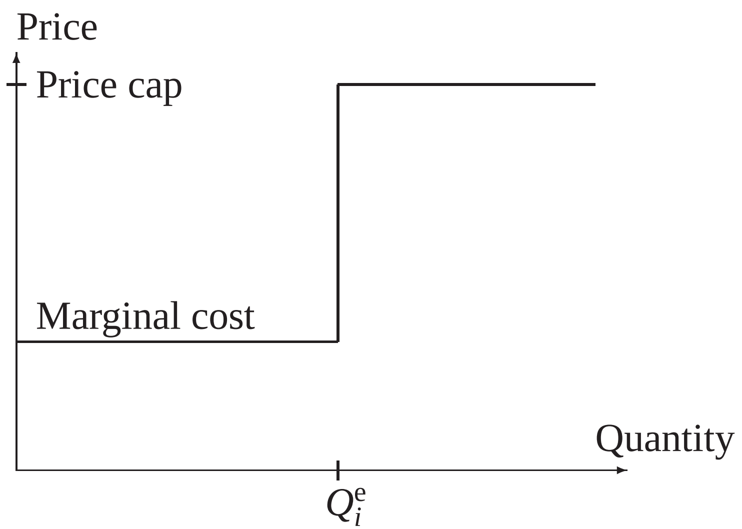

Fig. 2.6. Offer that results in fixed quantity Q being sold independent of price.

Demand uncertainty, continued

- The Cournot quantity Q_i^e that maximizes profit for generator i depends on the characteristics of demand:
  - the value of the demand parameter Q_0 in the previous example, and
  - the price responsiveness of demand.
- Even if price responsiveness of demand stays fixed, Cournot quantity will vary with Q_0.
- With demand uncertainty (or with residual demand uncertainty or if offer must be *fixed* over several pricing intervals), the strategy of offering a fixed quantity will be ineffective:
  - will not be a profit maximizing strategy for all values of demand!
- Offers into current ERCOT balancing market and into future nodal real-time market are used for multiple pricing intervals within an hour.
- In some market designs (Pennsylvania–New Jersey–Maryland (PJM), defunct England and Wales market) offers into day-ahead market must be same for all hours of day.

Demand uncertainty, continued

- Offer that has different prices for different quantities allows each participant to adapt offer to various possible demand realizations.
- Resulting offer prices will vary less abruptly (or in several jumps) rather than in one jump.

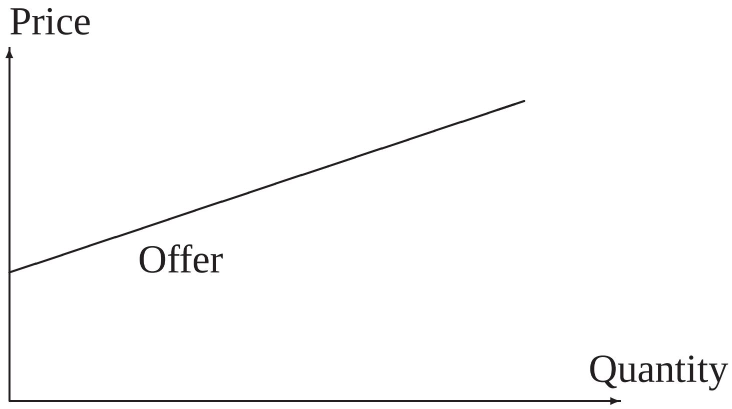

Fig. 2.7. Offer that results in smoother variation of prices.

Demand uncertainty, continued

- But if generator j, say, makes such an offer, then the variation of price with production faced by other generators will depend on both the demand and on generator j's offer.
- To consider this, we consider the residual demand faced by generator i:
  - the demand minus the supply of all the other generators besides generator i,
- Residual demand is more elastic than the actual demand.

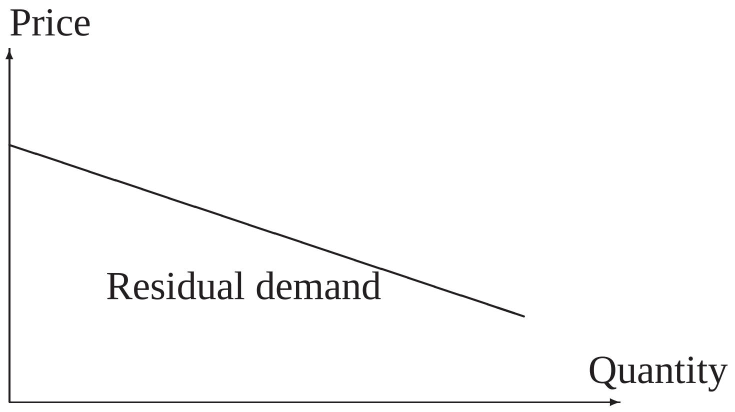

Fig. 2.8. Residual demand.

Demand uncertainty, continued

- To maximize profit, generator i behaves like a *monopolist* facing the residual demand (instead of facing the actual demand).
- But the residual demand is more elastic than the actual demand:
  - instead of other generators committing to a fixed generation level as in Cournot model, generation level of competitors will increase with market price,
  - residual demand will decrease more rapidly with price than in Cournot model.
- Generator i behaves closer to competitively when the residual demand is more elastic.
- Applying this argument symmetrically to all generators, the overall effect is to move the equilibrium prices closer to competitive levels:
  - There are a number of technicalities in such "supply function equilibrium" analysis.
  - Explore in later lectures in context of model of England and Wales market in 1990s.

Demand uncertainty, continued

- Group homework problem does not have demand uncertainty.
- However, offers were required to be functions, not quantities, and sloping portion of offer is elastic.
- So, result on competitiveness is similar in that sloping offer from other generators makes residual demand more elastic than the elasticity of demand itself:
  - vertical portion of demand curve is completely inelastic,
  - but residual demand can have some elasticity.
- At low demand:
  - many generators below capacity, so residual demand is relatively elastic due to sloping offers of many generators,
  - resulting prices relatively competitive.
- At high demand:
  - many generators at capacity, so residual demand is relatively inelastic due to sloping offers of few generators,
  - resulting prices relatively uncompetitive.

