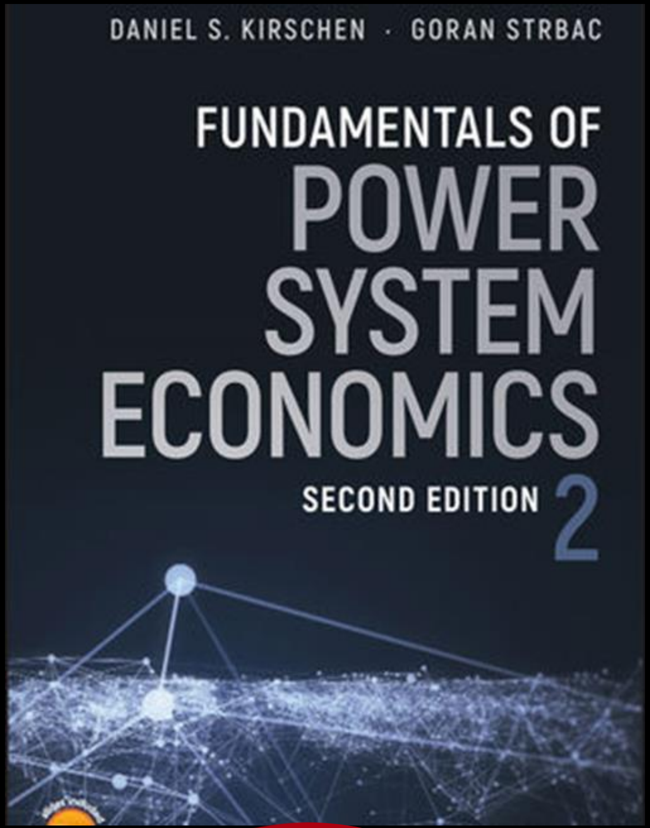
DR. ABEER ALMAIMOUNI

Participating in electricity markets

Disclaimer

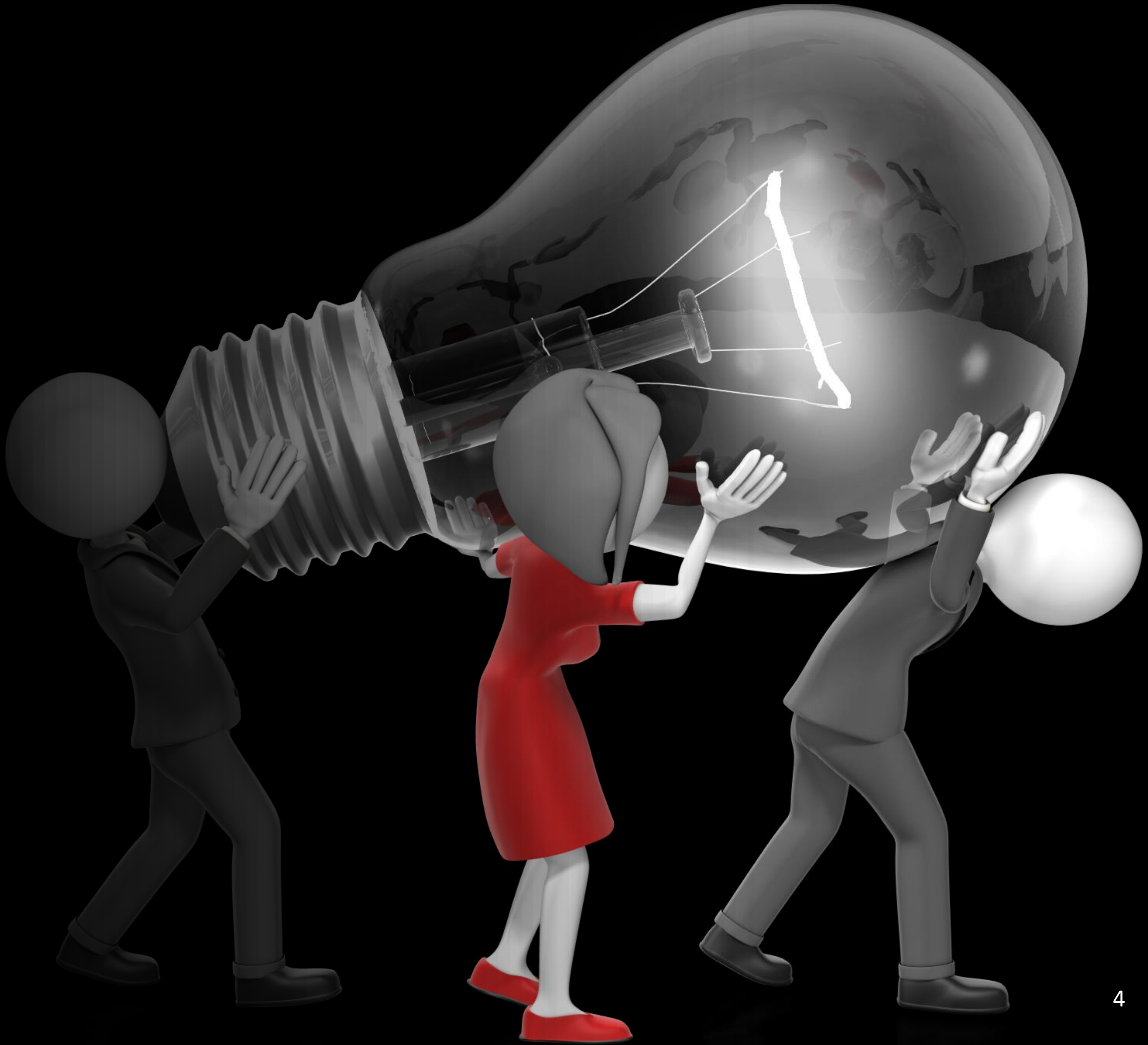
These slides were designed by Dr. Abeer Almaimouni and were used while teaching the course of Power System Economics at Kuwait University. Unless it is specified on individual slides, the content, graphs, and numerical examples were based on the book of Prof. Daniel Kirschen and Goran Strbac, Fundamentals of Power System Economics, or the slides that Prof. Kirschen used while teaching the course at the University of Washington. In many places, a direct quotation was made from either his slides or book.



Participating in Electricity Markets

- The consumer’s perspective
- The retailer’s perspective
- The producer’s perspective
- Perspective of plants that do not burn fossil fuels
- The storage owner’s perspective
- The flexible consumer’s perspective
- The neighbor’s perspective
- An overall Perspective

The Consumer's Perspective



The Consumer’s Perspective

- Customers pay a flat rate for each kilowatt-hour that they consume.
- They are insulated from the spot price of electricity, i.e. they are passive.
- Their demand is affected only by their activities.
- Averaged over a few weeks or months, their demand reflects only their willingness to pay this flat rate.
- The price elasticity of the demand for electricity is small.
- The slope of the demand curve is therefore very steep.
- Determining the shape of the demand curve is practically impossible for a commodity such as electrical energy.

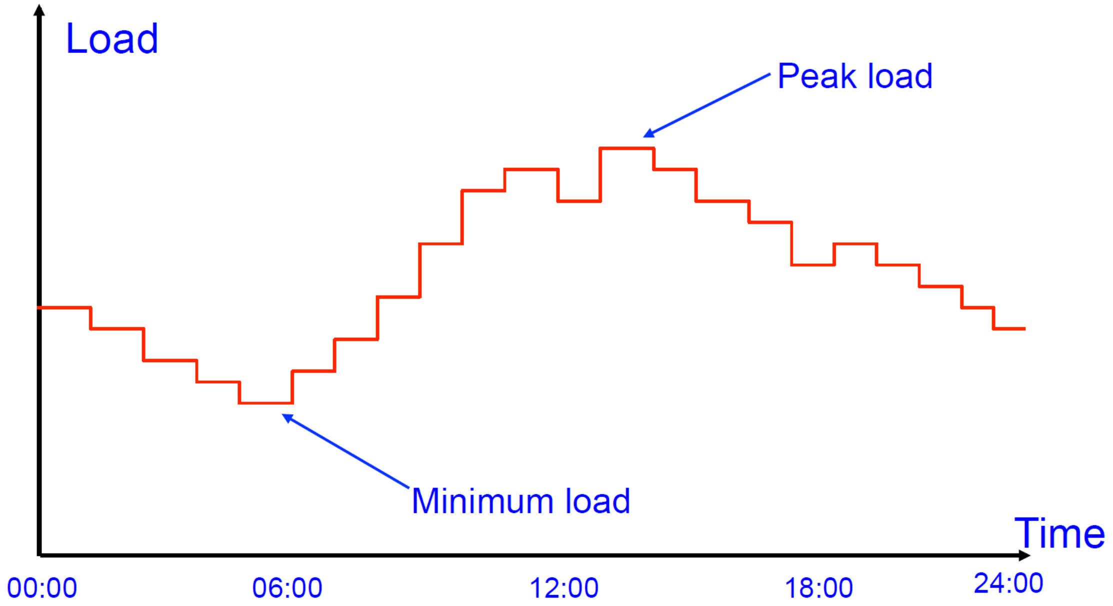
The Consumer's Perspective

The low elasticity of electricity

- The cost of electrical energy represents only a small fraction of the cost of living for most households.
- Historically, electricity has been marketed as a commodity that is easy to use and always available.
  - Very few people carry out a cost/ benefit analysis each time they turn on the light!
  - Consumers shift their demand instead of reducing it.
- Most small residential and commercial consumers are not interested in being charged on the basis of prices that change every hour or faster.
- Most consumers will probably continue purchasing electrical energy on the basis of a tariff,
  - Tarif: a constant price per kilowatt-hour that is adjusted at most a few times per year.

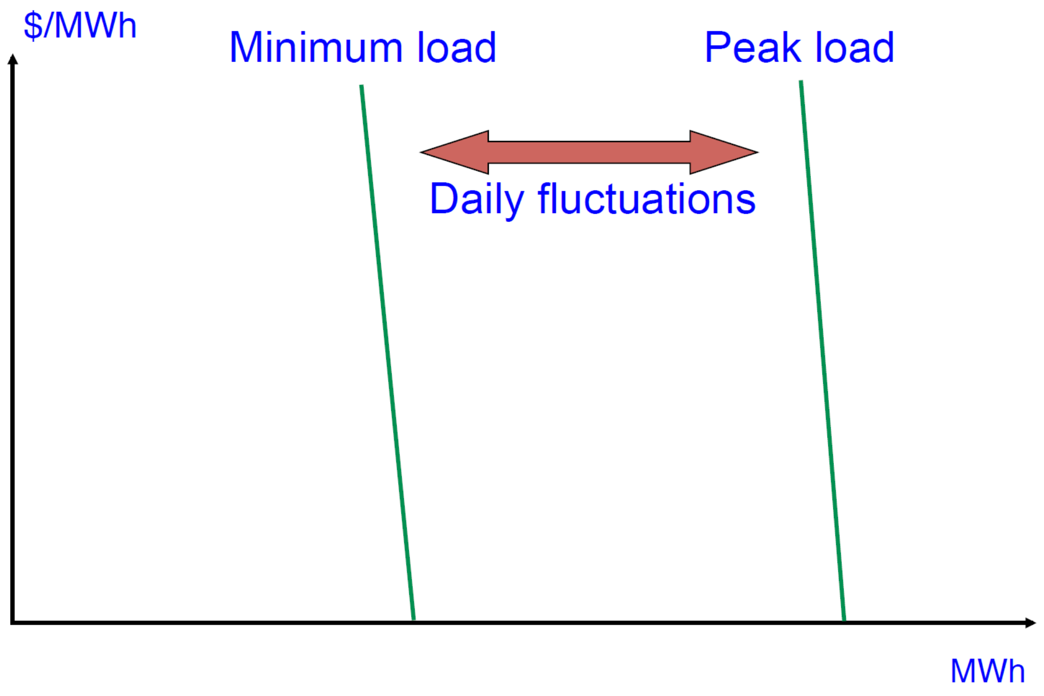
The Consumer's Perspective

Variations in the price of electricity

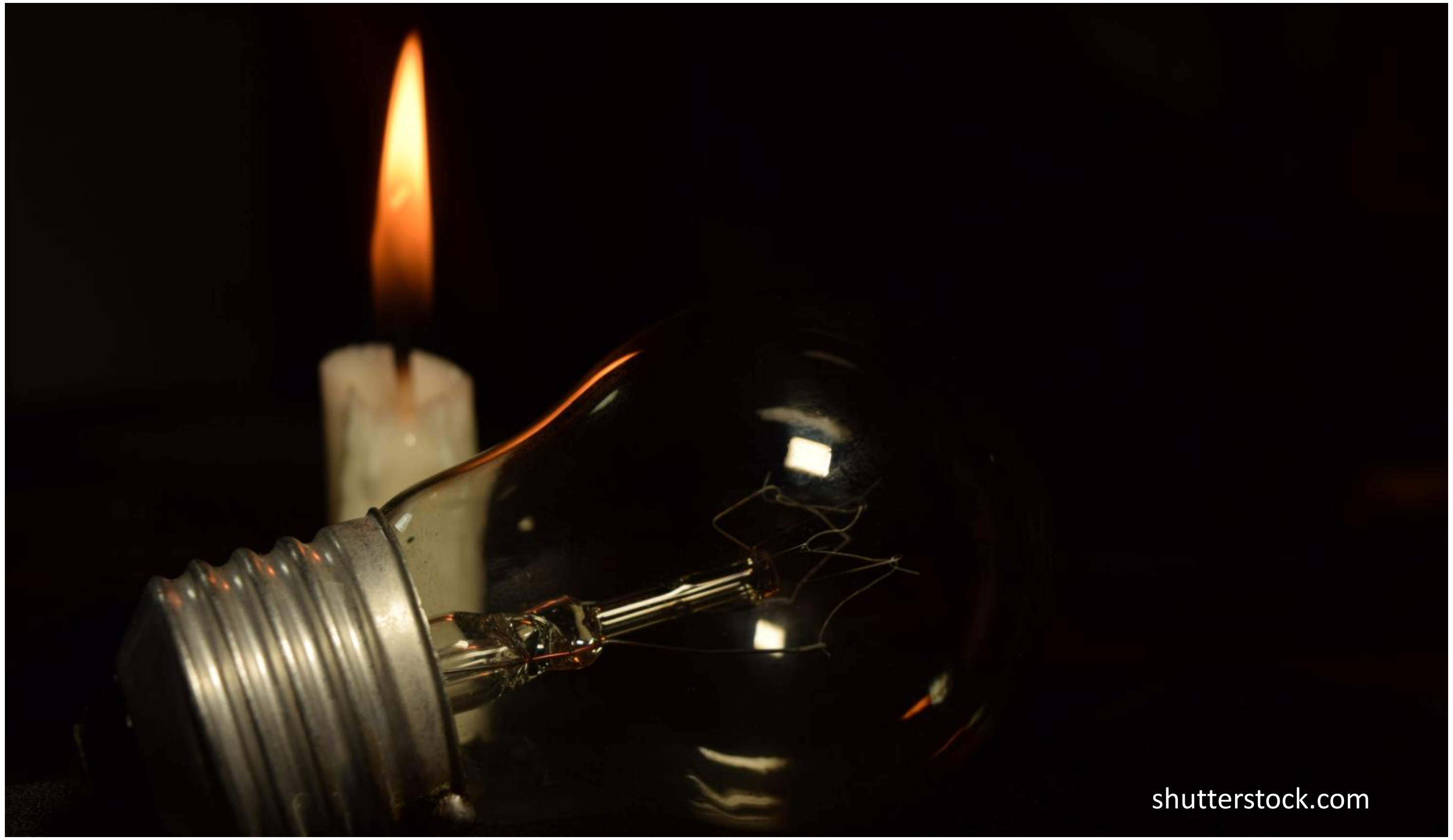


The Consumer's Perspective

Demand curves for electricity



The Value of Lost Load



- It is interesting to compare the average wholesale price for electrical energy sold on a competitive market with the Value of Lost Load (VoLL).
- A measure of the value that consumers place on the availability of electrical energy.
  - The VoLL is obtained through surveys of consumers and represents the average price per megawatt-hour that consumers would be willing to pay to avoid being disconnected without notice.
  - For example, from 2007 to 2013, the average day-ahead energy price at the MISO trading hubs was 35.85 $/ MWh, while MISO estimates VoLL to be 3500 $/ MWh.

The Retailer’s Perspective

The Retailer’s Perspective

- Large consumers (commercial or industrial) (demand is at least a few hundred kilowatts) participate directly and actively in the markets.
- Smaller consumers prefer purchasing on a tariff.
- Electricity retailers are in business to bridge the gap between the wholesale market and these smaller consumers.

The Retailer's Perspective

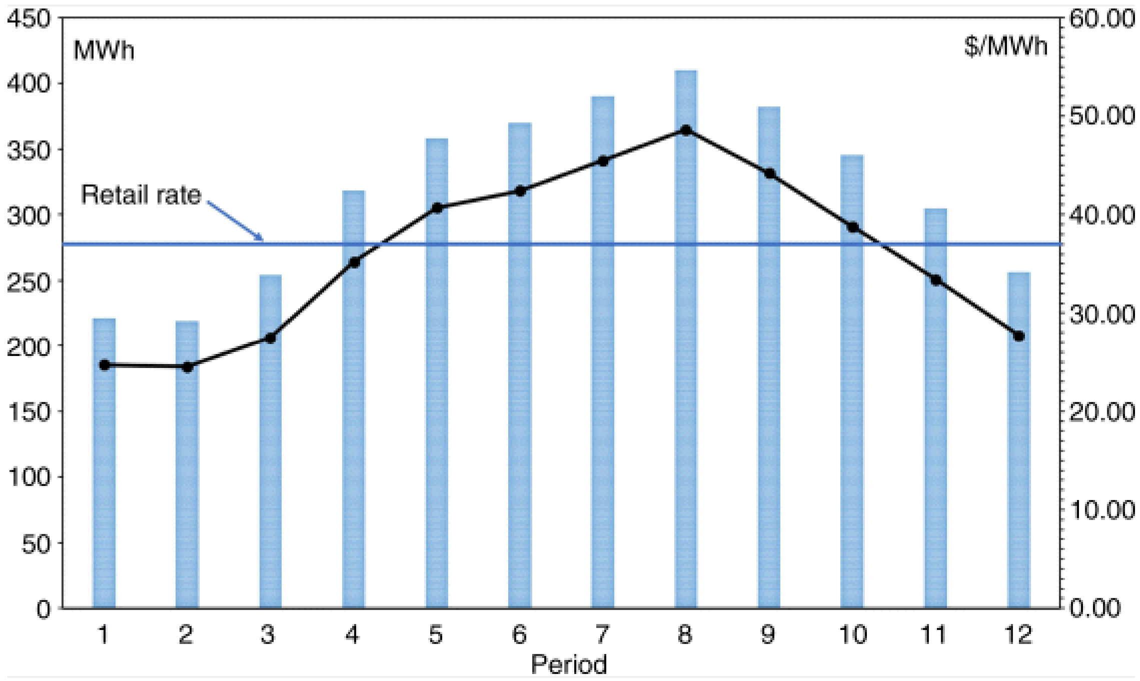
- They have to buy energy at a variable price on the wholesale market and sell it at a fixed price at the retail level.
- A retailer will typically lose money during periods of high prices and make a profit during periods of low prices.
- To stay in business, the quantity-weighted average price at which a retailer purchases electrical energy must be lower than the rate it charges its customers.
- This is not always easy to achieve.
  - Retailer does not have direct control over the amount of energy that its customers consume.
- If for any period the aggregate amount over all its customers differ from the amount that it has contracted to buy, the retailer has to purchase or sell the difference on the spot market at whatever value the spot price reached for that period.

