

Energy Market and Game Theory

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Learning Objectives

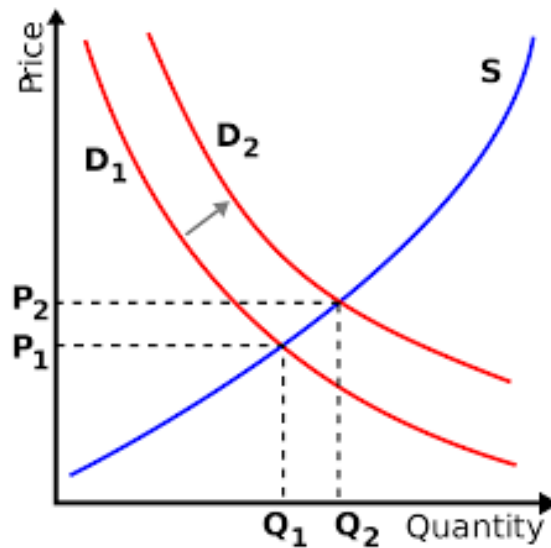
Through this lecture, the students should be able to

- Learn the **basic concepts** of game theory and **classic game models**
- Learn the basic concepts and principle of **energy market**
- Understand how game theory acts as a powerful tool to **model and analyze energy market**

Outline



Game Theory



Energy Market

STARTING WITH SOME EXAMPLES

Battle of the Sexes

You and your partner are spending weekend together.

You want to play an online game

Your partner wants to go shopping.

What will you choose?



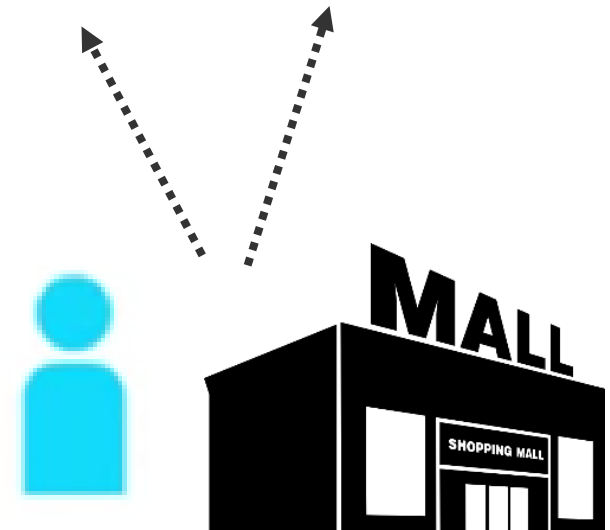
Selection of Power Sources

Oslo has two power companies **A** and **B** to provide electricity

- A is stable, but not green
- B is green, but not stable



How should a user choose A or B?



Common features in these examples



**Competitive situations or
situations of conflict**

Multiple players



Decision making

**Concerned more about
choices than 'best' solutions**

Background, Basic Concepts and Definitions

GAME THEORY

Game Theory: History

Cournot, Bertrand
and Stackelberg



John Von
Neumann

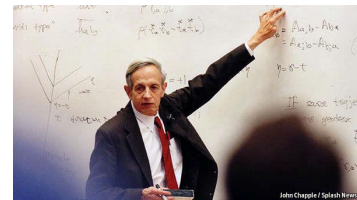


John Von Neuman and
Oskar Morgensten:
Game theory became
more widely known



John Harsanyi, John Nash
and Rienhard Selten
Were awarded Nobel Prize
for Economics

Important
Developments: Nash
equilibrium



1928

1944

1950-1960

1994

Game theory as a discipline

Game theory is an interdisciplinary field encompassing economics and mathematics and one that can be deployed to solve problems for numerous applications



Three key elements in a game



Players



Strategies



Payoffs

Figure source:

http://www.slate.com/articles/sports/sports_nut/2013/11/the_world_chess_championship_is_an_embarrassing_anachronism_it_s_time_to.html

Game theory as a discipline

Game theory is an interdisciplinary field encompassing economics and mathematics and one that can be deployed to solve problems for numerous applications

Three key elements in a game

Players: Each player can be an individual, a group or an organization

Strategies: a plan of actions by which a player has a decision rule to determine their moves for every possible situation in a game

Payoff: benefit received for a given strategy; often termed as **utility**



Figure source:

http://www.slate.com/articles/sports/sports_nut/2013/11/the_world_chess_championship_is_an_embarrassing_anachronism_it_s_time_to.html

Key Elements in “Battle of the Sexes” – an example



Two types of games

Non-cooperative game

A game with **competition between individual players**. Only self-enforcing (e.g. through credible threats) alliances (or competition between groups of players) are possible due to the **absence of external means to enforce cooperative behavior** (e.g. contract, law).