2.4.5 Fixing offers over multiple intervals

- Requiring offers to be fixed over multiple pricing intervals and in the face of uncertainty in demand (and requiring consistent offers in day-ahead and real-time markets) helps to mitigate market power.
- For example, Pennsylvania–New Jersey–Maryland (PJM) day-ahead market requires fixed offers over day (but real-time offers can vary from day-ahead, real-time offers can be different each hour, and other rules can be used to modify offers somewhat.)
- New York ISO establishes reference levels based on past offers:
  - Offers are reset if they deviate significantly from reference levels.
  - Effectively requires offers to be relatively fixed.

Fixing offers over multiple intervals, continued

- An argument against mandating fixed offers over a day is that costs may change over a day due to:

  (i) fuel cost variation, and
  (ii) temperature and pressure effects.

- However, even if fuel cost varies, the heat rate (conversion efficiency) relationship will not change, so offer could consist of:
  - fixed, or infrequently changed, heat rate-related offer, and
  - possibly varying fuel offer.
- Moreover, temperature and pressure effects can be incorporated into the offer function (and capacity) explicitly.

Fixing offers over multiple intervals, continued

- Upcoming ERCOT nodal market has no requirement for consistency across hours in day-ahead market.
- However, in ERCOT nodal:
  - if offer accepted in day-ahead, offer must stay fixed in real-time unless fuel changes or reduction in capacity occurs (section 4.4.8.3 of nodal protocols),
  - multiple pricing intervals within each hour provide demand variation in real-time market where offer is fixed for each hour,
  - uncertainty in day-ahead residual demand provides effective demand variation in each hour in day-ahead,
- Requiring consistency of offers across hours in day-ahead (unless demonstrated change in cost of generation occurs) has merit and deserves further investigation as a market power mitigation tool:
  - Will see further theoretical justification for this observation in later lectures.

2.4.6 Introducing elasticity of demand into ancillary services

- Requirements for ancillary services are typically calculated by ISO and are typically specified as fixed minimum quantities.
- For some ancillary services this is appropriate:
  - minimum spinning reserves to ensure "security" (that is, prevent any single and some double contingencies from resulting in cascading outages.)
  - minimum reactive reserves to ensure that voltage collapse does not occur (again, security-related).
- Security constraints are "hard constraints:"
  - should instigate rolling blackouts, for example, in preference to violating security,
  - so willingness-to-pay for satisfying these constraints is essentially same as or higher than value of lost load (VOLL).
- However, reserves beyond that required for security are "adequacy" related:
  - predominantly required to keep probability of rolling blackouts below acceptable levels.

Introducing elasticity of demand into ancillary services, continued

- Adequacy-related constraints are "soft" and, in principle, can be traded off with the cost of having to instigate rolling blackouts:
  - "demand" for adequacy-related reserves not inelastic,
  - marginal value, in terms of reducing probability of rolling blackouts, varies with amount of adequacy-related reserves,
  - willingness-to-pay for such reserves decreases from VOLL as the levels of reserves increase above the minimum needed for security.
- In ERCOT nodal market, section 6.5.7.3(6) of the nodal protocols originally specified that 100 MW of responsive reserves be available for dispatch in real-time to provide energy at prices that range up to price cap:
  - effectively incorporates demand curve for 100 MW of responsive reserves,
  - systematic choice of parameters to specify curve requires analysis of trade-off between reserves and the cost and probability of rolling blackouts.

Introducing elasticity of demand into ancillary services, continued

- Schematic demand curve for reserves (ignoring distinctions between classes of reserves).

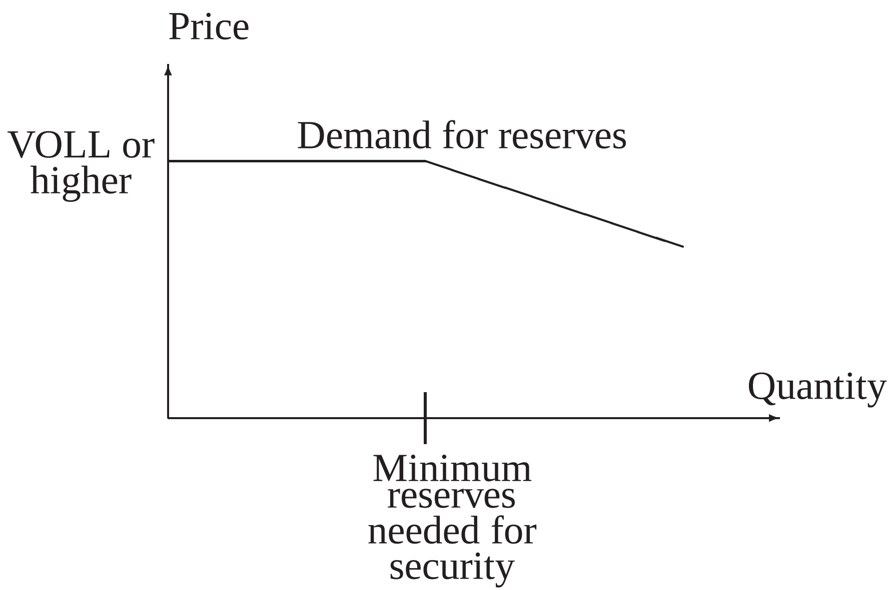

Fig. 2.9. Demand curve for reserves.

Introducing elasticity of demand into ancillary services, continued

- What is the effect on market power of elasticity of demand in ancillary services?
- Generator capacity provides for both production of energy and provision of ancillary services such as reserves.
- Specifying reserves with price elasticity would increase the elasticity of residual demand for both energy and reserves faced by generators.
- Introducing elasticity of demand into procurement of adequacy-related ancillary services therefore makes the market more competitive.
- Since ISOs in practice “sacrifice” provision of reserves when supply is tight (by under-providing reserves compared to stated requirements), reflecting this practice into the demand curve merely reflects the reality of operator action.
- Could possibly greatly increase region of elastic procurement compared to 100 MW in ERCOT nodal protocols:
  - no systematic studies justifying the particular choice of 100 MW.