The Retailer’s Perspective

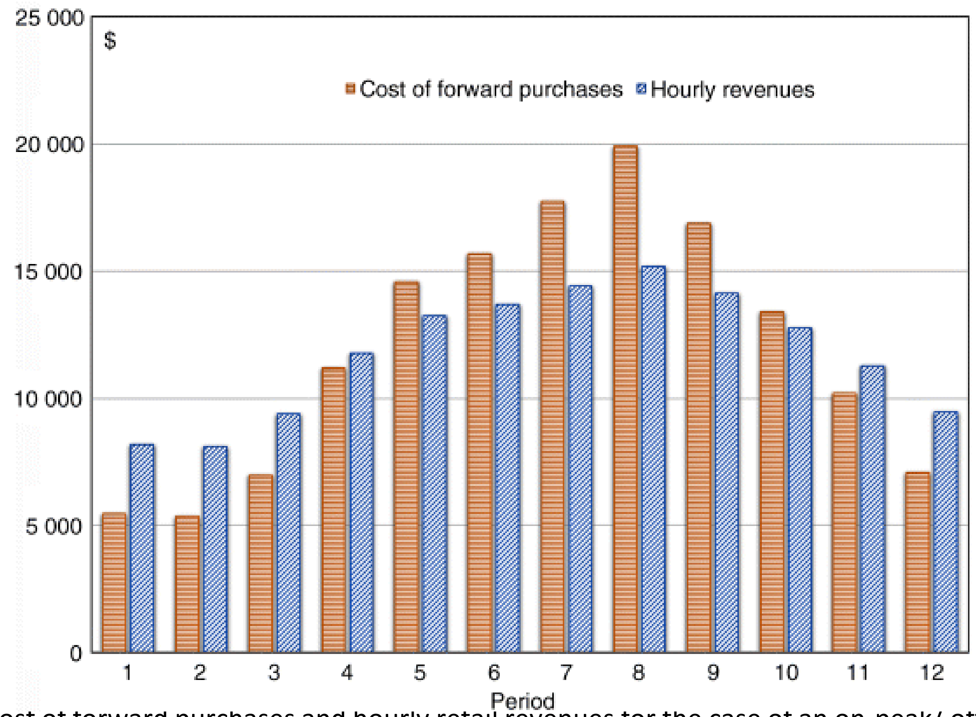
- A retailer tries to forecast as accurately as possible the demand of its customers.
- It then purchases energy on the forward markets to match this forecast.
- it is possible to predict the value of the demand at any hour with an average accuracy of about 1.5– 2%.
  - Possible only with large groups of consumers
  - Aggregation effects reduce the relative importance of random fluctuations.
- Difficult to accurately predict the demand if:
  - A retailer that does not have a monopoly in a given region.
  - Customers have the opportunity to change retailer to get a better tariff.

The Retailer’s Perspective-Example

- Pretty Smart Energy is a retailer who forecasts the demand of its consumers, purchases energy on the forward markets (long-term bilateral, forwards, futures, screen-based transactions) to cover this demand and resells this energy to the consumers on a retail tariff.
- Let us assume retail tariff is flat, i.e. that consumers are charged the same rate for the energy that they consume at every hour.



Forecast demand, average forward purchase price, and retail rate for the case of a flat retail tariff.



Cost of forward purchases and hourly retail revenues for the case of an on-peak/ off-peak tariff

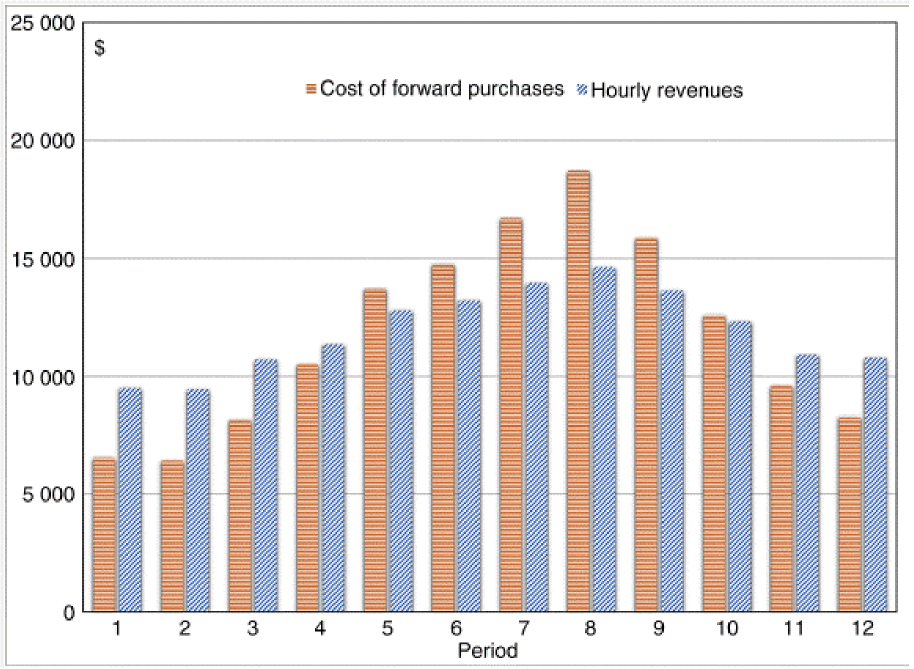
The Retailer's Perspective-Example

Retail operations over a 12-h period for the case of flat retail tariff of 37 $/ MWh

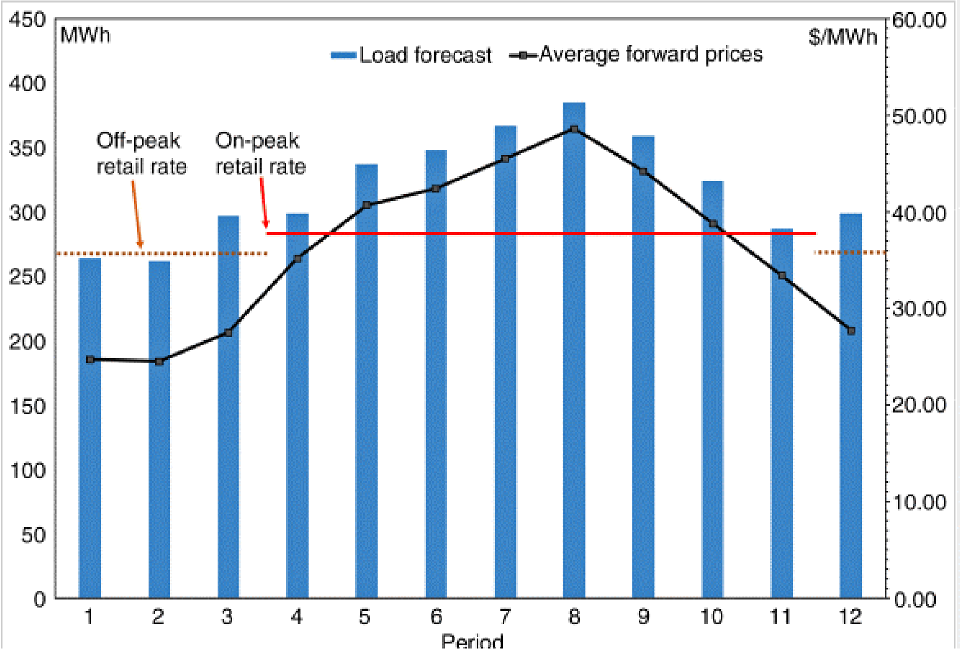
Hour	1	2	3	4	5	6	7	8	9	10	11	12	Total
Load Forecast(MWh)	221	219	254	318	358	370	390	410	382	345	305	256	3828
Forward purchases (MWh)	221	219	254	318	358	370	390	410	382	345	305	256	3828
Average forward prices ($/ MWh)	24.70	24.50	27.50	35.20	40.70	42.40	45.50	48.60	44.20	38.80	33.40	27.70	
Cost of forward purchases ($)	5459	5366	6985	11194	14571	15688	17745	19926	16884	13386	10187	7091	144482
Revenues ($)	8177	8103	9398	11766	13246	13690	14430	15170	14134	12765	11285	9472	141636
Profits	2718	2737	2413	572	− 1325	− 1998	− 3315	− 4756	− 2750	− 621	1098	2381	− 2846

The Retailer’s Perspective-Example

Alternatively, Pretty Smart Energy can try to modify the consumption pattern of its customers by offering them an on-peak/ off-peak tariff. The retail rate is set at 36 $/ MWh for hours 1, 2, 3, and 12 (the off-peak hours) and at 38 $/ MWh for the on-peak hours.



Cost of forward purchases and hourly retail revenues for the case of an on-peak/ off-peak tariff



Forecast demand, average forward purchase prices, and retail rate for the case of an on-peak/ off-peak tariff.

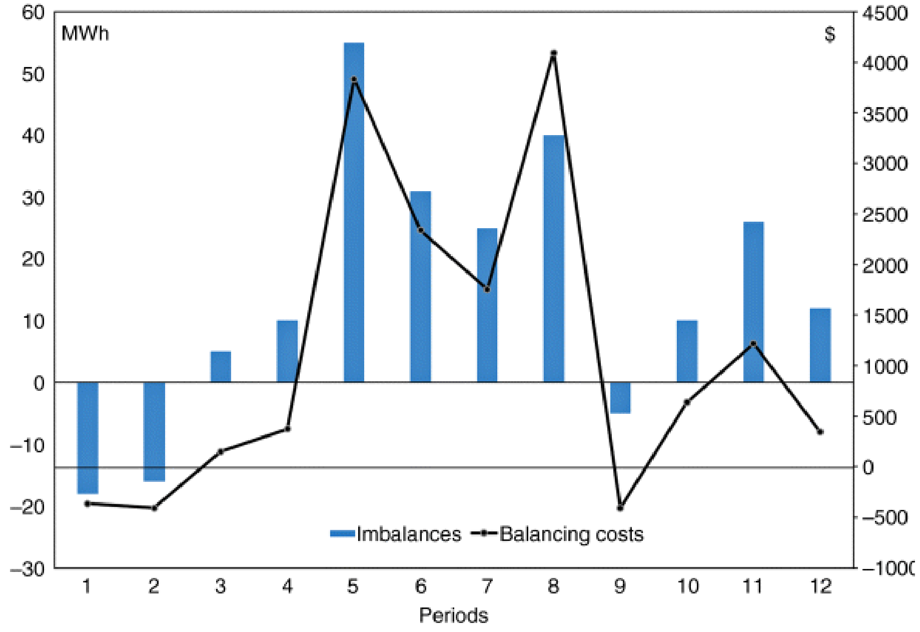
The Retailer’s Perspective

Retail operations over a 12-h period for an on-peak retail rate of 38 $/ MWh and an off-peak retail rate of 36 $/ MWh.

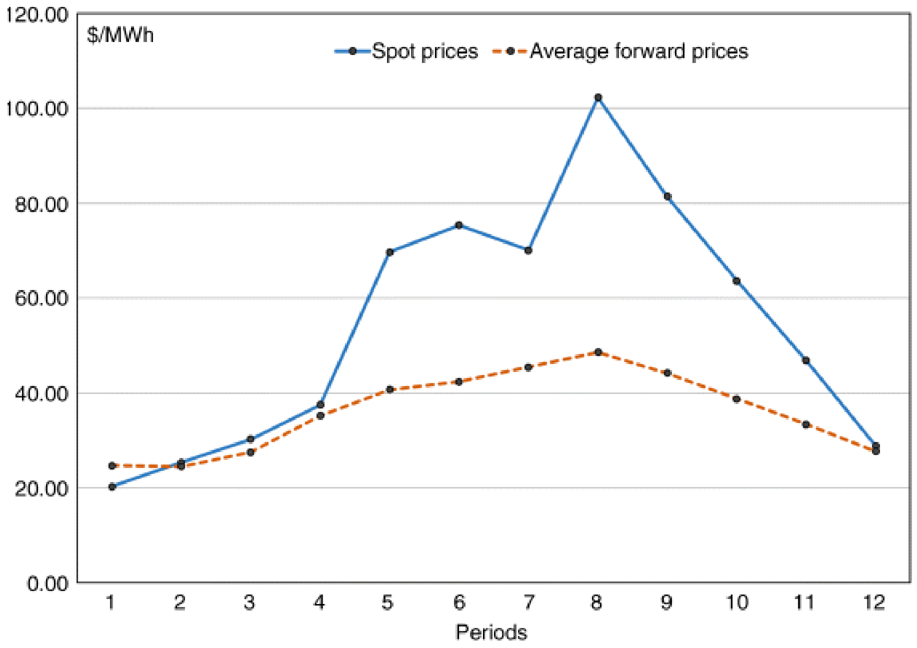
Hour	1	2	3	4	5	6	7	8	9	10	11	12	Total
Load Forecast(MWh)	264	262	299	337	348	367	385	359	324	345	387	299	3828
Forward purchases (MWh)	264	262	299	337	348	367	385	359	324	345	387	299	3828
Average forward prices ($/ MWh)	24.70	24.50	27.50	35.20	40.70	42.40	45.50	48.60	44.20	38.80	33.40	27.70	
Cost of forward purchases ($)	6521	6419	8168	10525	13716	14755	16699	18711	15868	12571	9586	8282	141821
Revenues ($)	9504	9432	10692	11362	12806	13224	13946	14630	13642	12312	10906	10764	143220
Profits	2983	3013	2524	837	−910	−1531	−2753	−4081	−2226	−259	1320	2482	1399

The Retailer’s Perspective-Example

illustrates these imbalances and the resulting cost of the implied trades on the spot market, given the spot market prices shown



Imbalances between forward purchases and actual energy consumed and corresponding balancing costs.



Spot prices and average forward prices.

The Retailer’s Perspective-Example

These imbalances significantly increase the retailer's loss

Hour	1	2	3	4	5	6	7	8	9	10	11	12	Total
Load Forecast(MWh)	221	219	254	318	358	370	390	410	382	345	305	256	3828
Forward purchases (MWh)	221	219	254	318	358	370	390	410	382	345	305	256	3828
Average forward prices ($/ MWh)	24.70	24.50	27.50	35.20	40.70	42.40	45.50	48.60	44.20	38.80	33.40	27.70	
Cost of forward purchases ($)	5459	5366	6985	11194	14571	15688	17745	19926	16884	13386	10187	7091	144482
Actual Loads (MWh)	203	203	259	328	413	401	415	450	377	355	331	268	4003
Imbalances	− 18	−16	5	10	55	31	25	40	−5	10	26	12	175
Spot Prices	20.30	25.40	30.30	37.50	69.70	75.40	70.10	102.30	81.40	63.70	46.90	28.90	
Balancing Costs ($)	−365	−406	152	375	3834	2337	1753	4092	−407	637	1219	347	13568
Total hourly cost ($)	5094	4960	7137	11569	18405	18025	19498	24018	16477	14023	11406	7438	158050
Revenues ($)	7511	7511	9583	12136	15281	14837	15355	16650	13949	13135	12247	9916 1	14811
Profits	2417	2551	2446	567	−3124	−3188	− 4143	−7368	−2528	−888	841	2478	−9939

The Producer’s Perspective

Plants that convert chemical energy into electrical energy by burning fossil fuels such as coal, oil, or natural gas.

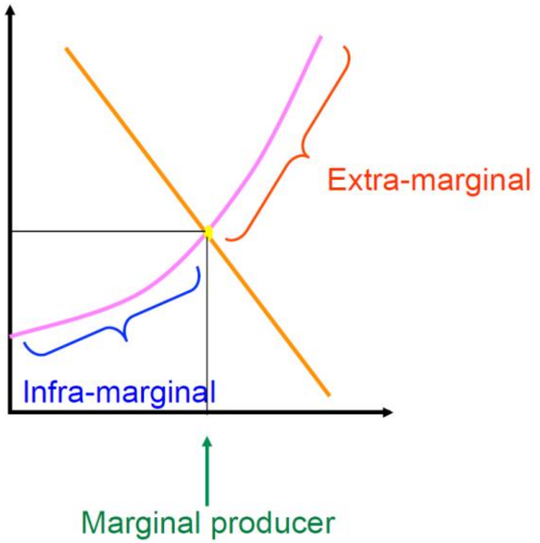
The Producer’s Perspective

Supply and Demand

The Producer's Perspective

Marginal, infra-marginal, extra-marginal producers

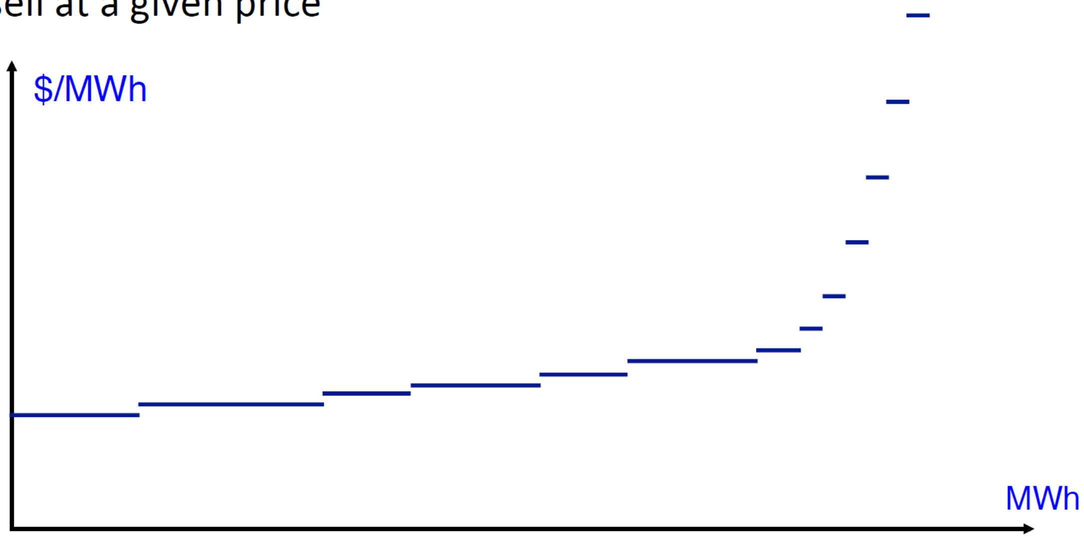
- Everything is sold at the market clearing price
- Price is set by the "last" unit sold
- Marginal producer:
  - Sells this last unit
  - Gets exactly its bid
- Infra-marginal producers:
  - Get paid more than their bid
  - Collect economic profit
- Extra-marginal producers:
  - Sell nothing
- No difference between centralized auction and bilateral market



The Producer's Perspective

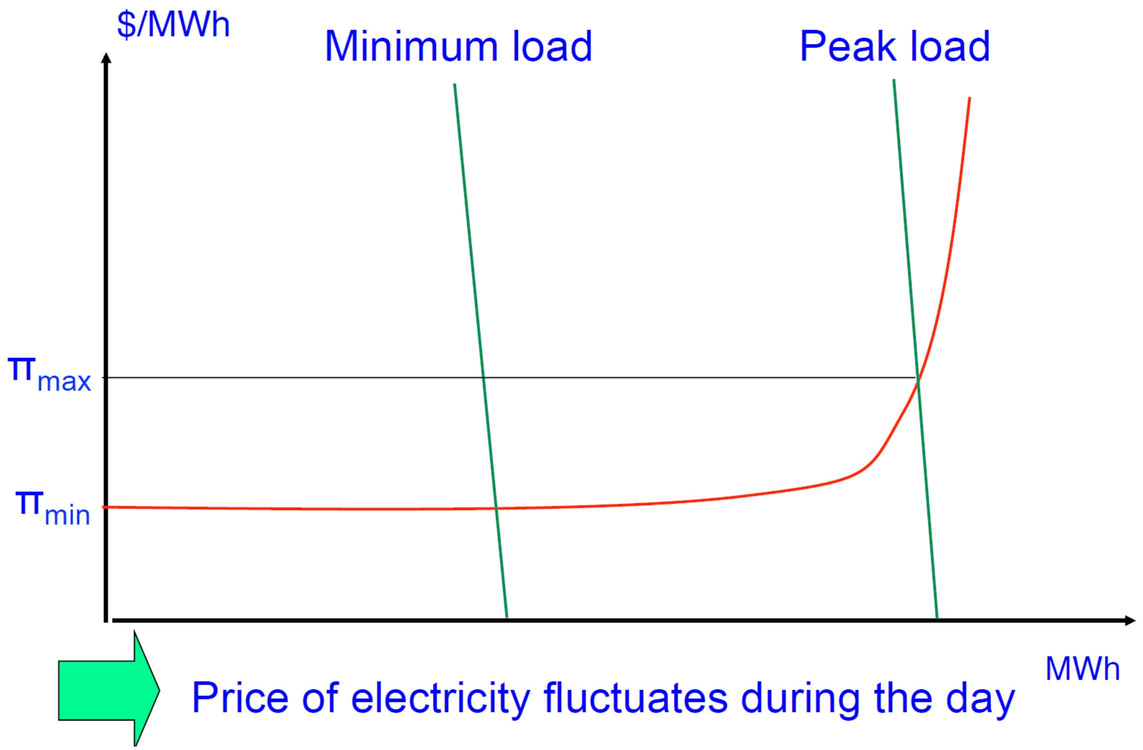
Supply curve for electricity

- In a centralized market, the supply curve is built by ranking the offers made by the generators
- An offer specifies the quantity that the generator is willing to sell at a given price