Cooperative game

A game with **competition between groups of players** due to the possibility of external enforcement of cooperative behavior (e.g. through contract)

Cooperation generally leads to higher payoffs. For example: countries cooperate on trading (reduced tariffs) leading to boost in exports



A classic non-cooperative game “Prisoner’s Dilemma”

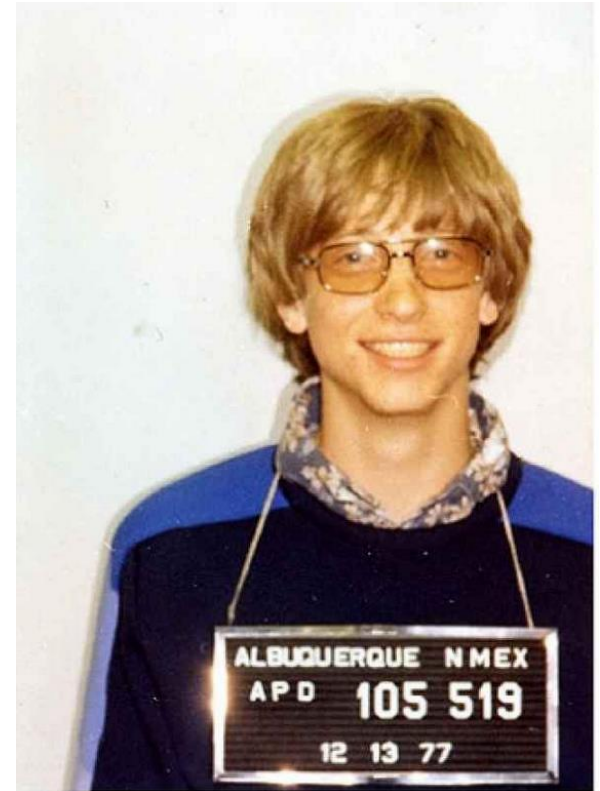
You and your friend Bill are arrested and thrown into prison in separate cells.

For three days, neither you nor Bill has told nothing

.....Then.....

You are told by the police: “We have your friend Bill and he is starting to talk”

Should you confess?



Bill Gates at the age of 19

How to choose strategy to minimize the number of years in prison?



Each prisoner is rational and selfish. Namely, he wants to maximize his own benefit and does not care about the other person's benefit.

Each prisoner is put in separate room and does not know the other person's choice.

When you and Bill can talk, you may not trust even if Bill claims to cooperate.

Prisoner's Dilemma – payoff matrix



The prisoner's dilemma

		Prisoner B	
		Confess	Keep quiet
Prisoner A	Confess	Both go to jail for ten years	Prisoner B gets life imprisonment, A goes free
	Keep quiet	Prisoner A gets life imprisonment, B goes free	Both go to jail for one year

Prisoner's Dilemma – payoff matrix

<u>You</u>	<u>Bill</u>	
	Confess	Don't Confess
Confess	(8, 8)	(0, 15)
Don't Confess	(15, 0)	(1, 1)

Payoff matrix: each cell is a pair of payoff, the number of years in prison.

– (8,8) → both you and Bill go to prison for 8 years

If both you and Bill confess, you both go to prison for 8 years

If you confess but Bill doesn't confess, then you are free while Bill goes to prison for 15 years

If both you and Bill remain silent, then you both go to prison for 1 year

Clearly the best result: both keep silent. (Q: Is this doable?)

Prisoner's Dilemma – shall you confess or not?