Introducing elasticity of demand into ancillary services, continued

- Section 6.5.7.3(6) of the nodal protocols was removed, effectively removing the demand curve for reserves.
- The demand curve for reserves was effectively replaced by "System Change Request" 751.
- "System Change Request" 751 specifies that there will be a price on violating power balance:
  - in market clearing *software*, supply of energy less than demand for energy incurs penalty and results in higher energy prices,
  - in physical reality, expect energy to actually be served through production by generating resources otherwise committed to providing ancillary services,
  - so physical effect will be scarcity of reserves and higher energy prices,
  - effectively incorporating some elasticity of "demand" for reserves, reducing market power.

2.5 Recovering fixed costs

(i) Can high marginal costs alone recover fixed costs?
(ii) Is market power needed to recover fixed costs?
(iii) Price formation under scarcity re-visited.
(iv) Summary.

2.5.1 Can high marginal costs alone recover fixed costs?

- As well as fuel costs, generators have fixed costs such as construction costs of building capacity.
- Let us suppose that prices never happen to clear on the demand side:
  - that is, prices are always set by the highest generator offer,
  - as typically the case in the group homework.
- If offers reflect marginal costs then, whenever the offer price is below the clearing price, there will be a positive operating profit that can contribute to “paying-off” or “recovering” fixed costs.
- An offer that is below the clearing price is called an “infra-marginal” offer.
- We consider whether fixed costs can be recovered through energy sales alone when:
  - offers are based on marginal costs, but
  - prices never clear on the demand side,
  - so that clearing prices always reflect left-hand marginal costs.

Can high marginal costs alone recover fixed costs? continued

- We focus on recovery of peaker capacity cost, although similar issues apply to other technologies:
  - typical annualized peaker capacity cost is about \$75,000 per MW-year.
- In principle, if average of proceeds from energy market is enough above generator operating costs then recovery of capacity costs can occur:
  - for example, if peaker marginal cost increases very rapidly as capacity is approached then proceeds from energy market may significantly exceed operating costs,
  - key empirical question is whether or not in practice the proceeds are enough to meet annualized peaker capacity cost.
- Restructured markets in the Northeast United States have adopted an additional mechanism, a "capacity market" to provide for capital cost recovery.
- ERCOT explicitly does not and will not have a capacity market:
  - proceeds from energy (and Ancillary Services) markets (and from forward markets) are the only revenues to cover both operating and capital costs.

Can high marginal costs alone recover fixed costs? continued

- We need a simple model of marginal costs of portfolio of peakers.
- Capture assumption of high marginal costs when operating close to capacity.

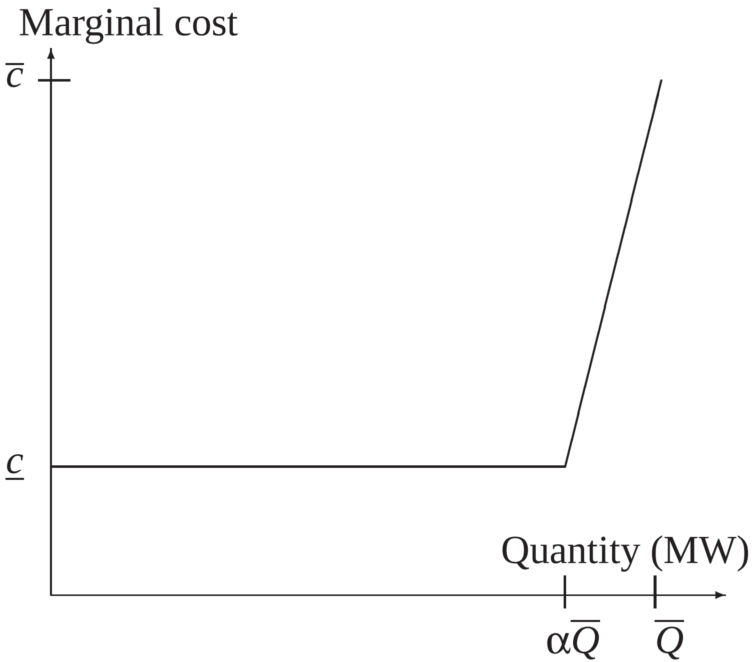

Fig. 2.10. Model of peaker marginal cost. Total capacity is $\overline{Q}$, of which $\alpha\overline{Q}$ operates at marginal cost $\underline{c}$. The last $(1-\alpha)\overline{Q}$ of capacity has a marginal cost linearly varying from $\underline{c}$ to $\overline{c}$.

Can high marginal costs alone recover fixed costs? continued

- Assumptions of simple model of peaker:
  - total peaker capacity of $\overline{Q}$,
  - For generation Q between 0 and $\alpha\overline{Q}$, peaker marginal cost is $\underline{c}$.
  - For generation Q between $\alpha\overline{Q}$ and $\overline{Q}$, peaker marginal cost increases linearly from $\underline{c}$ to $\overline{c}$:

$$\underline{c} + \frac{Q - \alpha\overline{Q}}{\overline{Q} - \alpha\overline{Q}}(\overline{c} - \underline{c}),$$

  - Qualitative results will not depend on specific assumption of the way in which marginal costs vary.
  - Peaker operating cost (integral of marginal costs) are:

$$\begin{array}{rl} Q\underline{c}, & \text{if } \; 0 \leq Q \leq \alpha\overline{Q}, \\ Q\underline{c} + \frac{1}{2}\frac{(Q - \alpha\overline{Q})^2}{\overline{Q} - \alpha\overline{Q}}(\overline{c} - \underline{c}), & \text{if } \; \alpha\overline{Q} \leq Q \leq \overline{Q}, \end{array}$$

  - peakers supply the "top" $\overline{Q}$ MW of demand and set price during this period.

Can high marginal costs alone recover fixed costs? continued

- Assumptions about demand:
  - total capacity is just sufficient to meet peak demand $\overline{D}$,
  - probability distribution of demand D is such that "top" $\overline{Q}$ of demand, from $(\overline{D}-\overline{Q})$ to $\overline{D}$ occurs during T hours in year,
  - conditioned on demand being in range from $(\overline{D}-\overline{Q})$ to $\overline{D}$, distribution of demand is uniform.
- Therefore, supply of peakers will occur for T hours in year and generation during these T hours is uniformly distributed between 0 and $\overline{Q}$.
- Price will equal marginal cost during these hours and range from $\underline{c}$ to $\overline{c}$.