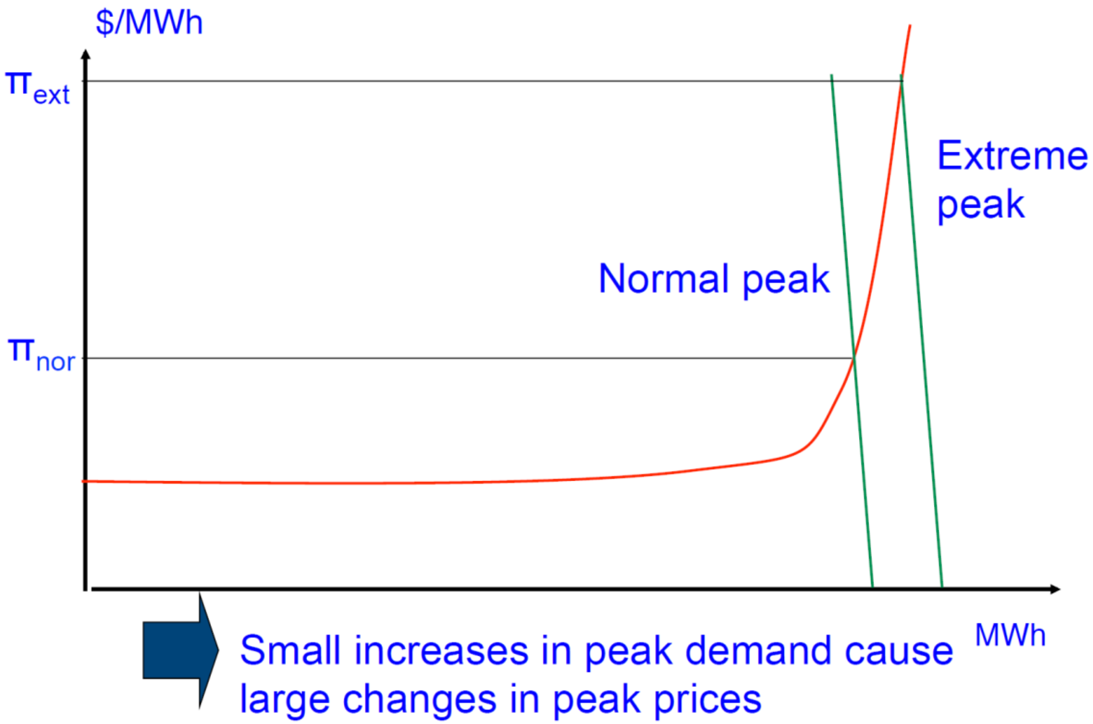
The Producer's Perspective

Supply and demand for electricity



The Producer's Perspective

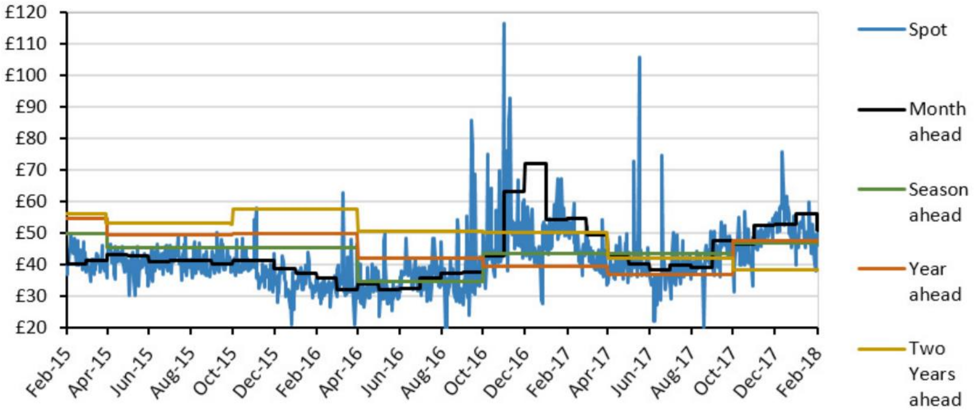
Price spikes because of increased demand



The Producer's Perspective

Price volatility in the balancing mechanism

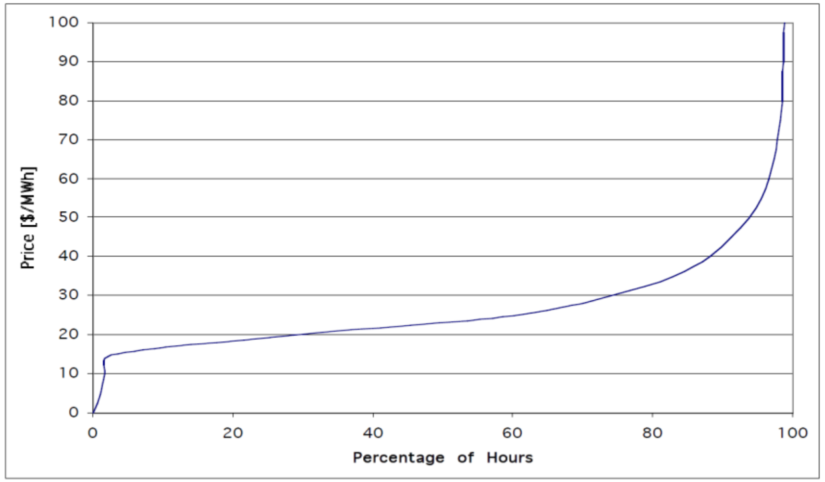
Average wholesale baseload UK power prices by delivery date, £/MWh



Source: EPEX Spot, ICE (Intercontinental Exchange)

The Producer's Perspective

Price duration curve



PJM system (USA) for 1999
Actual peak price reached $1000/MWh for a few hours
(Source: www.pjm.com)

The Producer's Perspective

Supply curve for electricity

- How should a generator bid to maximize its profit?
- It depends on how much competition it has!

The Producer’s Perspective

Market structure

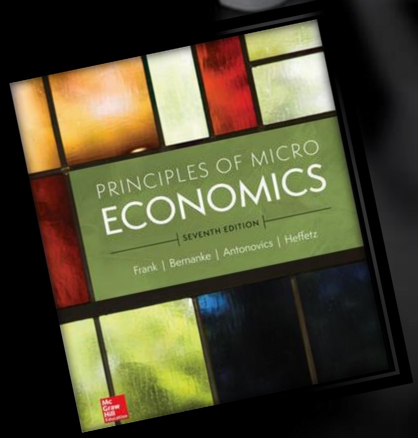
Perfect and imperfect competition

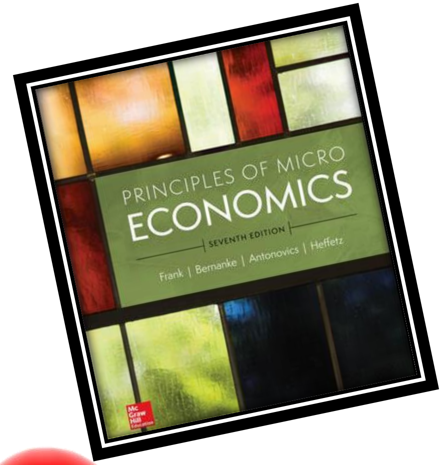
The Producer's Perspective

Market Structure

- Monopoly:
  - Monopolist sets the price at will
  - Must be regulated
- Perfect competition:
  - No participant is large enough to affect the price
  - All participants act as "price takers"
- Oligopoly:
  - Some participants are large enough to affect the price
  - Strategic bidders have market power
  - Others are price takers

Let’s review!


PRINCIPLES OF MICRO
ECONOMICS
SEVENTH EDITION
Frank | Bernanke | Antonovics | Heffetz

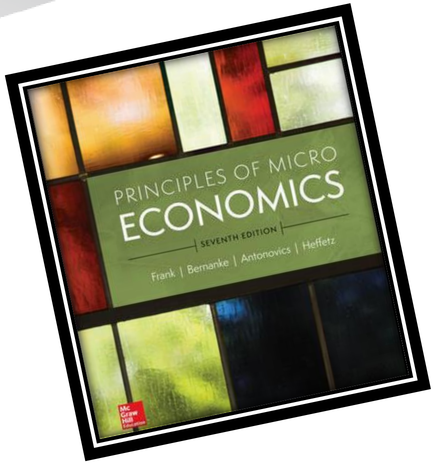


Characteristics of markets that are perfectly competitive

- All firms sell the same standardized product:
  - buyers can switch from one seller to another to obtain a lower price.
- The market has many buyers and sellers, each of which buys or sells only a small fraction of the total quantity exchanged.
  - buyers and sellers will be price takers.
- Productive resources are mobile.
  - If a potential seller are able to obtain the labour, capital, and other productive resources necessary to enter that market. By the same token, sellers who are dissatisfied with the opportunities they confront in a given market are free to leave that market and employ their resources else where.
- Buyers and sellers are well informed.
  - buyers and sellers are aware of the relevant opportunities available to them.

Profit:
the total revenue a firm receives from the sale of its product minus all costs-explicit and implicit-incurred in producing it.

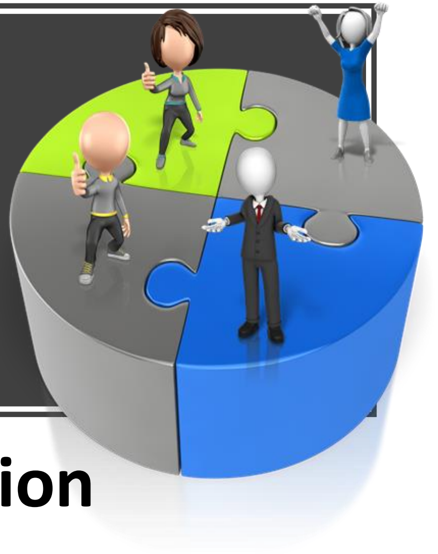
Profit-maximizing firm:
a firm whose primary goal is to maximize the difference between its total revenues and total costs



Perfectly competitive market
a market in which no individual supplier has significant influence on the market price of the product

Price taker
a firm that has no influence over the price at which it sells its product

IMPERFECT COMPETITION



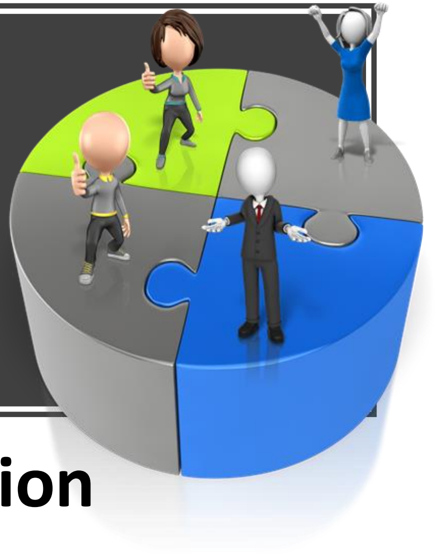
Perfect competition

An industry in which a large number of firms typically sell products that are essentially perfect substitutes for one another.

Monopolistic competition

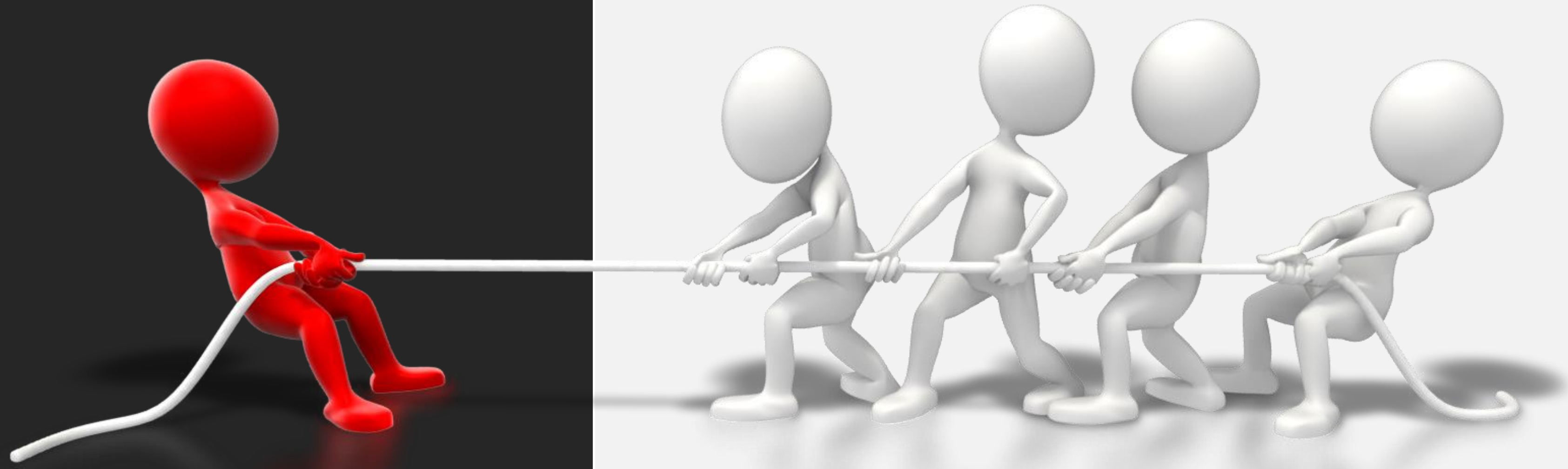
An industry structure in which a large number of rival firms sell products that are close, but not quite perfect, substitutes. Rival products may be highly similar in many respects, but there are always at least some features that differentiate one product from another in the eyes of some consumers.

IMPERFECT COMPETITION



Perfect competition	**Monopolistic competition**
Charge even just slightly more than the prevailing market price for its product, it would not sell any output at all	Can charge a slightly higher price than they do and not lose all its customers, because what it is offering is not a perfect substitute for those of its rivals

Pure monopoly:
a market in which a single firm is the lone seller of a unique product.



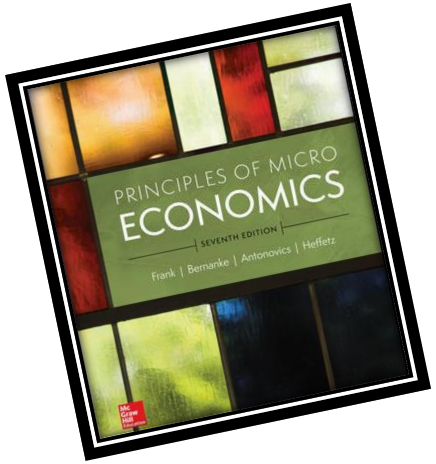
monopolistic competition:
An industry structure in which a large number of firms produce slightly differentiated products that are reasonably close substitutes for one another

price setter:
a firm with at least some latitude to set its own price

Terminologies associated with monopolistic competition

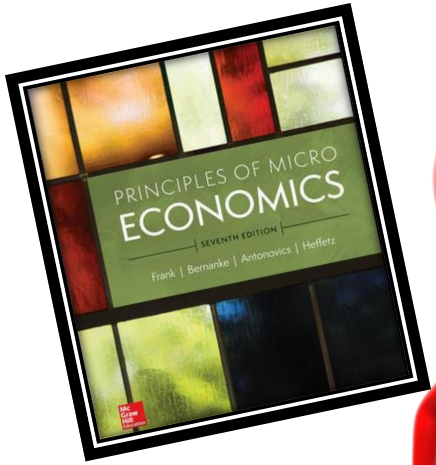
Oligopoly
a structure in which the entire market is supplied by a small number of large
oligopoly an industry structure firms.

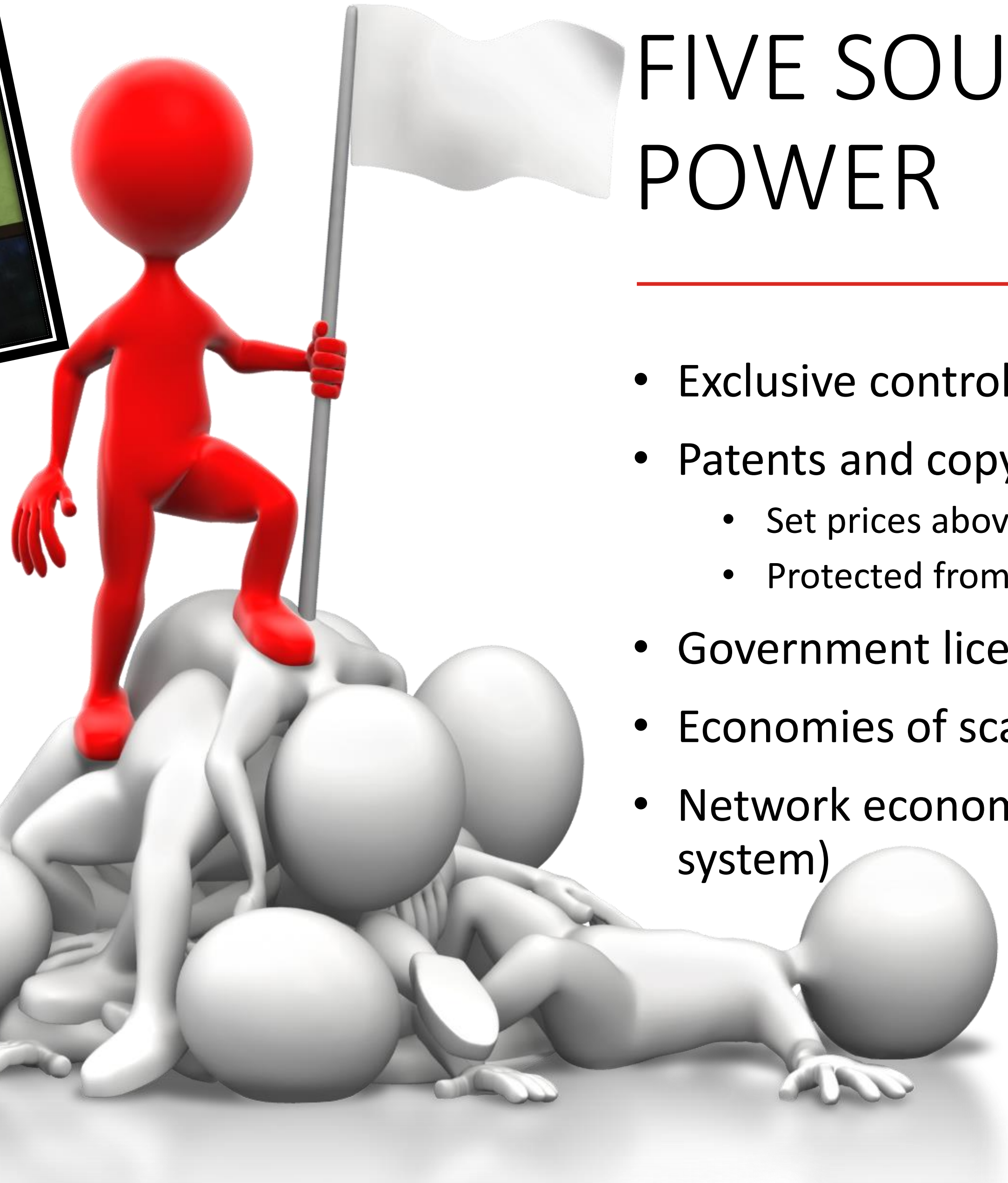
Let’s talk about Oligopoly



The cost advantages associated with large size are one of the primary reasons for pure monopoly. Oligopoly is also typically a consequence of cost advantages that prevent small firms from being able to compete effectively.

In some cases, oligopolists sell undifferentiated products.