	<u>Bill</u>	
<u>You</u>	Confess	Don't Confess
Confess	(8, 8)	(0, 15)
Don't Confess	(15, 0)	(1, 1)

You reason as follows:

- If Bill confess, then you intend to confess to get 8 years instead of 15 years prison
- If Bill does not confess, then you intend to confess to get 0 years instead of 1 year in prison
- **Conclusion: you will confess!**

Prisoner's Dilemma

<u>You</u>	<u>Bill</u>	
	Confess	Don't Confess
Confess	(8, 8)	(0, 15)
Don't Confess	(15, 0)	(1, 1)

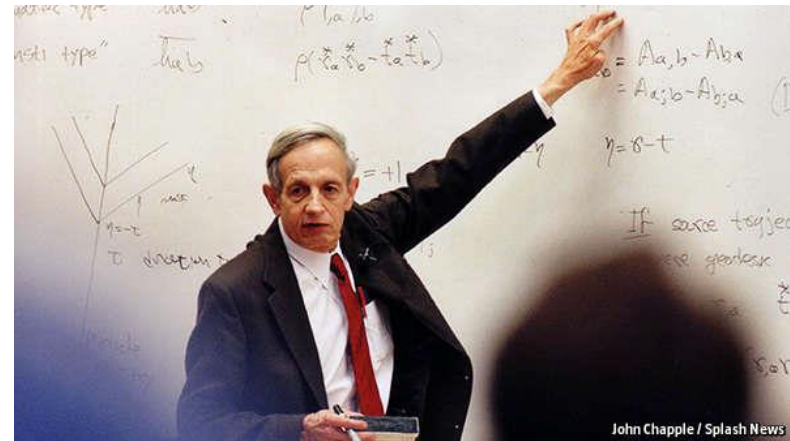
Dominant strategy

- Same as you, Bill will also confess! Both get 8 years in prison
- **Dominant strategy**: for both, confession is a dominant strategy that yields a better outcome regardless of the opponent's choice

Nash Equilibrium (NE)

Nash Equilibrium (NE): A combination of strategies is called a Nash Equilibrium **if neither player has an incentive to change strategy, given the other player's choice** mutual best response.

Best response: the strategy which produces the most favorable outcome, taking other players' strategies as given



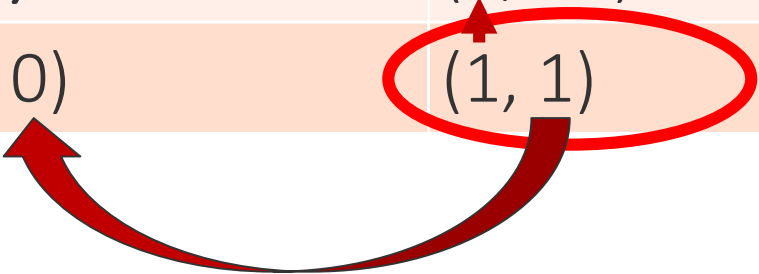
John Nash, Jr. (1928-2015)

Both confess is a Nash Equilibrium

Both don't confess is not a Nash Equilibrium. Why?

Both don't confess is not a Nash Equilibrium

<u>You</u>	<u>Bill</u>	
	Confess	Don't Confess
Confess	(8, 8)	(0, 15)
Don't Confess	(15, 0)	(1, 1)



Bill will confess, then be in prison from 1 year to zero

If both do not confess , the rival will always want to deviate

Equilibrium need not be efficient. Non-cooperative equilibrium in the Prisoner's dilemma results in a solution that is not the best possible outcome for the parties.

Individual's best choice is not the group's best choice. **An individual's rational choice may lead to group's non-rational choice**

Paradox

What would you and Bill decide if they could negotiate?



Cooperative solution: They could both have been better off if they had reached the cooperative solution

That is exactly why police interrogate suspects in separate rooms

Recall “Battle of the Sexes” Game

	<u>Your girlfriend</u> (Computer game)	<u>Your girlfriend</u> (Shopping)
<u>You</u> (Computer game)	(10,5)	(3,3)
<u>You</u> (Shopping)	(0,0)	(5,10)

Two equilibria: both play computer game; both go shopping.

However, either solution is unfair for one of you. (What is the equilibrium?)