Can high marginal costs alone recover fixed costs? continued

- Consider distribution of prices and profits over "top" T hours in year.
- For simplicity, re-order chronology of these hours so that:
  - at time $t = 0$:
    - demand is equal to peak minus $\overline{Q}$,
    - peakers supply 0,
    - marginal cost and clearing price is $\underline{c}$,
  - at time $t = T$:
    - demand is equal to peak,
    - peakers supply $\overline{Q}$,
    - marginal cost and clearing price is $\overline{c}$,
  - at time t:
    - peakers supply $Q = t\overline{Q}/T$
    - marginal cost and clearing price is:

$$\begin{array}{ll} \underline{c}, & \text{if } \; 0 \leq t \leq \alpha T, \\ \underline{c} + \dfrac{Q - \alpha\overline{Q}}{\overline{Q} - \alpha\overline{Q}}(\overline{c} - \underline{c}) = \underline{c} + \dfrac{t/T - \alpha}{1 - \alpha}(\overline{c} - \underline{c}), & \text{if } \; \alpha T \leq t \leq T. \end{array}$$

Can high marginal costs alone recover fixed costs? continued

- When $0 \leq t \leq \alpha T$, revenue per unit time is equal to operating costs, and no contribution is made to operating profit:
  - if marginal costs increase somewhat with production when Q is between 0 and $\alpha\overline{Q}$ then there would be some contribution to operating profit when $0 \leq t \leq \alpha T$,
  - qualitative results would be similar even if marginal costs vary with production when Q is between 0 and $\alpha\overline{Q}$.
- For $\alpha T \leq t \leq T$, $Q = t\overline{Q}/T$ and revenue per unit time exceeds operating costs:

$$\begin{aligned}
\text{revenue per unit time} &= \frac{t}{T}\overline{Q}\left(\underline{c} + \frac{t/T - \alpha}{1-\alpha}(\overline{c} - \underline{c})\right), \\
\text{operating costs} &= \frac{t}{T}\overline{Q}\underline{c} + \frac{1}{2}\overline{Q}\frac{(t/T - \alpha)^2}{1-\alpha}(\overline{c} - \underline{c}).
\end{aligned}$$

Can high marginal costs alone recover fixed costs? continued

- Subtracting operating costs from revenue per unit time and dividing by $\overline{Q}$, for $\alpha T \leq t \leq T$, operating profit per MW capacity per unit time is:

$$\text{operating profit}(t) = \frac{1}{2}\frac{(t/T)^2 - (\alpha)^2}{1-\alpha}(\overline{c} - \underline{c}).$$

- Integrating operating profit per MW capacity per unit time over the time when the peakers are generating yields the annual operating profit:

$$
\begin{aligned}
\int_{t=0}^{T} \text{operating profit}(t)\,dt &= \int_{t=0}^{\alpha T} 0\,dt + \int_{t=\alpha T}^{T} \frac{1}{2}\frac{(t/T)^2-(\alpha)^2}{1-\alpha}(\overline{c}-\underline{c})\,dt, \\
&= \frac{1}{2}\frac{(\overline{c}-\underline{c})}{1-\alpha}\int_{t=\alpha T}^{T} \frac{(t)^2}{(T)^2}-(\alpha)^2\,dt, \\
&= \frac{1}{2}\frac{(\overline{c}-\underline{c})}{1-\alpha}\left[\frac{(t)^3}{3(T)^2}-t(\alpha)^2\right]_{t=\alpha T}^{T}, \\
&= \frac{1}{2}\frac{(\overline{c}-\underline{c})}{1-\alpha}\left[\frac{(T)^3}{3(T)^2}-\frac{(\alpha T)^3}{3(T)^2}-T(\alpha)^2+\alpha T(\alpha)^2\right], \\
&= \frac{1}{2}\frac{(\overline{c}-\underline{c})}{1-\alpha}\left[\frac{T}{3}(1-(\alpha)^3)-T(\alpha^2)(1-\alpha)\right], \\
&= \frac{1}{2}\frac{(\overline{c}-\underline{c})}{1-\alpha}T(1-\alpha)\left[\frac{1}{3}(1+\alpha+(\alpha)^2)-(\alpha)^2\right].
\end{aligned}
$$

Can high marginal costs alone recover fixed costs? continued

- Therefore:

$$\begin{aligned}
\text{annual operating profit} &= \int_{t=0}^{T} \text{operating profit}(t)\, dt, \\
&= \frac{(\overline{c} - \underline{c})T}{2} \left[\frac{1}{3} + \frac{1}{3}\alpha - \frac{2}{3}(\alpha)^2 \right].
\end{aligned}$$

- Annual operating profit increases with $(\overline{c} - \underline{c})$ and with T.
- Note that different assumptions about variation of marginal costs would result in somewhat different function of α.
- Annual operating profit would still increase with $(\overline{c} - \underline{c})$ and with T.

Can high marginal costs alone recover fixed costs? continued

- Under what conditions does annual operating profit cover annualized peaker capacity cost?

$$\frac{(\overline{c}-\underline{c})T}{2}\left[\frac{1}{3}+\frac{1}{3}\alpha-\frac{2}{3}(\alpha)^2\right] \geq \text{\$75,000 per MW-year.}$$

- To cover annualized peaker capacity cost, want terms on left-hand side as large as possible.
- That is, want marginal cost term $\overline{c}-\underline{c}$ as large as possible and want term involving parameter α as large as possible.
- Marginal costs:
  - Assume that $\overline{c}$ is less than the \$2,250/MWh offer cap in place in ERCOT, since this is meant to be a loose upper bound on marginal costs.
  - Note that $\overline{c}-\underline{c}<\overline{c}$, but the difference between $\overline{c}-\underline{c}$ and $\overline{c}$ is small if $\overline{c}\approx$\$2,250/MWh,
  - We assume $(\overline{c}-\underline{c})\approx$\$2,250/MWh.