FIVE SOURCES OF MARKET POWER

- Exclusive control over important inputs
- Patents and copyrights (Pharmaceutical companies)
  - Set prices above marginal costs to recover the high research cost.
  - Protected from competition for a period of time (~20 years).
- Government licenses or franchises
- Economies of scale and natural monopolies
- Network economies (Microsoft's Windows operating system)

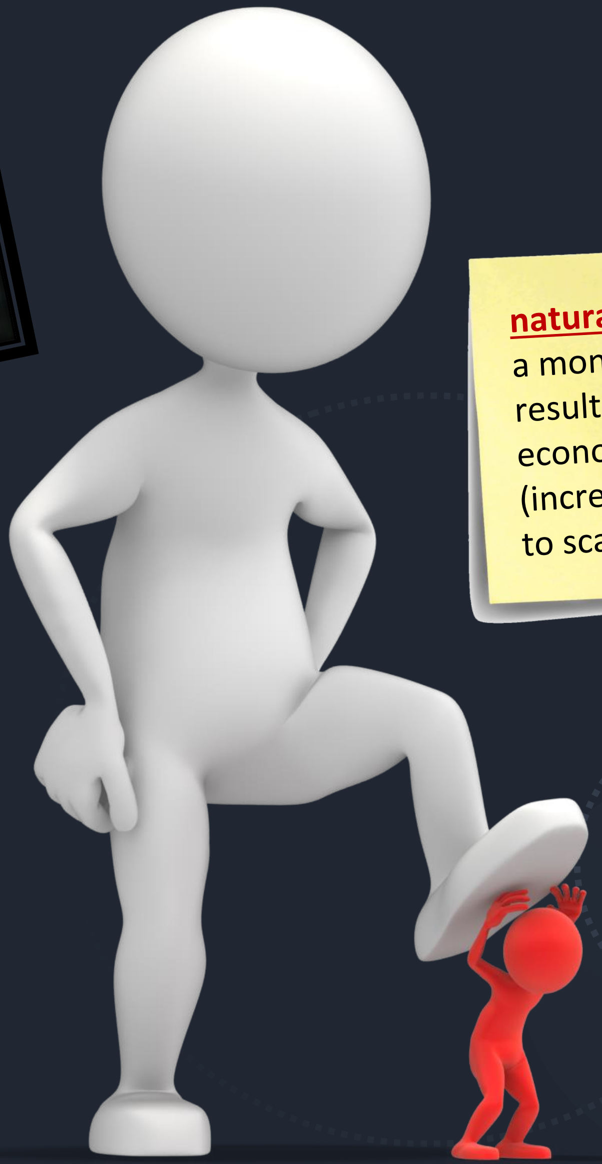
Market power: a firm's ability to raise the price of a good without Losing all its sale

Let's talk about Economies of Scale

Let's talk about Economies of Scale

increasing returns to scale (or economies of scale)
An a production process is said to have increasing returns to scale if, when all inputs are changed by a given proportion, output changes by more than that proportion

constant returns to scale:
a production process is said to have constant returns to scale if, when all inputs are changed by a given proportion, output changes by the same proportion



natural monopoly:
a monopoly that results from economies of scale (increasing returns to scale)

ECONOMIES OF SCALE AND THE IMPORTANCE OF START-UP COSTS

- Companies whose production entails large fixed start-up costs and low variable costs, will be subject to significant economies of scale.
- Fixed costs don't increase as output increases, the average total cost of production for such goods will decline sharply as output increases.

Let’s go back to the producer’s perspective!

The Producer's Perspective

Perfect competition

- All producers have a small share of the market
- All consumers have a small share of the market
- Individual actions have no effect on the market price
- All participants are "price takers"

The Producer's Perspective

Short run profit maximization for a price taker

y : Output of one of the generators

$$\max_{y} \{\underbrace{\pi . y}_{\text{Revenue}} - \underbrace{c(y)}_{\text{Production cost}}\}$$

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

Independent of quantity produced because price taker

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

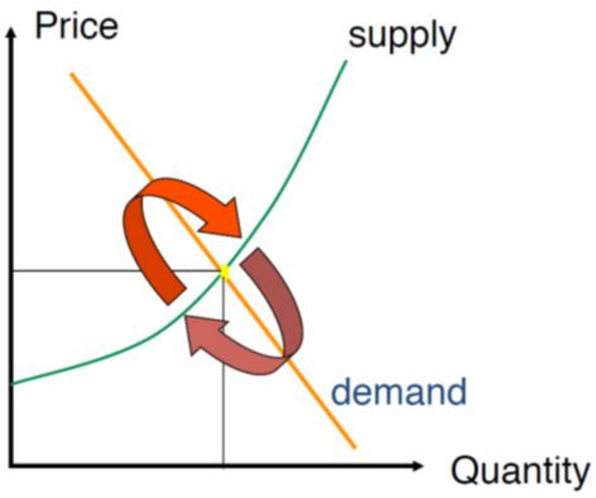
Adjust production y until the marginal cost of production is equal to the price π

The Producer's Perspective

Bidding under perfect competition

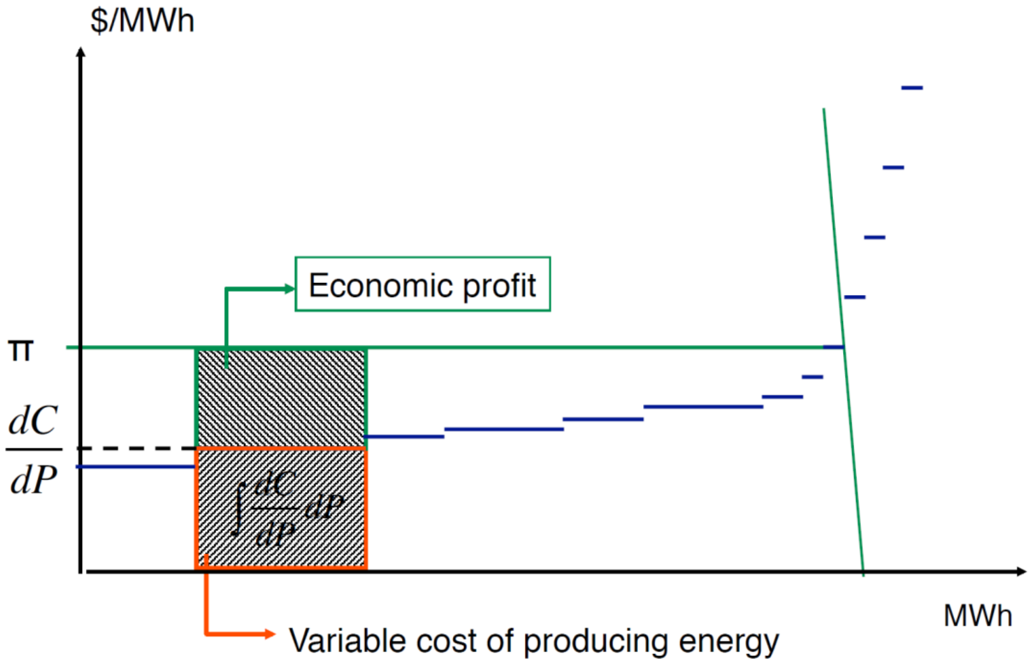
- Since there are lots of small producers, a change in bid causes a change in the order of the bids
- If I bid at my marginal cost
  - I get paid the market clearing price if marginal or infra-marginal producer
- If I bid higher than my marginal cost
  - I could become extra-marginal and miss an opportunity to sell at a profit
- If I bid lower than my marginal cost
  - I could have to produce at a loss

- No incentive to bid anything else than marginal cost of production



The Producer's Perspective

Profit of an infra-marginal producer



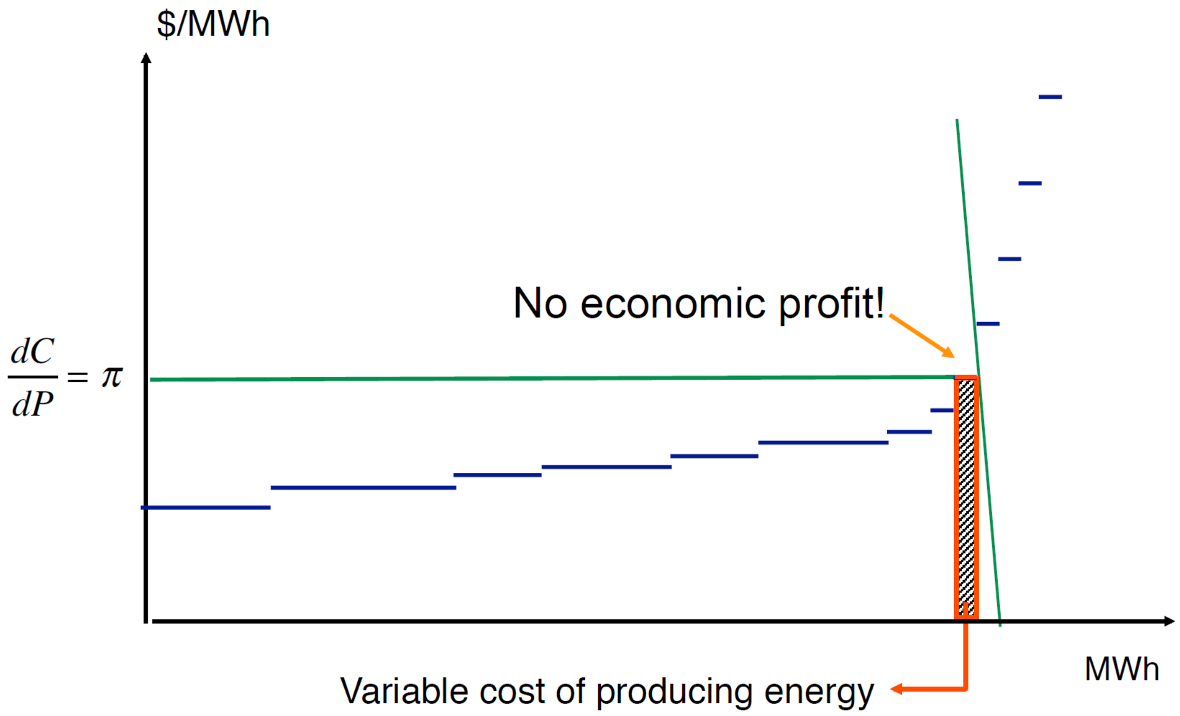
The Producer's Perspective

Profit of an infra-marginal producer

- Selling at marginal cost covers the variable cost of production
- The difference between the market price and the marginal cost must pay for the fixed costs:
  - No-load cost, startup cost
  - Cost of building the plant
  - Interest payments for the bank, dividends for the shareholders
- A plant must therefore be infra-marginal often enough to cover its fixed costs
  - Market price > marginal cost for enough hours of the year

The Producer's Perspective

Profit of a marginal producer



The Producer's Perspective

Profit of a marginal producer

- If a marginal generator bids at its marginal cost, it makes no economic profit
  - Covers only its variable cost of production
  - Does not cover its fixed cost
- Generators that are too often marginal or just below marginal will not recover their fixed costs if they bid at their marginal cost of production
  - They must include part of their fixed costs in their offer price
  - Their offer price is therefore higher than their marginal cost
  - They can do it because competition is not perfect when the load is high because most generators are already producing

The Producer’s Perspective

Oligopoly and market power

A firm exercises market power
when
– It reduces its output *(physical withholding)*
or
– It raises its offer price *(economic withholding)* in order to change the market price

The Producer's Perspective

When market power is more likely?

- Imperfect correlation with market share
- Demand does not have a high price elasticity
- Supply does not have a high price elasticity:
  - Highly variable demand
  - All capacity sometimes used
  - Output cannot be stored

➡ Electricity markets are more vulnerable than others to the exercise of market power

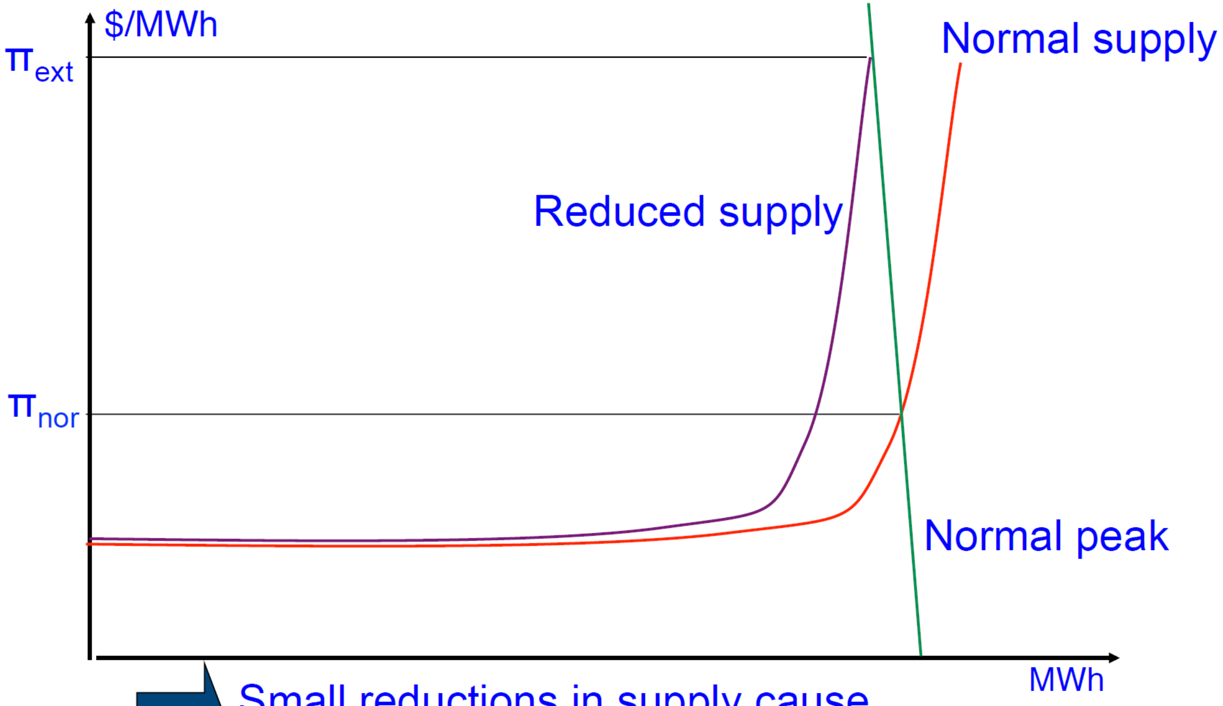
The Producer's Perspective

Oligopoly and market power- Example

- A firm sells 10 units and the market price is $15
  - Option 1: offer to sell only 9 units and hope that the price rises enough to compensate for the loss of volume
  - Option 2: offer to sell the 10th unit for a price higher than $15 and hope that this will increase the price
- Profit increases if price rises sufficiently to compensate for possible decrease in volume

The Producer’s Perspective

Price spikes because of reduced supply



Small reductions in supply cause large changes in peak prices

The Producer's Perspective

Short run profit maximization with market power

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

y_i : Production of generator i

$Y = y_1 + \cdots + y_n$

is the total industry output

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

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

Not zero because of market power

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

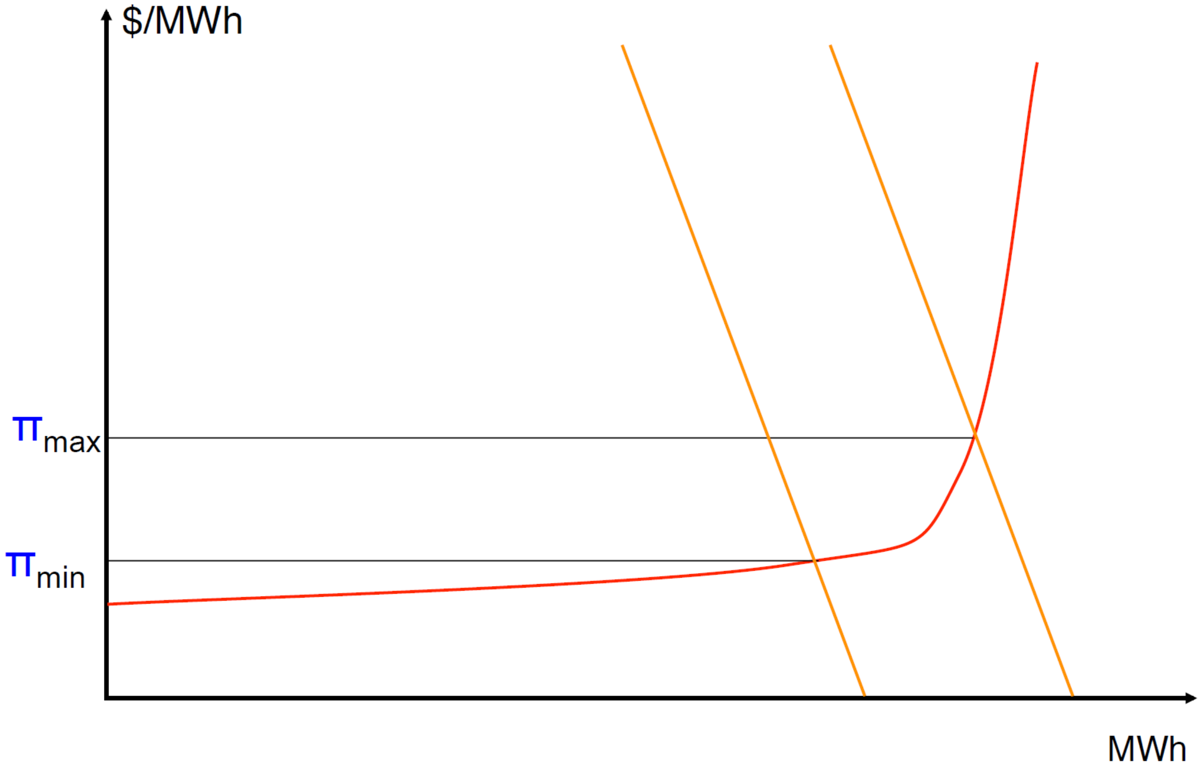
The Producer's Perspective

Mitigating market power

- Increase elasticity
- Increase number of competitors

The Producer's Perspective

Increasing the elasticity reduces price spikes and the generators' ability to exercise market power



The Producer's Perspective

Increasing the elasticity of the demand

- Obstacles
  - Tariffs
  - Need for communication
  - Need for storage (heat, intermediate products, dirty clothes)
- Not everybody needs to respond to price signals to get substantial benefits
- Increased elasticity reduces the average price
  - Not in the best interests of generating companies
  - Impetus will need to come from somewhere else

The Producer's Perspective

Further comments on market power

- ALL firms benefit from the exercise of market power by one participant
- Unilaterally reducing output or increasing offer price to increase profits is legal
- Collusion between firms to achieve the same goal is not legal
- Market power interferes with the efficient dispatch of generating resources
  - Cheaper generation is replaced by more expensive generation

The Producer’s Perspective

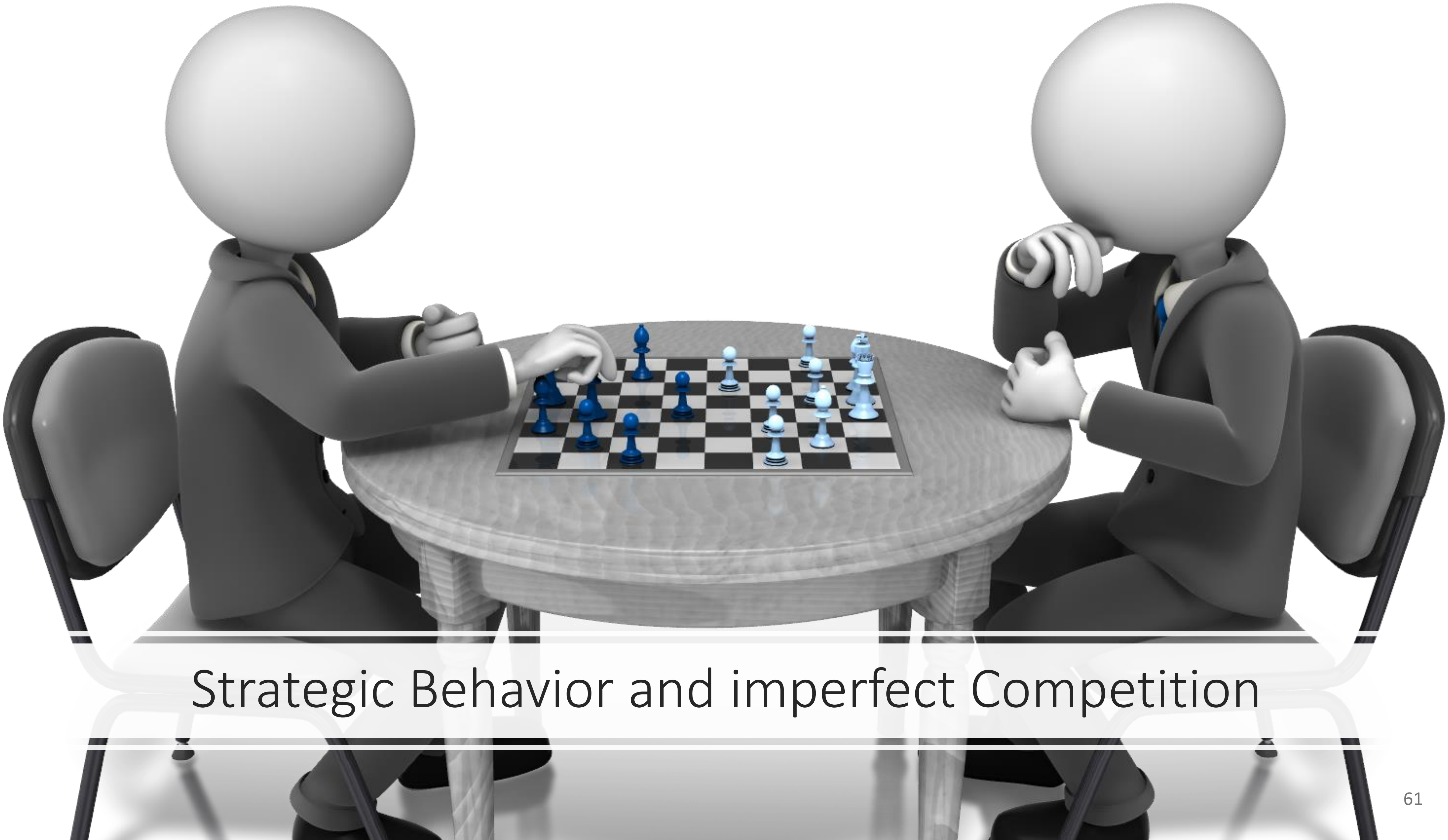
Modelling Imperfect Competition :

- Bertrand model
- Competition on prices
- Cournet model
- Competition on quantities

The Producer's Perspective

Imperfect Competition

- Some firms (the strategic players) are able to influence the market price through their actions.
- It is quite common for an electricity market to consist of a few strategic players and a number of price takers.
- A company that owns more than one generating unit is likely to have a greater influence on the market price if it optimizes the combined output of its entire portfolio of units.



Strategic Behavior and imperfect Competition

The Producer's Perspective

Game theory and Nash equilibrium

- Each firm must consider the possible actions of others when selecting a strategy
- Classical optimization theory is insufficient
- Two-person non-co-operative game:
  - One firm against another
  - One firm against all the others
- Nash equilibrium:
  - given the action of its rival, no firm can increase its profit by changing its own action:

$$\Omega^i(a_i^*, a_j^*) \geq \Omega^i(a_i, a_j^*) \quad \forall i, a_i$$

Terminologies associated with monopolistic competition

Basic elements of a game:
The players, the strategies available to each player, and the payoffs each player receives for each possible combination of strategies

Dominanted strategy
any other strategy available to a player who has a dominant strategy

Nash Equilibrium:
Any combination of strategy choices in which each player’s choice is his or her best choice, given the other players' choice

Payoff matrix:
a table that describes the payoffs in a game for each possible combination of strategies

Dominant strategy
one that yields a higher payoff no matter what the other players in a game choose

The Producer's Perspective

Game Theory

Should G_A spend money on advance filtering system for its coal generator?

Payoff matrix:

		G_A's choices	
		Raise the spending	Leave the spending the same
G_A's choices	Raise the spending	\$5,500 for G_A \$5,500 for G_B	\$8,000 for G_A \$2,000 for G_B
	Leave the spending the same	\$2,000 for G_A \$8,000 for G_B	\$6,000 for G_A \$6,000 for G_B

The Producer’s Perspective

Game Theory-Prisoner’s Dilemma

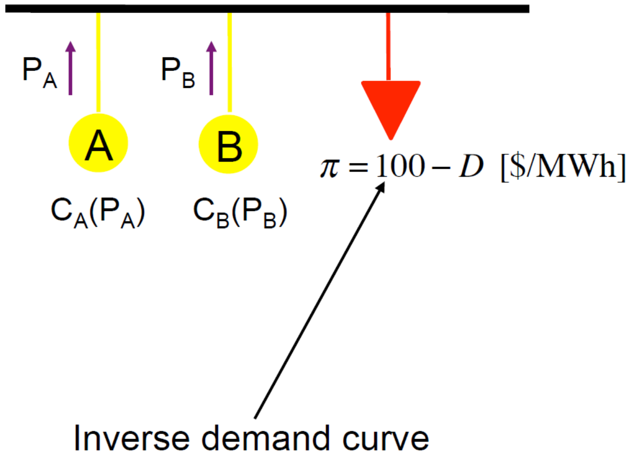
		Jasper: Confess	Jasper: Remain Silent
Horace	Confess	5 years for each	0 years for Horace 20 years for Jasper
Horace	Remain Silent	20 years for Horace 0 years for Jasper	I year for each

The Producer's Perspective

Bertrand Competition Example1

- These firms compete by setting their prices and letting the market decide how much each firm sells.

- Example 1
  - $C_A = 35 \,.\, P_A$ \$/h
  - $C_B = 45 \,.\, P_B$ \$/h



- Bid by A?
- Bid by B?
- Market price?
- Quantity traded?

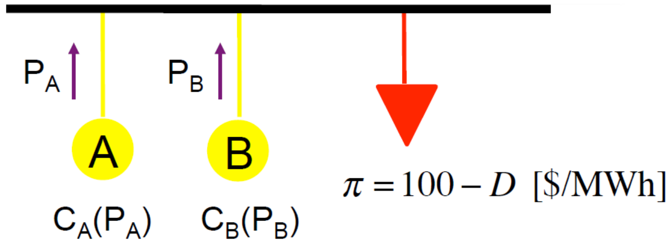
- By setting its price just below 45 \$/ MWh, Generator A would capture the whole market .
- The market price in this example is thus (45 − ε) \$/ MWh.

The Producer's Perspective

Bertrand Competition Example 2

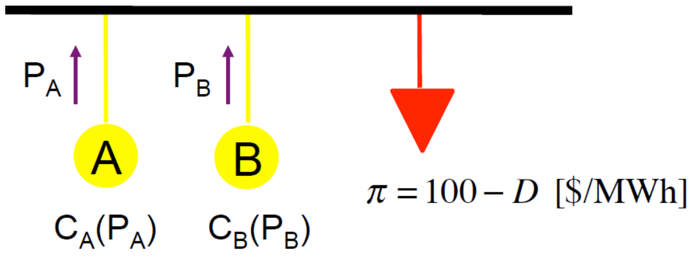
- Example 2
  - $C_A = 35 \,.\, P_A$ \$/h
  - $C_B = 35 \,.\, P_B$ \$/h

- Bid by A?
- Bid by B?
- Market price?
- Quantity traded?



The Producer's Perspective

Bertrand Competition Example 2



- Example 2
  - $C_A = 35 \, . \, P_A$ $/h
  - $C_B = 35 \, . \, P_B$ $/h

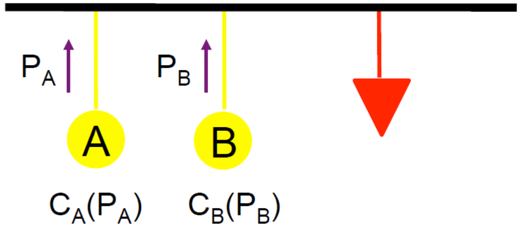
- A cannot bid below 35 $/MWh because it would lose money on every MWh
- A cannot bid above 35 $/MWh because B would bid lower and grab the entire market
- Market price: 35 $/MWh

- Paradox of Bertrand model of imperfect competition
  - Identical generators: bid at marginal cost
  - Non-identical generators: cheapest gets the whole market
  - Not a realistic model of imperfect competition

The Producer's Perspective

Cournot Competition Example 1

- The state of the market is determined by the production decisions made by each firm.



- $C_A = 35 \,.\, P_A$ \$/h
- $C_B = 45 \,.\, P_B$ \$/h
- $\pi = 100 - D$ [\$/MWh]

- Suppose $P_A = 15$ MW and $P_B = 10$ MW
- Then $D = P_A + P_B = 25$ MW
- $\pi = 100 - D = 75$ \$/MW
- $R_A = 75 \,.\, 15 = \$ 1125$; $C_A = 35 \,.\, 15 = \$ 525$
- $R_B = 75 \,.\, 10 = \$ 750$; $C_B = 45 \,.\, 10 = \$ 450$
- Profit of A = $R_A - C_A = \$ 600$
- Profit of B = $R_B - C_B = \$ 300$

The Producer’s Perspective

Cournot Competition Example 1

Summary:

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

Demand

Profit of A

25	600
300	75

Profit of B

Price

The Producer's Perspective

Cournot Competition Example 1

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

Demand	Profit A
Profit B	Price

The Producer's Perspective

Cournot Competition Example 1

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

Demand	Profit A
Profit B	Price

- Price decreases as supply increases
- Profits of each affected by other
- Complex relation between production and profits

The Producer's Perspective

Cournot Competition Example 1

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

Demand	Profit A
Profit B	Price

Equilibrium solution!

A cannot do better without B doing worse
B cannot do better without A doing worse
Nash equilibrium

The Producer's Perspective

Cournot Competition Example 1

Demand

Profit of A

	$P_A=25$
$P_B=15$	40	625
	225	60

Profit of B

Price

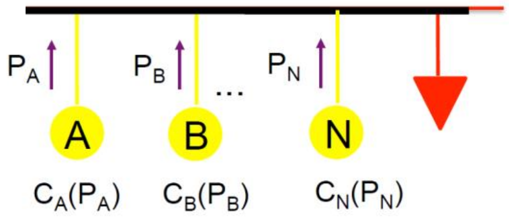
$C_A = 35 \,.\, P_A$ \$/h
$C_B = 45 \,.\, P_B$ \$/h

- Generators achieve price larger than their marginal costs
- The cheapest generator does not grab the whole market
- Generators balance price and quantity to maximize profits
- Warning: price is highly dependent on modeling of demand curve and are thus often not realistic

The Producer's Perspective

Cournot Competition Example 2

- $C_A = 35 \,.\, P_A$ \$/h
- $C_B = 45 \,.\, P_B$ \$/h
- …
- $C_N = 45 \,.\, P_N$ \$/h

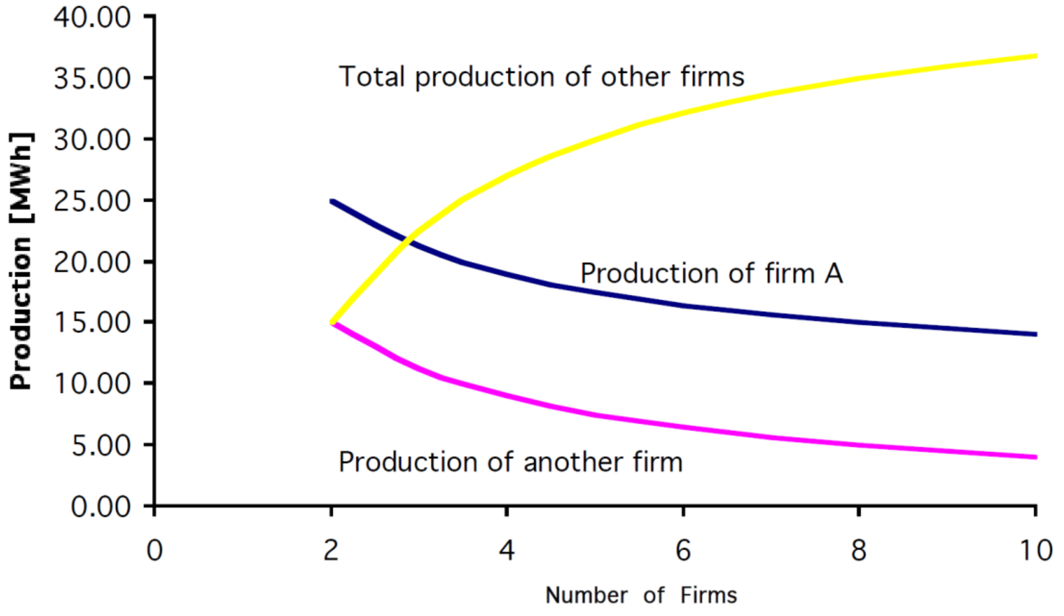


$\pi = 100 - D$ [\$/MWh]

- A is a "strategic" player
  - i.e. with market power
- The others are "the competitive fringe"

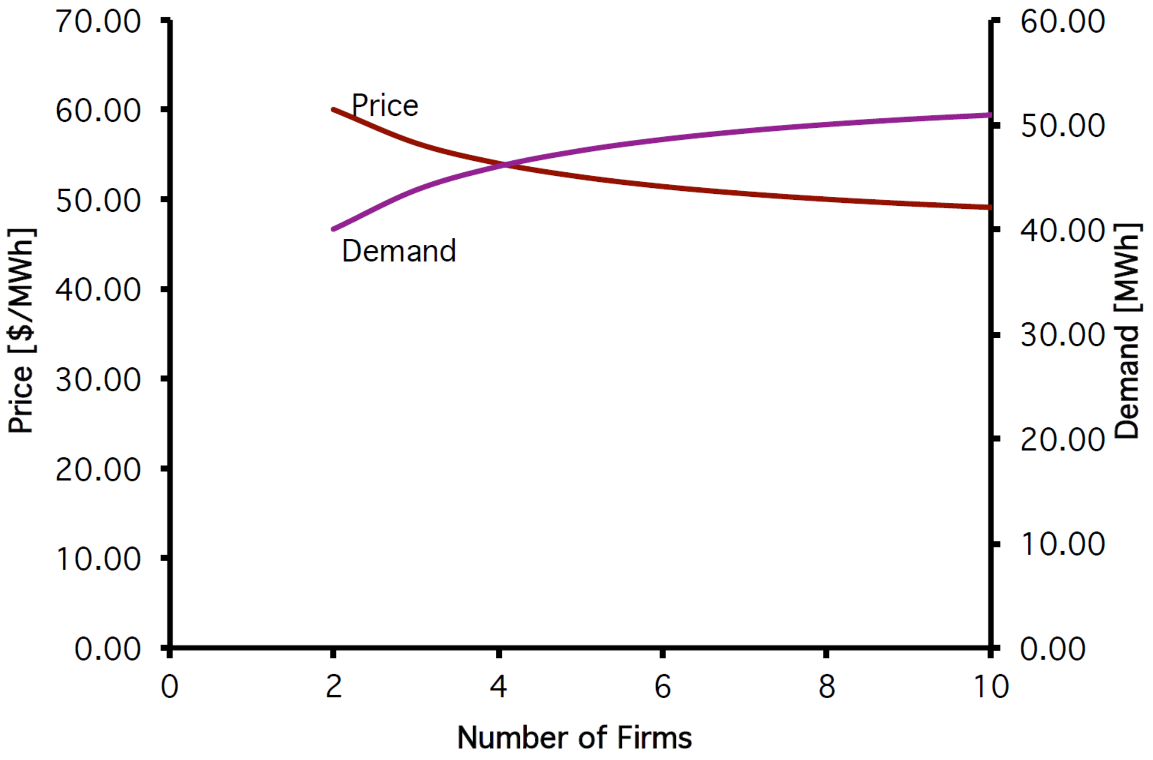
The Producer's Perspective

Cournot Competition Example 2



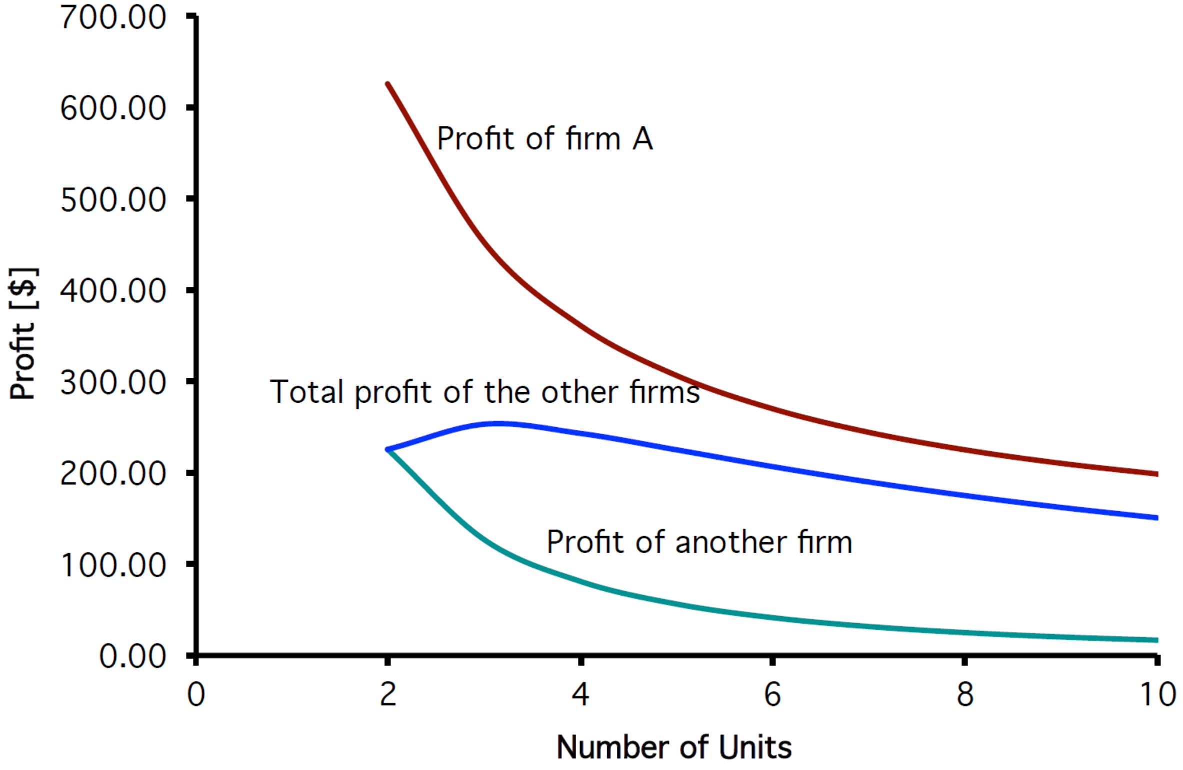
The Producer's Perspective

Cournot Competition Example 2



The Producer's Perspective

Cournot Competition Example 2



The Producer's Perspective

Other competition models

- Supply functions equilibrium
  - Bid price depends on quantity
- Agent-based simulation
  - Represent more complex interactions
- Maximising short-term profit is not the only possible objective
  - Maximizing market share
  - Avoiding regulatory intervention

The Producer’s Perspective

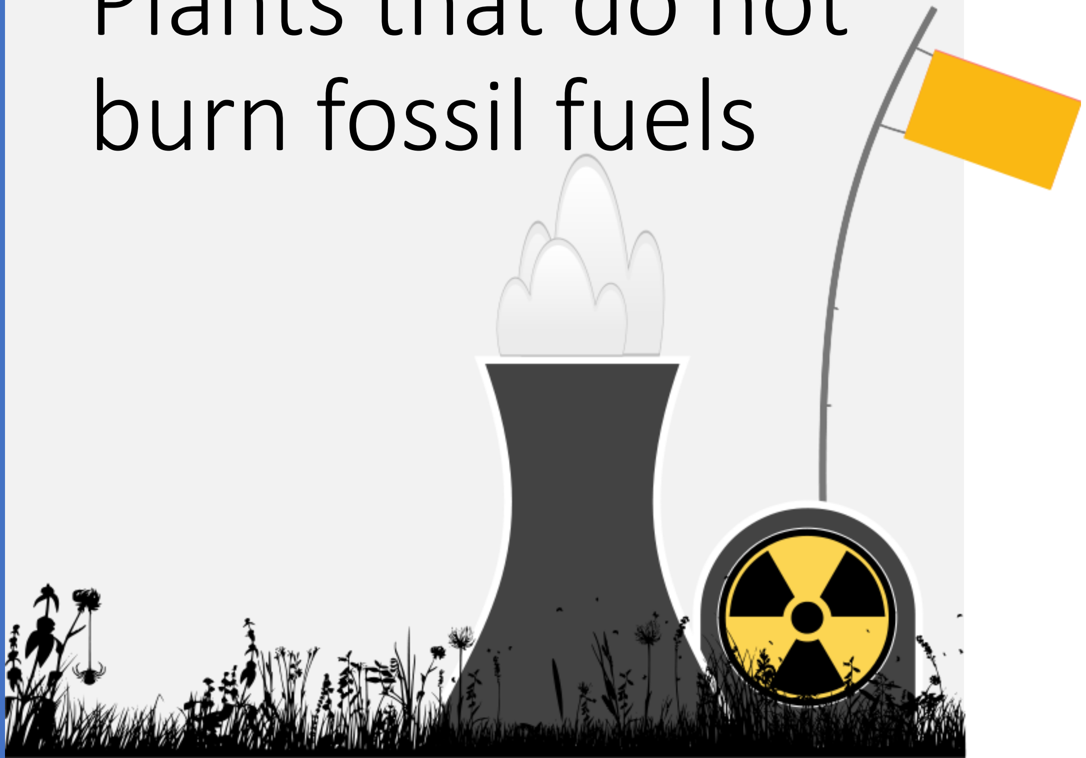
Other competition models

- Electricity markets do not deliver perfect competition
- Some factors facilitate the exercise of market power:
  - Low price elasticity of the demand
  - Large market shares
  - Cyclical demand
  - Operation close to maximum capacity
- Study of imperfect competition in electricity markets is a difficult research topic
  - Generator’s perspective
  - Market designer’s perspective

Perspective of Plants that do not burn fossil fuels

Plants that do not burn fossil fuels have much lower (e.g. nuclear) or negligible (e.g. hydroelectric, wind, solar) marginal cost.