Can high marginal costs alone recover fixed costs? continued

- Parameter α:
  - The function $\frac{1}{3} + \frac{1}{3}\alpha - \frac{2}{3}(\alpha)^2$ is quadratic and concave in α,
  - Setting its derivative equal to zero yields the maximizer:

$$0 = \frac{1}{3} - \frac{4}{3}\alpha,$$

  - so $\alpha = (1/4)$ ("high" marginal costs for 3/4 of peaker operating range), and

$$\begin{aligned} \frac{1}{3} + \frac{1}{3}\alpha - \frac{2}{3}(\alpha)^2 &= \frac{1}{3} + \frac{1}{12} - \frac{2}{48}, \\ &= \frac{3}{8}. \end{aligned}$$

Can high marginal costs alone recover fixed costs? continued

- What are implications for duration of peaker operation T in order for annual operating profit to cover annualized peaker capacity cost?
- Re-arranging condition on annual operating profit, we obtain:

$$\begin{aligned} T &\geq \frac{2 \times (\$75{,}000 \text{ per MW-year})}{(\overline{c} - \underline{c})\left[\frac{1}{3} + \frac{1}{3}\alpha - \frac{2}{3}(\alpha)^2\right]}, \\ &\geq \frac{2 \times (\$75{,}000 \text{ per MW-year})}{(\$3{,}000/\text{MWh})\frac{3}{8}}, \\ &\approx 133 \text{ hours}. \end{aligned}$$

- Top 133 hours of demand corresponds to very roughly 5,000 MW to 6,000 MW of capacity in ERCOT, which is not unreasonable as a ballpark value of what would be considered "peaking" capacity.
- Given our choices of $(\overline{c} - \underline{c})$ and of α, it would be possible for peakers to recover annualized capacity cost from operating profit alone.

Can high marginal costs alone recover fixed costs? continued

- However, the choices of $(\overline{c} - \underline{c})$ and of α are not realistic!
- Marginal costs:
  - the high marginal cost $\overline{c}$ is unlikely to be an order of magnitude above $\underline{c}$,
  - for example, marginal costs of operation such as "duct firing" are only tens of percent higher than normal operation,
  - more reasonable would be $\overline{c} \leq$\$500/MWh and $\underline{c} \approx$\$100/MWh,
- Amount of capacity that corresponds to region of high marginal cost may only be a few percent of total peaker capacity:
  - More reasonable value for α is $\alpha \geq 0.9$.

Can high marginal costs alone recover fixed costs? continued

- Using more reasonable figures:

$$\begin{aligned} T &\geq \frac{2 \times (\$75{,}000 \text{ per MW-year})}{(\overline{c} - \underline{c}) \left[\frac{1}{3} + \frac{1}{3}\alpha - \frac{2}{3}(\alpha)^2\right]}, \\ &\geq \frac{2 \times \ \$75{,}000 \text{ per MW-year}}{(\$400/\text{MWh}) \times 0.0933}, \\ &\approx 4000 \text{ hours}, \end{aligned}$$

- which is just under half of the year:
  - implying peaker capacity is tens of thousands of MW,
  - and with peakers in high marginal cost operation for around 400 hours per year.
- This is probably unreasonable since intermediate generation would be marginal for some of these 4000 hours per year:
  - in ERCOT today, combined-cycle is marginal for well over half the year.

Can high marginal costs alone recover fixed costs? continued

- Conclusion:
  - in principle, high marginal costs allow for recovery of peaker capacity cost,
  - however, realistic values are not apparently consistent with recovery of peaker capacity cost.
- Using realistic values, competitive entry of new peakers *can never be* profitable based on offers equaling left-hand marginal cost, independent of demand distribution and independent of installed capacity, *even if peakers were needed*:
  - at least some peaker investment can be expected to be part of an optimal expansion portfolio for ERCOT,
  - therefore, we need a mechanism that can set prices above left-hand marginal costs in order that annual operating profit exceeds annualized peaker capacity cost to make peaker investment profitable when such investment is needed for the system.

Can high marginal costs alone recover fixed costs? continued

- Even though peakers cannot be profitable, other technologies, such as baseload, can possibly be profitable based on offers equaling left-hand marginal cost:
  - for example, in current ERCOT market, combined cycle is marginal for most of year, so new baseload coal entry could potentially be profitable now given distribution of demand and distribution of installed capacity,
  - given distortion of incentives for peakers, incentives for baseload may also be distorted.
- General conclusion, however, is that high marginal costs alone cannot recover fixed costs for all generation needed:
  - need additional revenue to recover fixed costs.

2.5.2 Is market power needed to recover fixed costs?

- Given that offers based on high marginal costs alone are not enough to recover capacity cost of peaking generation, it is sometimes argued that market power is necessary in order for generators to recover their fixed costs:
  - PUCT rules specifying "scarcity pricing mechanism" explicitly allow market participants with less than 5% of total installed capacity to exercise market power in order for prices to raise above marginal.
  - Allows for recovery of capacity costs, but also allows for "thick hockey stick" offers differing from marginal can spoil economic dispatch.
  - High prices have been tolerated in ERCOT recently.
  - Such high prices are only imperfectly correlated with needs for new peaker capacity and are therefore unlikely to bring forth appropriate levels of peaker investment.

Is market power needed to recover fixed costs? continued

- However, if correctly defined, the competitive price is occasionally above the left-hand marginal costs of all generators:
  - need pricing rules (and, possibly, explicit demand bids) to ensure that competitive prices are realized,
  - somewhat problematic in nodal ERCOT market because there are no explicit demand bids in real-time and no mechanism (currently) for the ISO to reflect observed elasticity of demand for energy into the market clearing process!
  - demand curve for reserves/system change request 751 provide mechanisms for price to be set above left-hand marginal costs when supply is exhausted.

Is market power needed to recover fixed costs? continued

- Given competitive prices, fixed costs can be recovered without market power.
- But getting competitive prices in electricity markets is not straightforward as the discussion of ERCOT indicates.
- Stoft identifies two basic impediments to functioning of electricity markets, which he calls "demand-side flaws:"

  (i) little or no real-time metering and real-time billing, and
  (ii) little or no real-time control to specific customers.