Perspective of Plants that do not burn fossil fuels



Nuclear Plants

- operated at an almost constant generation level because adjusting their output is technically difficult.
- Ideally, these plants should be shut down only every 12– 18 months for refueling.
- Restarting them is a slow and costly process.
- In a centralized market, nuclear power plants often bid at 0.00 $/ MWh and they thus act as price takers.
- In a bilateral market, the owners of these plants enter into long-term contracts for base load power.
- Unplanned shutdowns of nuclear power plants are very costly
  - Their large capacity and the long duration of such outages require the purchase of a large amount of replacement energy on the spot and short-term forward markets.
  - Such large purchases can significantly drive up prices on these markets.

Perspective of Plants that do not burn fossil fuels

Hydroelectric power plants

- High flexibility :
  - Their production can be ramped up or down very quickly over a wide range.
  - shut down frequently without a significant impact on their expected life.
- loosely constrained in terms of power, but significantly constrained in terms of the energy that they can or must produce over a given amount of time.
- The maximum amount of energy determined by the amount of rain or snow that falls in its river basin.
- The minimum amount of energy is dictated by the need to let some water through the dam either to avoid overfilling its reservoir or for environmental reasons (e.g. providing the right amount of water for fish preservation) or for other uses (e.g. irrigation, transportation, recreation).
- Given a forecast of prices for electrical energy, the operation should be optimized.

Perspective of Plants that do not burn fossil fuels

Wind and solar generation

- Their primary energy sources are free.
- Intermittent and stochastic: in most places the wind does not always blow and the sun does not always shine.
- The availability of wind and sunshine may or may not line up with the periods of peak demand.
- Owners try their very best to forecast when and how much energy they expect to produce and sell this energy on forward markets.
- It is impossible to forecast with perfect accuracy the amount or the time of the energy their plants will produce.
- Imbalances due to errors in forecast need to settle in the spot market.

Perspective of Plants that do not burn fossil fuels

Wind and solar generation

- Wind and solar plants resolve to some mitigation techniques reduce the price risk they are exposed:
  - Improve the accuracy of their generation forecasts using numerical weather forecasting (for wind generation) and satellite images of cloud covers (for solar generation).
  - Trade in the short-term forward markets.
  - Partner with a flexible conventional generator or an energy storage facility.
    - This partner can change its energy output to compensate for any deficit or surplus in the renewable generation.

Perspective of Plants that do not burn fossil fuels

Wind and solar generation
Government Policies and Subsidies

- Government policies aim at reducing carbon dioxide emissions.
- These policies aim to help renewable generators by:
- mandating the purchase of renewable energy

or

- by subsidizing investments in renewable generation capacity or the energy produced by these facilities.

Perspective of Plants that do not burn fossil fuels

Wind and solar generation Government Policies and Subsidies

- ***Renewable portfolio standards or renewable energy standards***
  - Oblige retailers to produce or buy a certain fraction of the energy that they sell from certain types of renewable sources.
    - This fraction often increases over time.
    - For example, in the State of California, these percentages are 33% by 2020, 40% by 2024, 45% by 2027, and 50% by 2030.
    - These standards sometimes also specify fractions for different renewable technologies.
- ***Investment tax credits***
  - Gives a rebate on the investor's taxes for each kilowatt of installed renewable energy generation capacity.
- ***Production subsidies take different forms:***
  1. **A production tax credit**

     A rebate that the owner of a renewable generating plant receives on its taxes for each kilowatt-hour produced by this plant.
  2. ***Feed-in tariffs***

  Guarantee that all the electrical energy produced from renewable sources will be bought at a favorable per kilowatt-hour rate.

Perspective of Plants that do not burn fossil fuels

Wind and solar generation Government Policies and Subsidies

3. ***Renewable energy certificates***

- Given to renewable energy producers for each megawatt-hour that they generate.
- These certificates can then be sold either on a voluntary or a compliance market.
- Buyers on the voluntary markets are companies or individuals who want to make sure that an amount of energy equal to what they consume has been produced from renewable source.
- Buyers on the compliance markets are retailers who must meet their renewable portfolio standard.

- Tax credits, feed-in tariffs, and the strike price of contracts decrease over time the cost of deploying these technologies is expected to decrease such that renewable generation achieves “grid parity,” i.e. that it no longer requires subsidies to be competitive with conventional generation on the electricity markets.
- The cost of these subsidies is socialized, i.e. borne by either taxpayers or electricity consumers.

Perspective of Plants that do not burn fossil fuels

Wind and solar generation Effect on the Markets

- The average price decreases because renewable generators are willing to sell at a low price.
- They displace other forms of generation and often force them to retire.
- When there is no wind or sunshine, prices can rise significantly.
- Subsidies distort the market: renewable generators get paid a fixed amount on top of the market price
- When demand is low and renewable resources are abundant, this can lead to negative market prices (i.e. generators have to pay to produce).
- Renewable generators can tolerate negative prices as long as the absolute value of the negative market price does not exceed the production tax credit.
- When the amount solar generation capacity that residential and commercial consumers is significant, they can cause a significant drop in demand during the middle of the day when solar irradiance is strongest.

The storage owner’s perspective

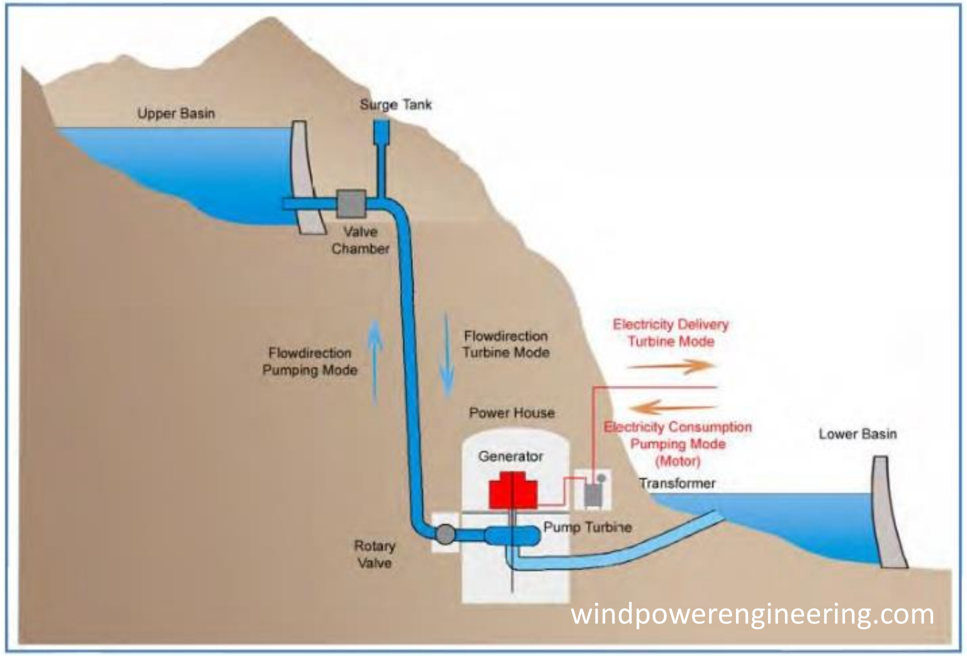
The storage owner’s perspective

Electric Storage

- We assume that batteries or other energy storage devices perform only temporal arbitrage, i.e. they buy and store energy when the price is low and release and sell this energy when the price is high.
- Temporal arbitrage can be profitable if the revenue generated by selling energy during periods of high prices is larger than the cost of the energy consumed during periods of low prices.
- Because of the losses, not all of the energy bought and stored can be sold back.

The storage owner's perspective

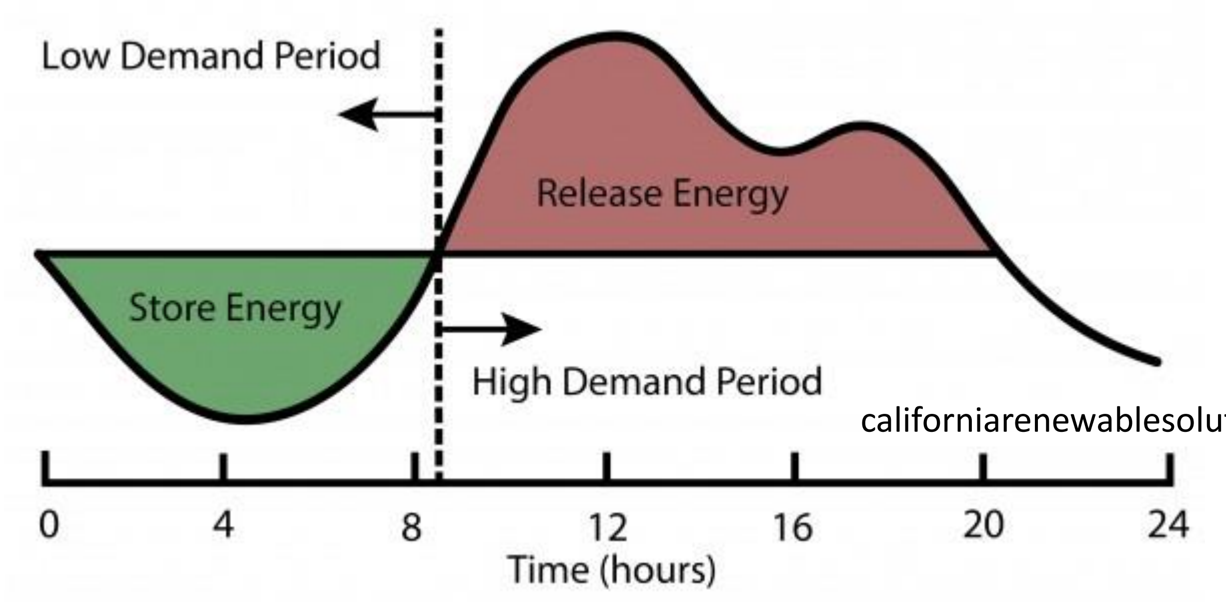
Pumped hydro plants- has been around for a long time



consume energy by pumping water uphill during periods of light load and produce energy by releasing this water through turbines during periods of high load.

The storage owner's perspective

Flattening the demand curve



californiarenewablesolutions.org

- Cycling consumption and production in this manner reduces the difference between the peaks and the troughs in the demand curve.
- This allows nuclear power plants to operate at a constant power output, reduces the need to cycle conventional power plants on and off or to operate them at less than their optimal efficiency, and thus decreases the system operating cost.

The storage owner's perspective

Self-scheduling example

- Let us first consider the case of a storage operator who decides ahead of time for the next T periods when to charge and when to discharge a storage device on the basis of a forecast of prices. This operator seeks to maximize its operating profit, which is given by the following expression:

$$\Omega = \sum_{t=1}^{T} \pi(\mathrm{t})(P_D(t) - P_C(t))\Delta t$$

Where:

π(t) is the forecast market price during period t ($/ MWh)

$P_D(t)$ is the rate of discharge of the storage device during period t (MW)

$P_C(t)$is the rate of charge of the storage device during period t (MW)

Δt is the duration of each period (h).

The storage owner's perspective

Self-scheduling

- During each hour, the battery is charging, discharging, or idle, which means that PC(t) and PD(t) cannot be nonzero simultaneously. The amount of energy stored (i.e. the state of charge of the storage device) is given by the following expression:

$$\mathrm{E}(t) = E(t-1) + [\eta P_C(t) - P_D(t)]$$

Where:

$E(t)$ is the state of charge at the end of period t (MWh).

η is the round-trip efficiency of the storage device.

The storage owner's perspective

Self-scheduling
This optimization constraints:

- $0 \leq E(t) \leq E^{max}, \forall t = 1, \cdots, T$
- $0 \leq P_D(t) \leq P^{max}, \forall t = 1, \cdots, T$
- $E(t) \leq E(0) = E_0$

where:

E^{max} is the energy rating of the storage device.

P^{max} is its power rating

E_0 is the initial state of charge.

The storage owner's perspective

Centralized Operation

- Storage devices can also be treated as another resource that the system operator can use to meet the load at minimum cost.
- The optimization problem that the system operator must solve to clear the market is a regular unit commitment problem the exception of the load generation balance constraint that becomes:

$$\sum_{i=1}^{N} P_i(t) + P_D(t) - P_C(t) = L(t), \forall t = 1, \cdots, T$$

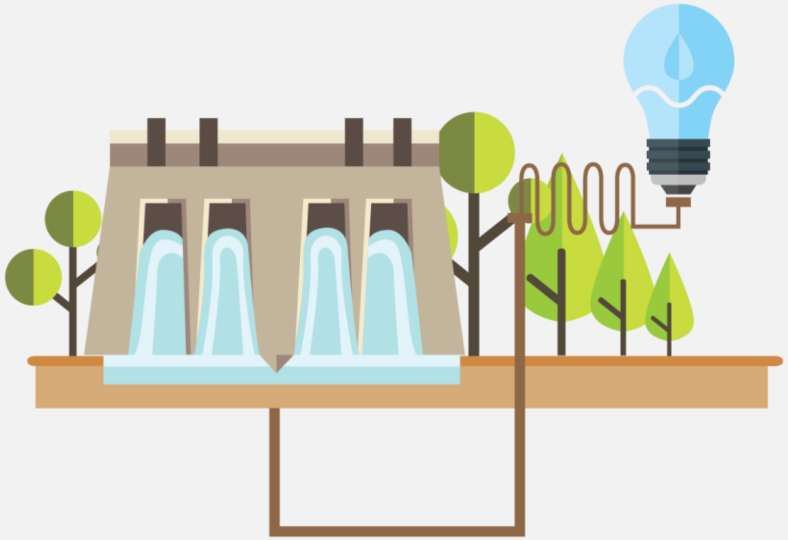
where:

$P_i(t)$ is the power produced by generating unit i during period t.

N is the number of generating units

L(t) is the load forecast for period t.

The storage owner's perspective



Example

- Let us consider a simple example, involving a market with three generators, a scheduling horizon of 3h, and a trading period of 1 h.

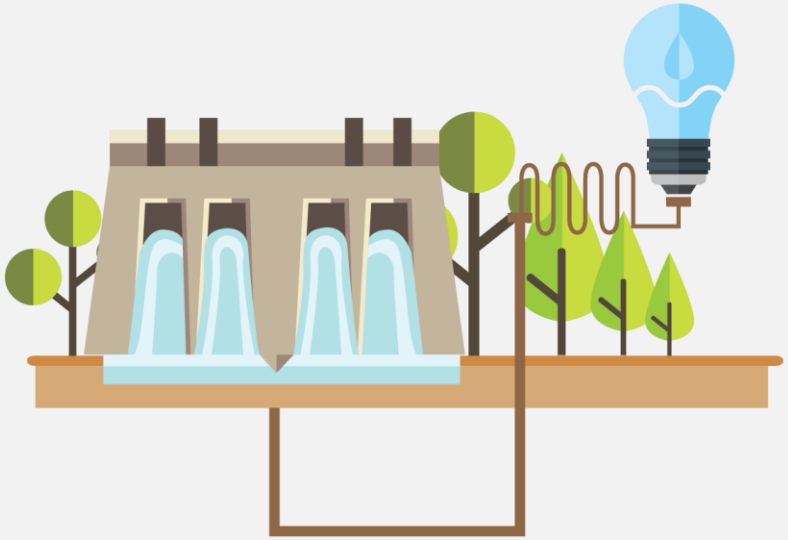
Generating unit data

Generating unit i	P_i^{min} (MW) minimum generation	P_i^{max} (MW) maximum generation	α_i ($/MWh) marginal cost	β_i ($/MWh) fixed cost
1	0	500	10	500
2	100	350	25	250
3	0	200	200	100

Demand Data

Time Period t	1	2	3
L(t)(MW)	495	750	505

The storage owner's perspective



Example

- For simplicity, we ignore the start-up costs, the ramp rate limits as well as the minimum up- and down-time constraints. These simplifications allow us to consider each period separately. We also assume that the cost functions of the generators involve only a fixed cost αi and a constant marginal cost β_i :

$$C_i\big(P_i(t), u_i(t)\big) = \alpha_i \;\; u_i(t) + \beta_i P_i(t)$$

The storage owner’s perspective Example

Let us introduce in this market a 1 MW/ 10 MWh battery with a round-trip efficiency of 0.83.
This battery is initially completely discharged and it self-schedules based on the published prices to perform temporal arbitrage.
We assume that its capacity is small enough compared to the rest of the system that it has no impact on the prices.

Market settlement without storage

Hour	Price ($/MWh)		Unit 1	Unit 2	Unit 3
1	10	Output (MWh)	495	0	0
		Revenue ($)	4950	0	0
		Cost ($)	5450	0	0
		Profit ($)	-500	0	0
2	25	Output (MWh)	500	250	0
		Revenue ($)	12500	6500	0
		Cost ($)	5500	6500	0
		Profit ($)	7000	-250	0
3	50	Output (MWh)	500	0	5
		Revenue ($)	25000	0	250
		Cost ($)	5500	0	350
		Profit ($)	19500	0	-100
		Total Profit ($)	26000	-250	-100
		Total cost ($)		23300	

The storage owner's perspective Example

The battery takes advantage of the low prices during hour 1 to charge at its maximum 1 MW rate. During period 2 it charges at a rate of 0.2 MW to compensate for its losses and ensure that it can discharge a full 1.0 MWh at the high price of period 3. This arbitrage cycle yields a profit of $ 35 for the battery and reduces the total generation cost by $ 50 over the case without storage.

Market settlement with a 1 MW/ 10 MWh battery.

Hour	Price ($/MWh)		Unit 1	Unit 2	Unit 3	Battery
1	10	**Output (MWh)**	496	0	0	-1
		Revenue ($)	4960	0	0	-10
		Cost ($)	5460	0	0	0
		Profit ($)	-500	0	0	-10
2	25	**Output (MWh)**	500	251	0	-0.2
		Revenue ($)	12500	6500	0	-5
		Cost ($)	5500	6500	0	0
		Profit ($)	7000	-250	0	-5
3	50	**Output (MWh)**	500	0	4	1
		Revenue ($)	25000	0	200	50
		Cost ($)	5500	0	300	15
		Profit ($)	19500	0	-100	50
		Total Profit ($)	26000	-250	-100	35
		Total cost ($)		23265		

The storage owner's perspective Example

If instead of having a power rating of 1 MW this battery was rated at 10 MW, it would be fully charged during hour 1 and fully discharged during hour 3 to take advantage of the biggest price difference. However, in this case our assumption that this battery would have no effect on the prices and the power balance would be questionable.

Market settlement with a 10 MW/ 10 MWh battery.

Hour	Price ($/MWh)		Unit 1	Unit 2	Unit 3	Battery
1	25	Output (MWh)	500	0	0	-5
		Revenue ($)	12500	0	0	-125
		Cost ($)	5500	0	0	0
		Profit ($)	7000	0	0	-125
2	25	Output (MWh)	500	251	0	-1
		Revenue ($)	12500	6276	0	-26
		Cost ($)	5500	6526	0	0
		Profit ($)	7000	-250	0	-26
3	30.12	Output (MWh)	500	0	0	5
		Revenue ($)	15060	0	0	150.6
		Cost ($)	5500	0	0	0
		Profit ($)	9560	0	0	150.6
		Total Profit ($)	23560	-250	0	0
		Total cost ($)		23026		

The storage owner's perspective

Example

- Unit 1 is operating at its maximum during hour 1.
- it does not set the price.
- Since Unit 2 is marginal during hour 2, it therefore sets the price not only for hour 2 but also for hour 1.
- The battery is charged at a rate of 5 MW during hour 1 and at a rate of 1 MW during hour 2.
- Because the battery is able to discharge 5 MWh during hour 3, Unit 3 does not need to be committed.
- A marginal increase in load at hour 3 would require the battery to charge more at hour 2.
- The price at hour 3 is therefore 30.12 \$/ MWh, which is 25 \$/ MWh divided by the 0.83 round-trip efficiency.
- While the battery makes no profit over this scheduling horizon, it flattens the load profile and reduces the system operating cost by \$ 274 compared to the case without storage.

Market settlement with a 10 MW/ 10 MWh battery.

Hour	Price (\$/MWh)		Unit 1	Unit 2	Unit 3	Battery
1	25	**Output (MWh)**	500	0	0	-5
		Revenue (\$)	12500	0	0	-125
		Cost (\$)	5500	0	0	0
		Profit (\$)	7000	0	0	-125
2	25	**Output (MWh)**	500	251	0	-1
		Revenue (\$)	12500	6276	0	-26
		Cost (\$)	5500	6526	0	0
		Profit (\$)	7000	-250	0	-26
3	30.12	**Output (MWh)**	500	0	0	5
		Revenue (\$)	15060	0	0	150.6
		Cost (\$)	5500	0	0	0
		Profit (\$)	9560	0	0	150.6
		Total Profit (\$)	23560	-250	0	0
		Total cost (\$)		23026		

The flexible consumer's perspective

The flexible consumer's perspective

Who are the flexible consumers?

- Consumers who are able to shift their demand in time, either through self-scheduling or by offering this ability to the system operator
- Instead of storing energy in chemical or gravitational form, these consumers store heat, intermediate products in a manufacturing process, or dirty dishes.

The flexible consumer's perspective

energycentral.com

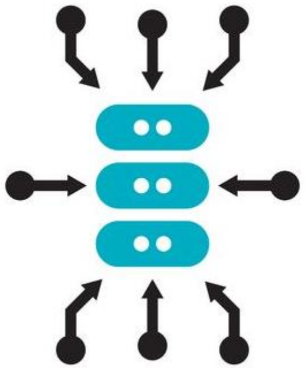
Flexible Demand Vs Storage

- Advantage:
- The storage facility has often already been built.
- Does not require the large investments needed for batteries or pumped hydro plants.
- The downside:
- Providing services to the power system is not the primary purpose of these facilities.
  - Constraints on the manufacturing process or the comfort of residential users limit their usage as a system resource.

The flexible consumer's perspective

energycentral.com

Aggregation



- Smaller consumers must be aggregated to have a measurable effect.
- Some large industrial consumers are able to shift loads that are sufficiently large to be significant at the system level.

The flexible consumer’s perspective

energycentral.com

Remunerating

- Price-based:
  - Consumers are exposed to time-varying price.
  - They to schedule their consumption in a way that minimizes their cost while meeting their needs for production efficiency or comfort.
- Incentive-based:
  - Consumers are not exposed to time-varying prices.
  - They agree to reduce or shift their load in response to a signal from their utility, their retailer, or their aggregator.
  - They are entitled to a favourable tariff.

The flexible consumer's perspective

energycentral.com

Remunerating

The contract between the flexible consumer and the entity sending the signal must also specify the following:

- How often the consumer is expected to respond
- How large should the load reduction be
- How much time must elapse before the consumer can return to its normal consumption pattern and start recovering the energy not consumed
- How the consumer's response will be measured

The flexible consumer’s perspective

energycentral.com

Implementation issues

Centralized paradigm:

- Considered along with the supply side in a centralized optimal scheduling process.
- consumers submit the technical and economic characteristics of their flexibility to the ISO.
- ISO schedules their operation simultaneously with the generating units through a global optimization problem.
- Dispatch signals are then sent to each individual flexible load and generating unit.

The flexible consumer’s perspective

energycentral.com

Implementation issues

- Self-schedule in response to posted prices.
  - Consumers take advantage of price differences to reduce their electricity bills.
  - Prices are higher during peak demand periods and lower during off-peak demand periods.
  - Consumers would have an incentive to shift their demand from peak to off-peak periods.
  - A naive application of such a pricing scheme, combined with an automatic response of the appliances to these prices, could concentrate the demand at the periods with the lowest prices, potentially creating new demand peaks during originally periods of low demand, leading to inefficient system operation.
  - Similarly, flexible demand has been shown to “rebound” after a period of high prices.

The flexible consumer's perspective

energycentral.com

Example-Centralized Scheduling of Flexible Appliances

- Let us consider an electricity market that is centrally scheduled over two, one-hour market periods.
- The participants in this market are as follows:
  - A generator, producing $P_t(t)$(MW) at hour t with a cost function C(P_t) $= 100P_t^2$ ($) and a maximum output P^{max} = 8 MW.
  - An inflexible demand, consuming D_1 =1 MW during period 1 and D_2 = 2 MW during period 2.
  - One thousand identical flexible appliances with continuously adjustable demands d_t. Each of these appliances must consume E= 6 kWh over the two market periods but cannot consume more than d^{max}= 5 kWh during each period.

The flexible consumer’s perspective

energycentral.com

Example-Centralized Scheduling of Flexible Appliances

- The objective of the centralized schedule is to determine the demand of the flexible appliances during each of the two periods that minimize the total generation cost.
- Because the cost function of the generator is quadratic, minimizing this total cost is equivalent to minimizing the absolute value of the difference between the power produced by the generator during these two periods:

$$\min|P_1 - P_2|$$

The flexible consumer's perspective

energycentral.com

Example-Centralized Scheduling of Flexible Appliances

- Since the total generation must be equal to the total demand at each period, we have:

$$P_1 = D_1 + 1000 * d_1$$

$$P_2 = D_2 + 1000 * d_2$$

- Inserting these two equations into the objective function, we get:

$$\min |(D_1 + 1000 * d_1) - (D_2 + 1000 * d_2)|$$

The flexible consumer's perspective

energycentral.com

Example-Centralized Scheduling of Flexible Appliances

- We must also take into account the operating constraints on the generation:

$$D_1 + 1000 * d_1 \leq P^{max}$$

$$D_2 + 1000 * d_2 \leq P^{max}$$

- And on the flexible appliances:

$$d_1 \leq D^{max}$$
$$d_2 \leq D^{max}$$
$$d_1 + d_2 = E$$

Example-Centralized Scheduling of Flexible Appliances

$$
\begin{aligned}
P^{max} &= 8 \text{ MW.} \\
D_1 &= 1 \text{ MW} \\
D_2 &= 2 \text{ MW} \\
d_1 + d_2 &= E = 6 \text{ kWh} \\
d^{max} &= 5 \text{ kWh} \\
\mathrm{C}(P_t) &= 100P_t^2 \ (\$)
\end{aligned}
$$

The flexible consumer's perspective

energycentral.com

Feasible flexible scheduling options

d_1	d_2	P_1	P_2	C(P_1)+C(P_2)
5.0	1.0	6.0	3.0	4500
4.5	1.5	5.5	3.0	4500
4.0	2.0	5.0	3.0	4500
3.5	***2.5***	***4.5***	***3.0***	***4500***
3.0	3.0	4.0	5.0	4100
2.5	3.5	3.5	5.5	4250
2.0	4.0	3.0	6.0	4500
1.5	4.5	2.5	6.5	4850
1.0	5.0	2.0	7.0	5300

Optimal values are in red.

The flexible consumer’s perspective

energycentral.com

Example-Unlimited Self scheduling of Flexible Appliances

- Suppose that each flexible appliance is informed ahead of time that the price will be π_1 during hour 1 and π_2 during hour 2.
- Because the inflexible demand is lower during hour 1, the market operator would set $\pi_1 \leq \pi_2$ to encourage a shift in demand from hour 2 to hour 1.
- If, as we assume, the appliances respond entirely to prices, as much of the flexible demand as possible would be reallocated to the period of low price, i.e. hour 1. We would then have:

$$d_1 = d^{max} = 5 \text{ kW}$$
$$d_2 = E - d_1 = 1 \text{ kW}$$

The flexible consumer’s perspective

energycentral.com

Example-Unlimited Self scheduling of Flexible Appliances

- To balance generation and load, the generation schedule would then have to be:

$$P_1 = D_1 + 1000d_1 = 6 \text{ MW}$$
$$P_2 = D_2 + 1000d_2 = 3 \text{ MW}$$

- Hour 1 would then no longer be the off-peak period and the total generation cost would be:

$$100P_1^2 + 100P_2^2 = \$4500$$

which is significantly higher than the cost under optimal centralized scheduling because the prices π_1 and π_2 are not consistent with the actual generation schedule.

The flexible consumer’s perspective

energycentral.com

Example-Unlimited Self scheduling of Flexible Appliances

- To balance generation and load, the generation schedule would then have to be:

$$P_1 = D_1 + 1000d_1 = 6 \text{ MW}$$
$$P_2 = D_2 + 1000d_2 = 3 \text{ MW}$$

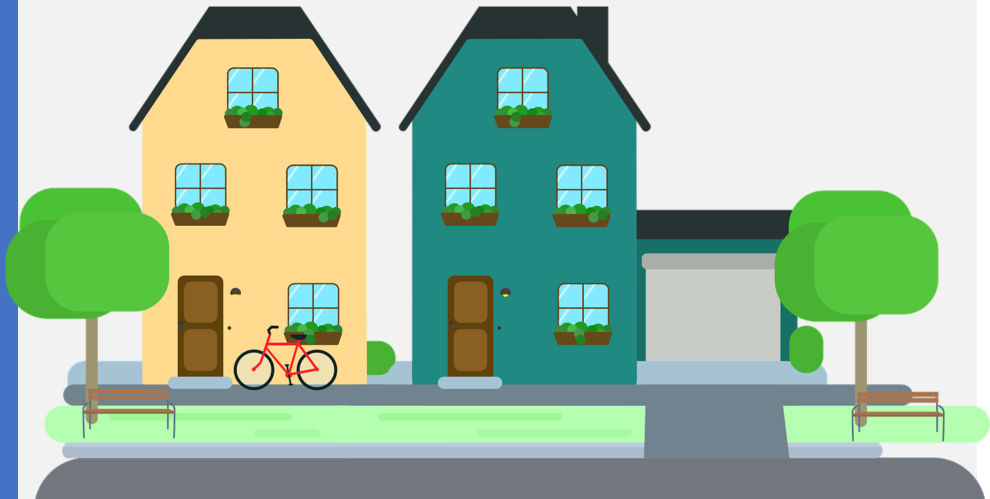
- Hour 1 would then no longer be the off-peak period and the total generation cost would be:

$$100P_1^2 + 100P_2^2 = \$4500$$

which is significantly higher than the cost under optimal centralized scheduling because the prices π_1 and π_2 are not consistent with the actual generation schedule.

The neighbor’s perspective

The neighbor's perspective



Example-Unlimited Self scheduling of Flexible Appliances

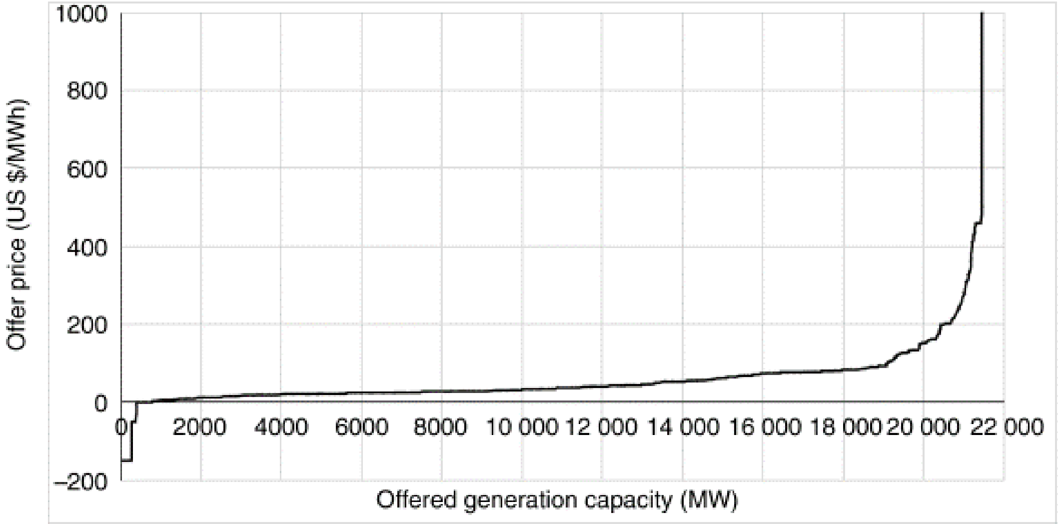
- Some power systems where a competitive electricity market has been introduced are interconnected with neighbouring systems that are operated by vertically integrated utilities. (e.g. Washington state and California state)
- These utilities often take part in the competitive market.
- If the price paid for electrical energy is higher than their marginal cost of production, they sell power on the market.
- If the price is lower than their marginal cost of production, they purchase power on the market.

An Overall Perspective

An overall Perspective

Clearing the market

An offer curve derived from data collected on the ISO-New England website.
This curve was built by stacking 556 price/ quantity offers submitted by generators in increasing order of price.

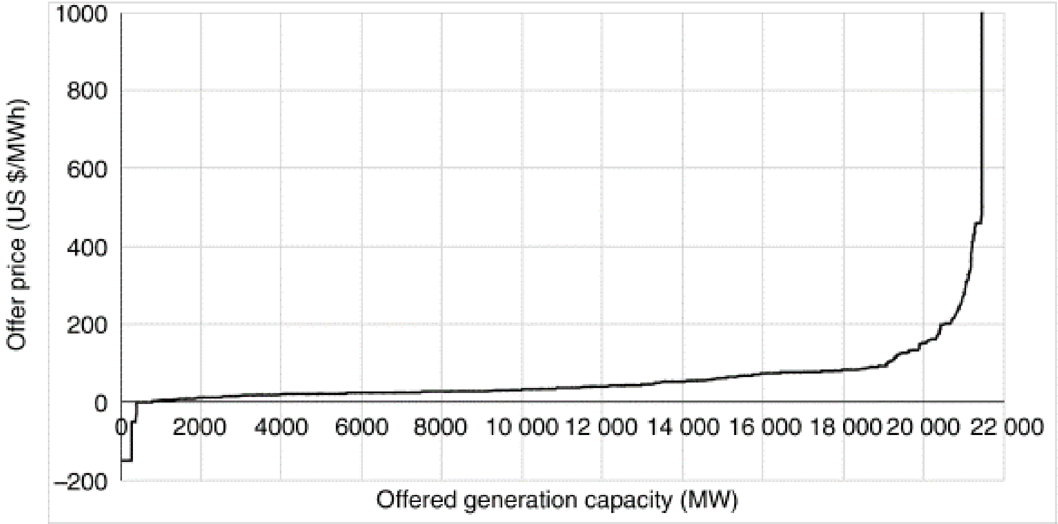


Offer curve for the ISO-New England day-ahead market of March 30, 2016.

An overall Perspective

Clearing the market

An offer curve derived from data collected on the ISO-New England website.
This curve was built by stacking 556 price/ quantity offers submitted by generators in increasing order of price.

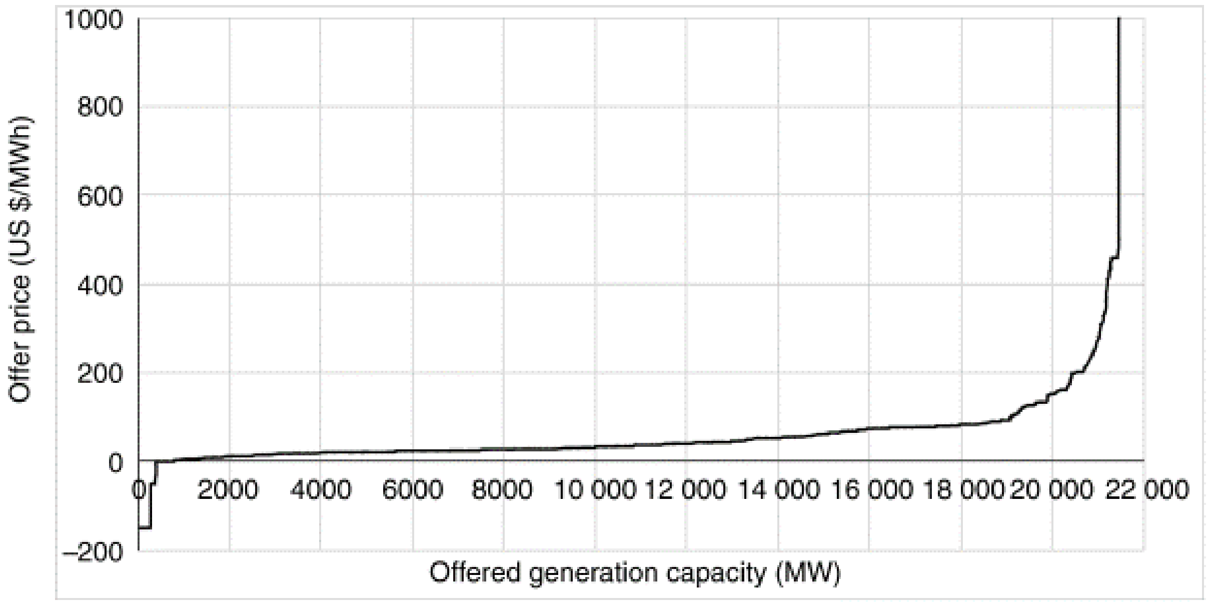


Offer curve for the ISO-New England day-ahead market of March 30, 2016.

An overall Perspective

Clearing the market

Offer curve for the ISO-New England day-ahead market of March 30, 2016.