- The first flaw means that there is little price elasticity:
  - The market-design choice to charge retail residential customers by default an average price based on an assumed demand profile means that they will not exhibit (significant) price elasticity because they are not exposed to the true variation in prices.
  - When real-time meters are fully deployed and if profiling is abolished, this flaw will be removed.
- In the absence of enough price elasticity, there may literally be no intersection of demand and supply curves.

Is market power needed to recover fixed costs? continued

- The second flaw means that there is no way to enforce forward contractual obligations, so that the ISO is responsible for:
  - meeting demand in real-time, if possible, or
  - curtailing otherwise when demand and supply do not intersect.
- Under curtailment, the ISO must set the price:
  - in principle, should be set to VOLL, but
  - without explicit bidding there is no market-based way to elicit VOLL, necessitating administrative setting of proxy to VOLL.
- If there is not enough elasticity of demand then competitive price is either:
  - highest generation offer, typically no more than $300/MWh, or
  - VOLL, around $3000/MWh or more.
- That is, prices will tend to either reflect left-hand marginal costs or VOLL, jumping between the two depending whether or not curtailment occurs.
- Administrative valuation of VOLL will then effectively determine level of generation entry that is profitable and hence implicitly determine level of adequacy of system.

2.5.3 *Price formation under scarcity re-visited*

- In the absence of market power, offers will reflect marginal prices.
- To be profitable, prices must occasionally rise above the (left-hand) marginal costs of all generators.
- How would price ever be set above the left-hand marginal cost of the highest cost generator?
  - demand bids for energy,
  - demand curve for reserves,
  - administrative mechanism or rule,
  - offers based on right-hand marginal costs,
  - market power.
- If there is explicit demand-side bidding for purchase of energy then, when supply is tight, demand willingness-to-pay will set the market clearing price and this should be used to set the price in the market.
- As we have discussed, there is no demand-side bidding by market participants for real-time energy in the ERCOT nodal design.

Price formation under scarcity re-visited, continued

- How about the effect of demand for reserves?
  - By introducing elasticity of demand into reserves, prices for both energy and reserves could rise above the highest supply offer.
- With the removal of the demand curve for reserves from the Protocols there is no *explicit* mechanism for price to rise above offers due to scarcity of reserves.
- But System Change Request 751 will result in increased prices for energy whenever reserves are used to restore power balance:
  - administrative rule will result in implicit mechanism for price to rise above offer due to scarcity.

Price formation under scarcity re-visited, continued

- "Thin hockey stick" offers that reflect right-hand marginal costs would also allow for prices to rise above left-hand marginal costs:
  - As noted previously, in absence of demand bids, still do not provide for determination of competitive prices.
- Current protocols allow such offers by some small market participants.
- However, current rules actually allow for "thick hockey stick" offers by these participants, allowing for exercise of market power by small market participants:
  - unlikely to lead to optimal capital formation.

2.5.4 Summary

- There are several mechanisms to allow for recovery of fixed costs.
- Mechanisms that rely on exercise of market power are unlikely encourage an optimal amount of generation capacity.
- Demand side participation in the market to occasionally set the price under tight supply or scarcity conditions is ultimately the only mechanism that can provide signals to generator developers about what capacity is really needed:
  - demand price response has dual role of helping to mitigate market power and signalling needs for new generation capacity,
  - electricity markets today, including ERCOT, do not have a significant amount of price based demand response.
- Ongoing need to develop and encourage more active participation in market by demand.

2.6 Predicting market power

(i) Factors that HHI ignores,

(ii) The Lerner index is unreliable.

2.6.1 Factors that HHI ignores

(i) Demand elasticity,
(ii) The style of competition,
(iii) Forward contracting,
(iv) Geographical extent of market.

2.6.1.1 Demand elasticity

- By itself, HHI is a poor predictor of market power:
  - HHI does not include any representation of demand elasticity,
  - but even in the simple Cournot model need demand elasticity to predict Lerner index.
- Moreover, even combining HHI with demand elasticity to obtain the estimated Lerner index is a poor predictor of market power:
  - typical realistic demand elasticity would imply prices that are very high all the time as in the five generator example.
  - will also see this in the context of empirical studies.
- HHI ignores demand elasticity and several other issues:
  - for example, forward contracting, retail obligations, uncertainty of demand, and the form of the offer functions.
- HHI is not a useful quantitative measure of market power since it ignores issues that are very important in determining price.

2.6.1.2 The style of competition

- The Cournot model is an abstraction that literally does not model the flexibility in offers.
- To respond to variation in demand, offers will not arrange for fixed quantity independent of price, but will contribute to residual demand elasticity seen by other market participants.
- Appropriate model of style of competition should recognize such issues.
- In later lectures we will discuss more complete modelling of the style of competition.

2.6.1.3 Forward contracting

- Forward contracting changes the incentives to exercise market power.
- For example, if a generator has forward contracted *all* of its capacity then it has no short-term incentive to raise prices.
- In other cases, the extent of forward contracting will determine incentives:
  - In the retail obligation example, four out of five generators had retail obligations (similar in effect to forward contracts) that accounted for all their capacity, but the total capacity of the four generators was not enough to meet their peak demand.
  - If a generator forward contracts for *more* than its (available) capacity (or its net position including retail obligations is that it must buy energy from the market) then it prefers to *decrease* the market price since it has to buy at the market price and must sell at the forward price.

Forward contracting, continued

- Suppose that generator i has a forward contract for quantity Q_i^{f} at a price P_i^{f} as in the retail obligation example.
- Suppose that in addition to the forward contract, the generator also participates in the real-time market:
  - "mechanics" of this involve a "contract for differences," but this does not concern us here.
- Profit depends on what it has sold forward at the forward price and what, in addition (the "deviation" from the forward position), it sells in real-time at the real-time price:
  - Similar issues apply if it participates in the day-ahead market, but we will ignore this for simplicity.