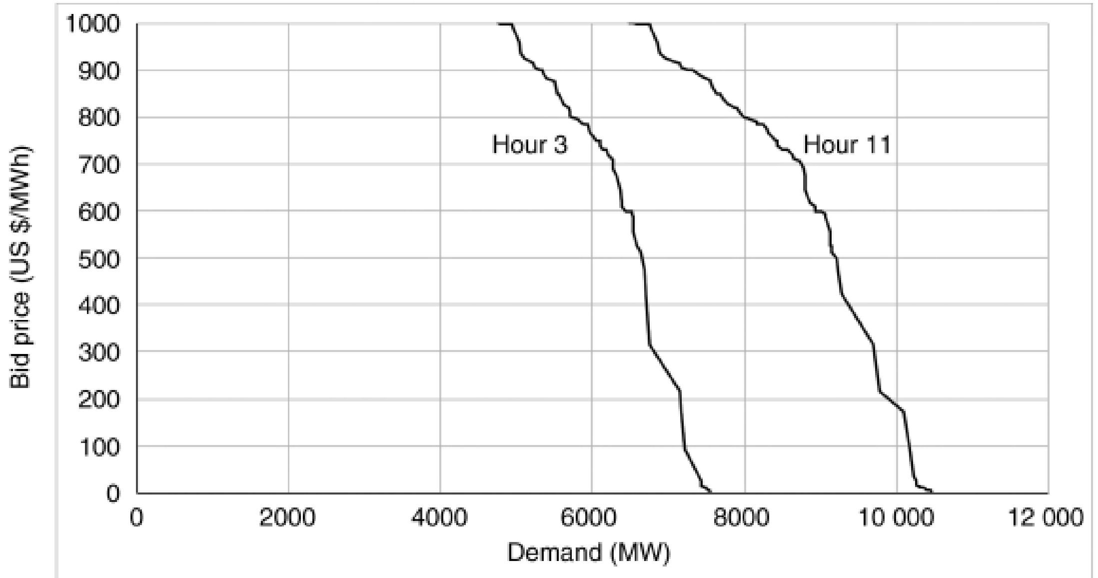


We can discern four distinct parts on this curve:

1. About 750 MW of capacity is offered at zero or negative prices. Some of these bids are submitted by nuclear, run-of-the-river hydro, trash burning, and other generators that have to run and thus want to make sure that they are included in the production schedule, no matter the price. Other offers might come from renewable generators who receive production subsidies and can thus remain profitable even if the price is negative.
2. From about 750 MW to about 19000 MW, the offer price increases gradually and is likely to reflect each generator's marginal production cost. Note that some generating units submit a single price/ quantity pair while others divide their offer into 10 segments, which is the maximum allowed by the market rules.
3. From 19000 to 21400 MW, the offer price increases much more steeply. These offers are submitted either by generators with a much higher marginal cost or by generators that run infrequently and thus need a much higher price to recover their fixed costs.
4. A few generators offer at the ceiling price of 1000 $/ MWh.

An overall Perspective

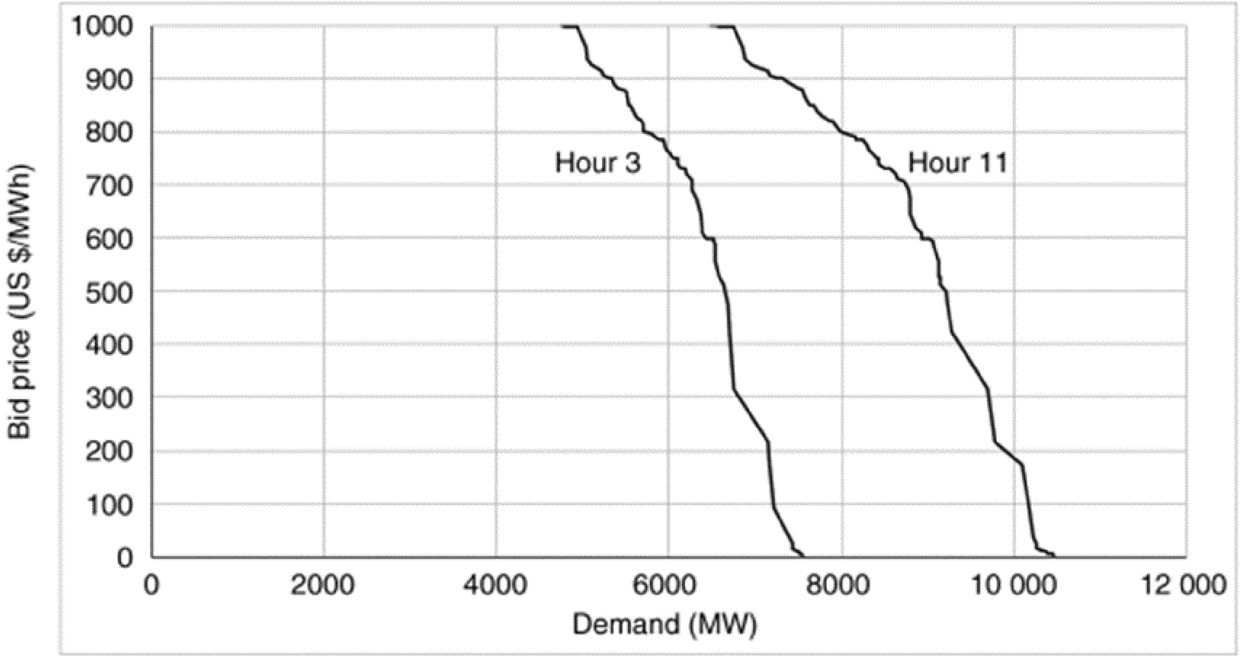
Clearing the market



Bid curves for the ISO-New England day-ahead market for hours 3 and 11 of March 30, 2016.

An overall Perspective

Bid curves for the ISO-New England day-ahead market for hours 3 and 11 of March 30, 2016



Clearing the market

The curve on the left is for the trading period ending at 3 a.m. (i.e. close to the minimum demand for that day) while the curve on the right is for the trading period ending at 11 a.m. (i.e. close to the maximum demand for that day).

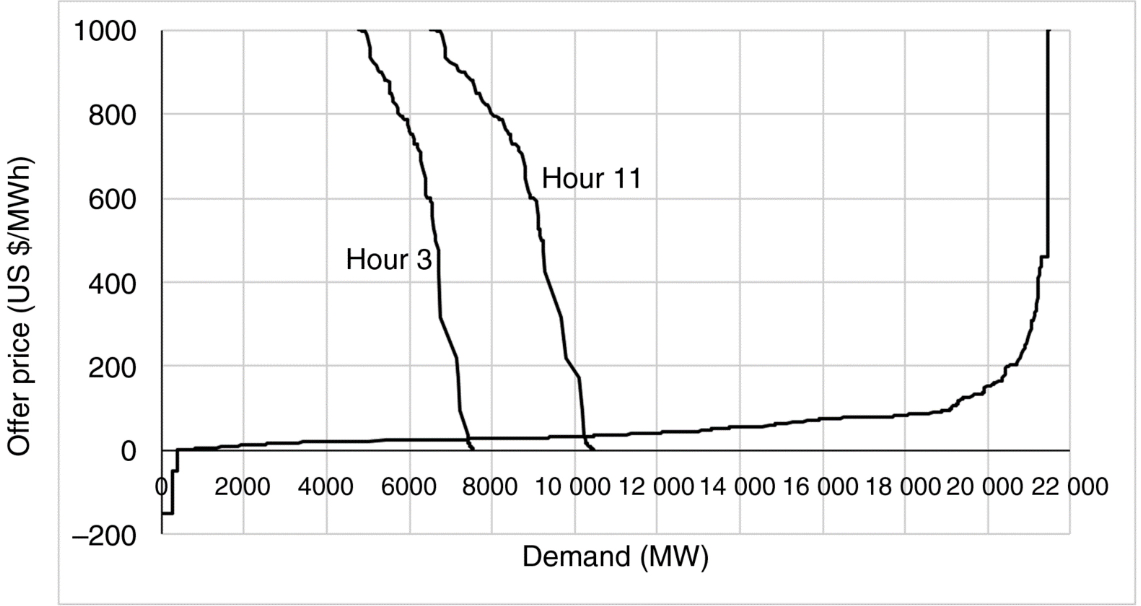
No price was submitted for about 7550 MW of demand bids at hour 3 and 10500 MW at hour 11, indicating that these consumers are not price-sensitive.

On the other hand, since roughly 2800 and 4000 MW of price-sensitive bids were submitted for hours 3 and 11, respectively, these demand curves exhibit some price elasticity.

However, a substantial part of this elasticity probably stems from virtual bids submitted in the day ahead market rather than from actual load flexibility.

An overall Perspective

Clearing the market

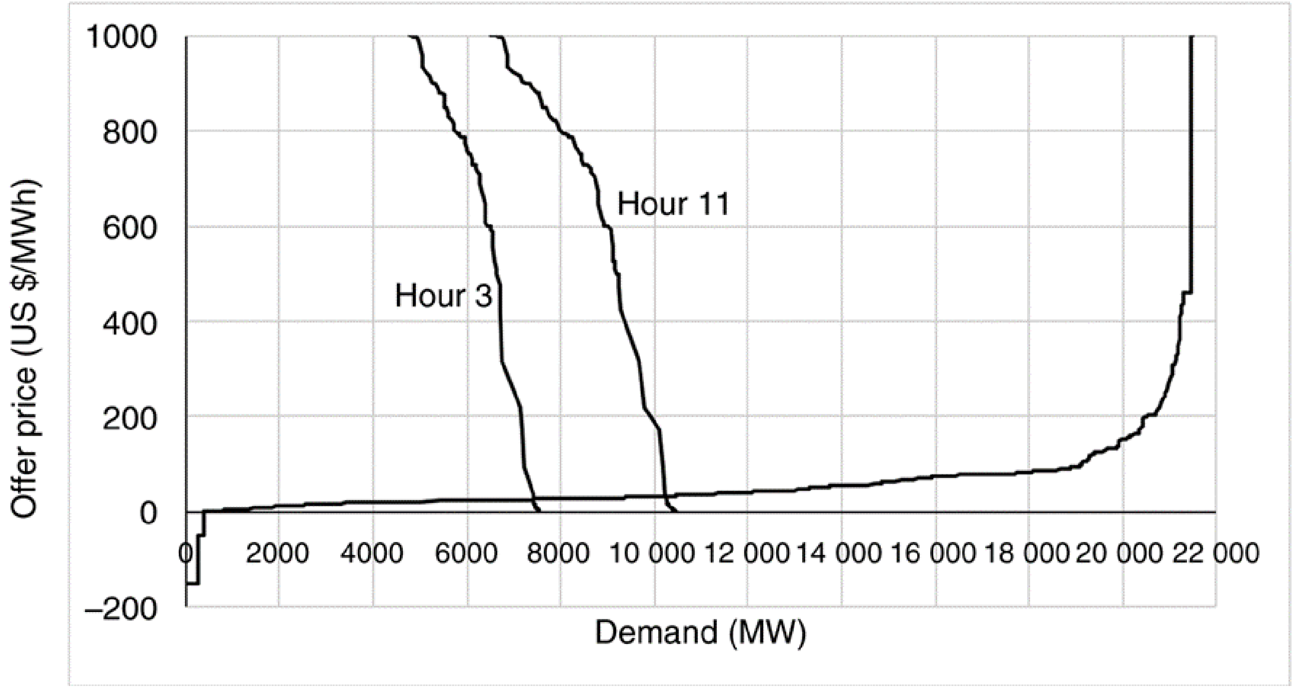


Market clearing for the ISO-New England day-ahead market for hours 3 and 11 of March 30, 2016.

An overall Perspective

Clearing the market

Market clearing for the ISO-New England day-ahead market for hours 3 and 11 of March 30, 2016.



The market clearing price for the various market periods of this particular day will vary within a relatively narrow range.

This is to be expected because March 30, 2016 was a relatively mild spring day that did not require much electric heating or cooling.

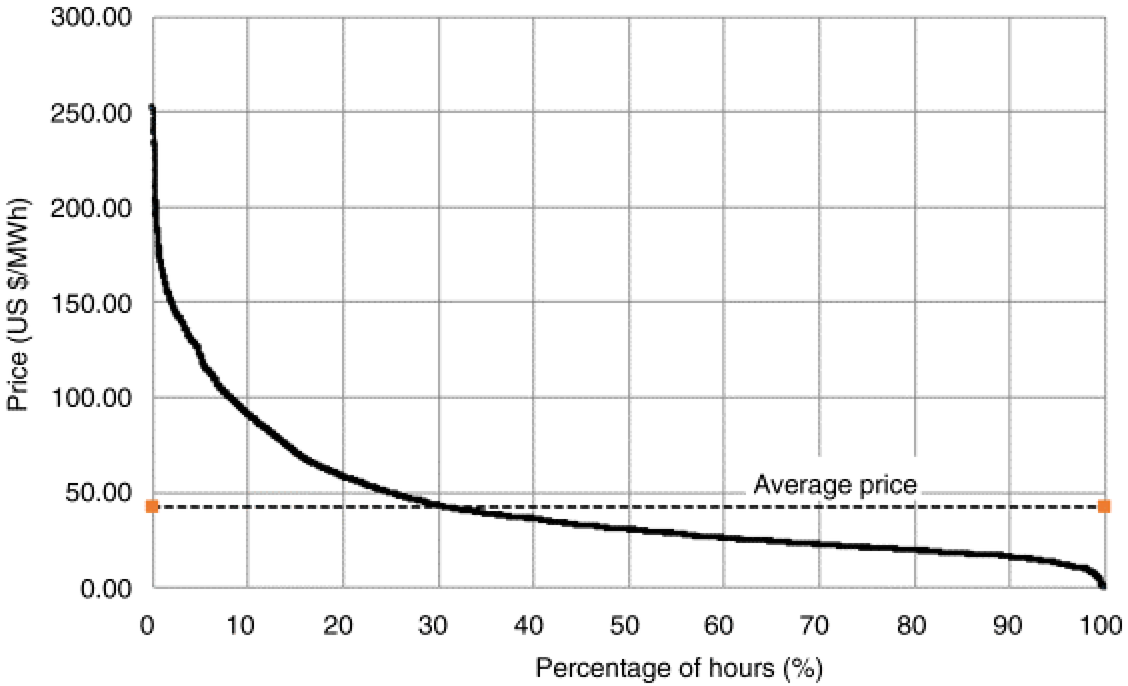
The generation capacity was much larger than the demand and none of the generating units that bid at a high price were needed.

On a particularly hot or cold day, the demand curve shifts far to the right. Because of their relative shapes, the intersection of the supply and demand curves can shoot up to very high prices for a small increment in load at peak time, creating price spikes.

An overall Perspective

Clearing the market

Day-ahead hourly price duration curve for the Boston area of ISO-New England for the year 2015. Prices are in US dollars.

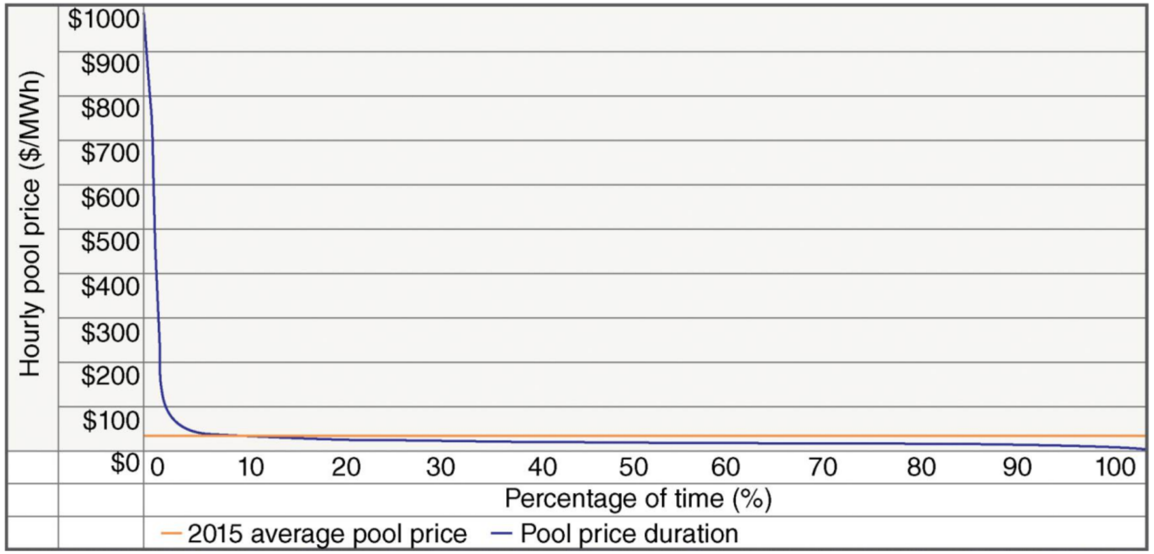


Summarizes how the ISO-New England market cleared during the year 2015 using a price duration curve, i.e. a plot showing the percentage of hours during which the market clearing price exceeded a given value.

An overall Perspective

Exercising Market Power

Price duration curve for the Alberta Electricity Market for 2015. Prices are in Canadian dollars.



shows that prices on the electricity market of the Canadian province of Alberta generally vary over a narrower range but spike to much higher values a few percent of the time.

An overall Perspective

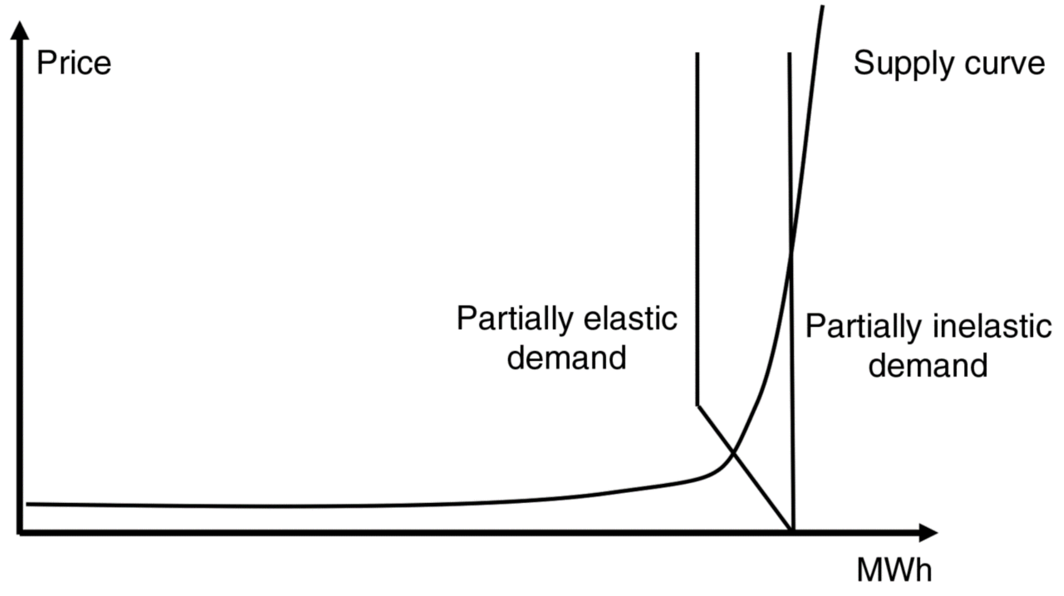
Exercising Market Power

- Economic withholding entails offering some capacity at a high price.
  - This means making the steep part of the offer curve even steeper to push up its intersection with the (also steep) demand curve.
- Physical withholding consists in not offering a substantial amount of generation into the market.
  - Withholding capacity thus shifts the rest of the offer curve to the left, resulting again in a higher market clearing price.

An overall Perspective

Exercising Market Power

Effect of a partially elastic demand on market clearing



- The exercise of market power is more likely to be significant during periods of high demand.
- Exercising market power is less effective if the price elasticity of the demand is higher.

An overall Perspective

Dealing with Market Power

- It is not unusual for firms to form a cartel and collude to divvy the market and keep prices high.
- Exercising market power is not prohibited.
- Collusion is illegal.
- Regulatory authorities impose substantial penalties when companies are caught in the act.
- However, collusion often takes a subtler form. Instead of discussing how to rig the market, firms that compete on a regular basis can send each other signals through published prices.

An overall Perspective

Dealing with Market Power

- Impose a price cap.
    - Automatically limit prices to a value set by the regulatory authority.
    - This cap must be set relatively high because high prices are occasionally justified because they signal a need to invest in additional generation capacity and because they help generators recoup their fixed costs.
- Some markets also implement bid caps, i.e. limits on the offer price that generators are allowed to submit.
- Bid mitigation techniques.
    - When the exercise of market power is suspected, offending offers are replaced by standard offers based on the characteristics of the generating unit and the current fuel cost.
    - Prices are then recalculated using these standard offers and compared to the original prices. If these new prices are significantly lower than the old prices, bids are capped at the standard offers.
- Punish perpetrators. However, it is difficult to prove that an abuse of market power has occurred

Questions?