Forward contracting, continued

- Let Q_i be the total sold in real-time, of which:
  - the quantity Q_i^{f} is the forward commitment paid at the price P_i^{f}, and
  - the quantity $(Q_i - Q_i^{\mathrm{f}})$, the deviation from the forward position, is paid at the real-time price.
- The "short-run" profit (per hour) in any pricing interval for generator i is:

$$\pi_i(Q_i, Q_{-i}) = P_i^{\mathrm{f}} Q_i^{\mathrm{f}} + p^{\mathrm{d}}\left(\sum_j Q_j\right)(Q_i - Q_i^{\mathrm{f}}) - c_i(Q_i).$$

- To find quantity Q_i^{e} that maximizes profit π_i for each generator i, set derivative of π_i with respect to Q_i equal to zero:

$$\begin{aligned} 0 &= \frac{\partial \pi_i}{\partial Q_i}(Q_i^{\mathrm{e}}, Q_{-i}^{\mathrm{e}}), \\ &= \frac{\partial p^{\mathrm{d}}}{\partial Q}\left(\sum_j Q_j^{\mathrm{e}}\right)(Q_i^{\mathrm{e}} - Q_i^{\mathrm{f}}) + p^{\mathrm{d}}\left(\sum_j Q_j^{\mathrm{e}}\right) - c_i'(Q_i^{\mathrm{e}}). \end{aligned}$$

- We will assume that sufficient conditions hold for this condition to characterize profit maximization.

- Re-arranging, we obtain:

$$\begin{aligned}
p^{\mathrm{d}}\Big(\sum_j Q_j^{\mathrm{e}}\Big) - c_i'(Q_i^{\mathrm{e}}) &= -\frac{\partial p^{\mathrm{d}}}{\partial Q}\Big(\sum_j Q_j^{\mathrm{e}}\Big)(Q_i^{\mathrm{e}} - Q_i^{\mathrm{f}}), \\
\frac{p^{\mathrm{d}}(\sum_j Q_j^{\mathrm{e}}) - c_i'(Q_i^{\mathrm{e}})}{p^{\mathrm{d}}(\sum_j Q_j^{\mathrm{e}})} &= -\frac{\partial p^{\mathrm{d}}}{\partial Q}\Big(\sum_j Q_j^{\mathrm{e}}\Big)\frac{(Q_i^{\mathrm{e}} - Q_i^{\mathrm{f}})}{p^{\mathrm{d}}(\sum_j Q_j^{\mathrm{e}})}, \\
&= \frac{1}{e}\frac{(Q_i^{\mathrm{e}} - Q_i^{\mathrm{f}})}{\sum_j Q_j^{\mathrm{e}}}.
\end{aligned}$$

- Defining $s_i^{\text{uncontracted}} = (Q_i^{\mathrm{e}} - Q_i^{\mathrm{f}})/\sum_j Q_j^{\mathrm{e}}$, the uncontracted production as a fraction of total production, we can write $L_i = s_i^{\text{uncontracted}}/e$.
- Note that since $s_i^{\text{uncontracted}} \leq s_i$, when there is forward contracting the Lerner index will be smaller.
- If $Q_i^{\mathrm{f}} > Q_i^{\mathrm{e}}$ then the Lerner index would be negative and profit maximizing behavior would be to offer below marginal cost:
  – as net purchaser, i would prefer to depress price in this case!

Forward contracting, continued

- The HHI ignores the issue of forward contracting.
- However, a simple modification (considering the uncontracted production as a fraction of total production) enables consideration of forward contracts.
- Extent of forward contracting is not necessarily public information, except in some cases:
  - in case of retail obligations, generator has implicitly forward contracted for retail obligation.
- Moreover, decisions about levels of forward contracting are endogenous, as analyzed in papers by Allaz and Vila and by Bushnell.
- As indicated earlier, results on effect of endogenous contracting are not known in full generality.

2.6.1.4 *Geographical extent of market*

- Transmission constraints make determination of geographical extent of market essential:
  - ERCOT-wide HHI is fairly small, but
  - Dallas–Forth Worth HHI is large, and transmission constraints limit the ability of generators outside of DFW to compete to sell in DFW.
- Effect of transmission constraints varies with demand and patterns of generation.
- We will discuss this effect in more detail in later lectures.

2.6.2 *The Lerner index is unreliable*

- The HHI enables a useful estimate of the Lerner index if:
  - demand elasticity is known,
  - the style of competition is Cournot,
  - forward contracts are known, and
  - the market participants were all located at one bus (or if no transmission constraints are binding).
- Even if these requirements are met, the Lerner index and the price mark-up may not be a useful index of market power because marginal cost can vary.
- Stoft argues that a better measure is the price distortion, $\Delta P_{\text{distort}}$, the deviation of market price from competitive price.
- Requires estimation of competitive price, which requires knowledge of costs and understanding of constraints on operation.
- Recall that calculating the Lerner index "only" required knowledge of market shares, extent of forward contracting, and (residual) demand elasticity.

The Lerner index is unreliable, continued

- It is difficult to estimate absolute measures of market power, such as price distortion, without considerable data.
- Such data may be available, but is likely to be only approximate and subject to debate:
  - We will see an example of this in discussion of high prices in California market during “California crisis.”
- Furthermore, design errors in the market can contribute to price distortion but may not be represented in the model:
  - we will discuss a framework for untangling design errors from market power in the context of an ERCOT case study.
- However, the effect of *change* in market structure may be well estimated even if absolute measure is not accurate:
  - “qualitative sensitivity analysis.”
  - See in more detail in context of equilibrium models.

2.7 Monitoring market power

(i) Regulatory versus economic,

(ii) Can we measure market power?

2.7.1 Regulatory versus economic

- Regulators typically qualify the definition of market power by defining market power as the ability to profitably change prices from competitive for *significant* periods of time.
- This is fine, in principle, but then need a definition of significant!
- As previously discussed, requires explicit policy consideration, including costs of mitigating market power.

2.7.2 Can we measure market power?

- High prices do not, by themselves, imply market power:
  - prices *should* be above left-hand marginal cost when demand or reserves are curtailed in order to reflect a market clearing price.
- However, market power can result in high prices!
  - Conditions close to curtailment are precisely the conditions where withholding is likely to be most profitable.
- Distinguishing market power from high competitive prices requires observing *withholding*.
- In particular, if the market price is above the right-hand marginal cost of a generator then the generator is withholding.

Can we measure market power? continued

- For example, consider a gas turbine of capacity 10 MW with marginal costs on the order of \$65/MWh for generation up to 10 MW and very high or infinite marginal costs for generation above 10 MW.
- If the market price is \$400/MWh and the gas turbine is not generating then it is withholding.
- If the withholding is profitable (in expectation) then the generator has exercised market power.

2.8 Summary

(i) Defining market power,
(ii) Exercising market power,
(iii) Modeling market power,
(iv) Designing to reduce market power,
(v) Recovering fixed costs,
(vi) Predicting market power,
(vii) Monitoring market power.

Homework exercise: Due Tuesday, March 9 at beginning of class

- Suppose the market is a "symmetric duopoly" with each firm $i = 1, 2$ having marginal cost function:

$$\forall Q_i, c_i'(Q_i) = 20 + 60Q_i/2500.$$

- Operating range $[0, \overline{Q}_i]$, where $\overline{Q}_i = 2500$ MW.
- Consider the following inverse demand functions:

$$\text{(i) } \forall Q, p^{\mathrm{d}}(Q) = \max\{50 - (Q - 2800)/2, 0\},$$
$$\text{(ii) } \forall Q, p^{\mathrm{d}}(Q) = \max\{75 - (Q - 3500)/2, 0\},$$
$$\text{(iii) } \forall Q, p^{\mathrm{d}}(Q) = \max\{500 - (Q - 4200)/2, 0\},$$

- where Q is in MW and $p^{\mathrm{d}}(Q)$ is in \$/MWh.
- Note that these inverse demands are qualitatively similar to the inverse residual demands faced in the group homework exercises.

Homework exercise: Due Thursday, March 9 at beginning of class

- For each inverse demand function, apply the Cournot model to find the predicted prices and quantities:
  - Cournot means that each firm maximizes profit, given the assumption that the other firm has committed to a fixed production.
  - Assume that there are no forward contracts.
  - The inverse demand is linear in quantity, which does not correspond to a fixed elasticity.
  - However, you can still write down the profit π_i of firm i as a function of firm i's quantity Q_i and find the maximum.

Homework exercise: Due Tuesday, March 9, by 10pm

- The recent group homeworks show that for the two lowest demand conditions, prices are close to competitive:
  - competition between market participants keeps prices close to competitive during the two lowest demand conditions,
  - from now onwards, we will focus on the peak demand condition only,
  - ignore offers for two lowest demand conditions.
- Homework assumed that peak demand level was known:
  - in fact, demand is uncertain and there may be multiple pricing periods over which demand changes but offers are fixed,
  - we will consider how this affects the competitiveness of the market.
- Suppose that the cost functions for the last homework exercise stayed exactly the same.

Homework exercise: Due Tuesday, March 9, by 10pm

- Suppose that the offer for peak demand will be used to clear market for three peak pricing periods with demand:
  - 4150 MW,
  - 4200 MW, and
  - 4250 MW.
- That is, one offer will be used for each of three pricing periods:
  - assume equal duration.
- Competitive price for these three demand levels is $80/MWh.
- Recent clearing prices for meeting a single period demand of 4200 MW have been between $450/MWh and $500/MWh.
- This homework will investigate what happens when your offers must remain valid for a range of demand levels.
- Update your offers for the peak demand period to try to improve your profits compared to your previous offers:
  - submit offers for all periods, but off-peak offers will be ignored.

Homework exercise: Due Sunday, March 21, by 10pm

- In most recent group homework, even with demand variation, the resulting clearing prices are high because firms 1 and 2 are *pivotal*:
  - Group 1 offered capacity at $500/MWh and at least some of its offer had to be used to meet demand.
- Suppose that the offer for peak demand will again be used to clear market for three peak pricing periods with demand:
  - 4150 MW,
  - 4200 MW, and
  - 4250 MW.
- That is, one offer will be used for each of three pricing periods:
  - assume equal duration.
- Suppose that the cost functions for the last homework exercise stayed exactly the same.

Homework exercise: Due Sunday, March 21, by 10pm

- However, instead of a fixed willingness-to-pay, the “top” 400 MW of demand in each period will be price responsive, with willingness-to-pay varying linearly from \$500/MWh down to \$100/MWh.
- Competitive price for the three demand levels is still \$80/MWh:
  - so, less than 10% of demand is price responsive, and
  - price responsive demand accounts for less than capacity of largest firm.
- Update your offers for the peak demand period to try to improve your profits compared to your previous offers:
  - submit offers for all periods, but off-peak offers will be ignored.

Homework exercise: Due Tuesday, March 30 at beginning of class

- Suppose "symmetric duopoly" with each firm $i = 1, 2$ having marginal cost function:

$$\forall Q_i, c_i'(Q_i) = 20 + 60Q_i/2500.$$

- Operating range $[0, \overline{Q}_i]$, where $\overline{Q}_i = 2500$ MW.
- Consider the following inverse demand functions:

$$\begin{aligned}
\text{(i) } \forall Q, p^{\mathrm{d}}(Q) &= \max\{50 - (Q - 2800)/20, 0\}, \\
\text{(ii) } \forall Q, p^{\mathrm{d}}(Q) &= \max\{75 - (Q - 3500)/20, 0\}, \\
\text{(iii) } \forall Q, p^{\mathrm{d}}(Q) &= \max\{500 - (Q - 4200)/20, 0\},
\end{aligned}$$

- where Q is in MW and $p^{\mathrm{d}}(Q)$ is in \$/MWh.
- Note that demand is more elastic than in previous version of this exercise!
- For each inverse demand function, apply the Cournot model to find the predicted prices and quantities.

Homework exercise: Due Tuesday, March 30, by 10pm

- Again, suppose that the offer for peak demand will be used to clear market for three peak pricing periods with demand:
  - 4150 MW,
  - 4200 MW, and
  - 4250 MW.
- That is, one offer will be used for each of three pricing periods.
- Suppose that the cost functions for the last homework exercise stayed exactly the same.
- Again assume that the "top" 400 MW of demand in each period will be price responsive, with willingness-to-pay varying linearly from $500/MWh down to $100/MWh.
- Update your offers for the peak demand period to try to improve your profits compared to your previous offers:
  - submit offers for all periods, but off-peak offers will be ignored.