Mixed Strategy

Two types of strategies: a **pure strategy** and a **mixed strategy**

A pure strategy: at every stage in the game, it specifies a particular move with complete certainty.

A mixed strategy: applies some **randomization** to at least one of the moves. The randomization is a set of fixed probabilities, where the sum of the probabilities is 1.

Game theory for the
ENERGY MARKET

Deregulated Energy Market

In regulated energy market, prices are all determined by the regulatory/government bodies:

- energy prices
- transmission and distribution prices

And, you cannot choose supplier

In deregulated energy market, prices are determined by the “**invisible hand**” of the market. There is competition among a set of suppliers. Norwegian electricity market was deregulated in 1991.

Deregulation allows different power suppliers to offer services to consumers. It allows you to choose your supplier.

For example, if you are unhappy with the price of your Internet service, you can change to another company. Deregulation in power market allows you the same **flexibility**.

Energy market players – power grid operators

Transmission system operators (TSOs)

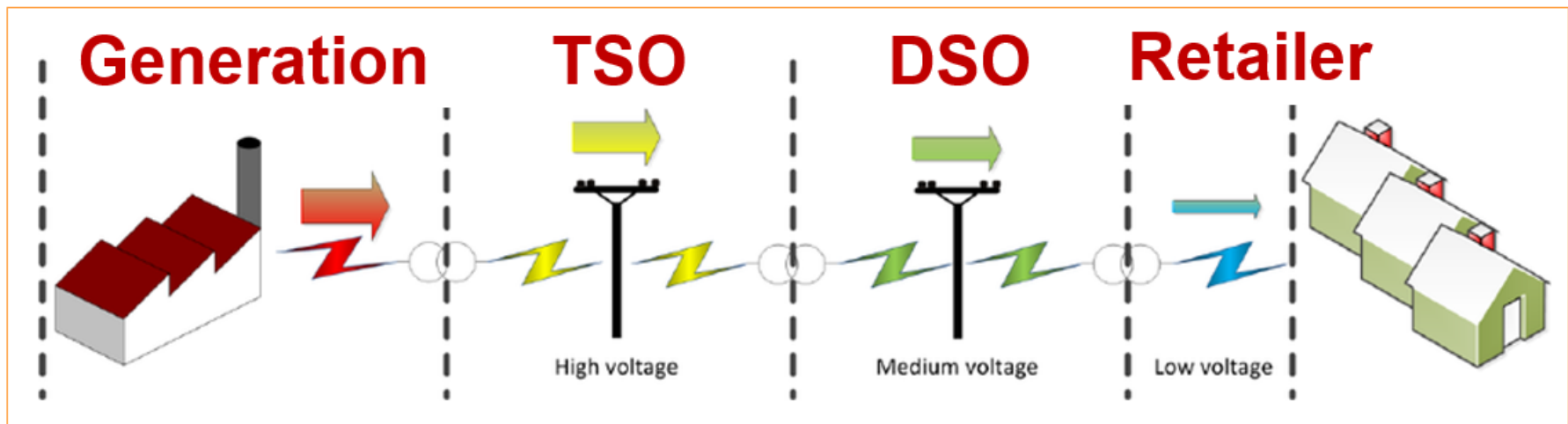
The TSO operates the transmission assets and is responsible for the power balance on the transmission system, e.g., Statnett

Statnett

Distribution system operators (DSOs)

Power distribution system to operate the distribution grid and transmit electricity to residential customers, e.g., Hafslund

Hafslund 



Energy market players – sell and buy

Generating company (**genco**)

The generators own production assets, whose generation is offered through the electricity market.



Retailer

The retailer buys electricity from the electricity market, then sell to the end-consumers.



Customers

Those eventually use the electricity for any purpose (from watching TV to heating to industrial production processes). There is a difference between small and large consumers, since the latter ones may be allowed to directly participate in the electricity market.



Energy market players – rule and operate the game

Regulators

Regulators effectively ‘police’ the energy market. The regulator is responsible for the market design and its specific rules. It also monitors the market in order to spot misbehavior in electricity markets (collusion, abuse of market power, etc.).

- NVE (The Norwegian Water Resources and Energy Directorate)

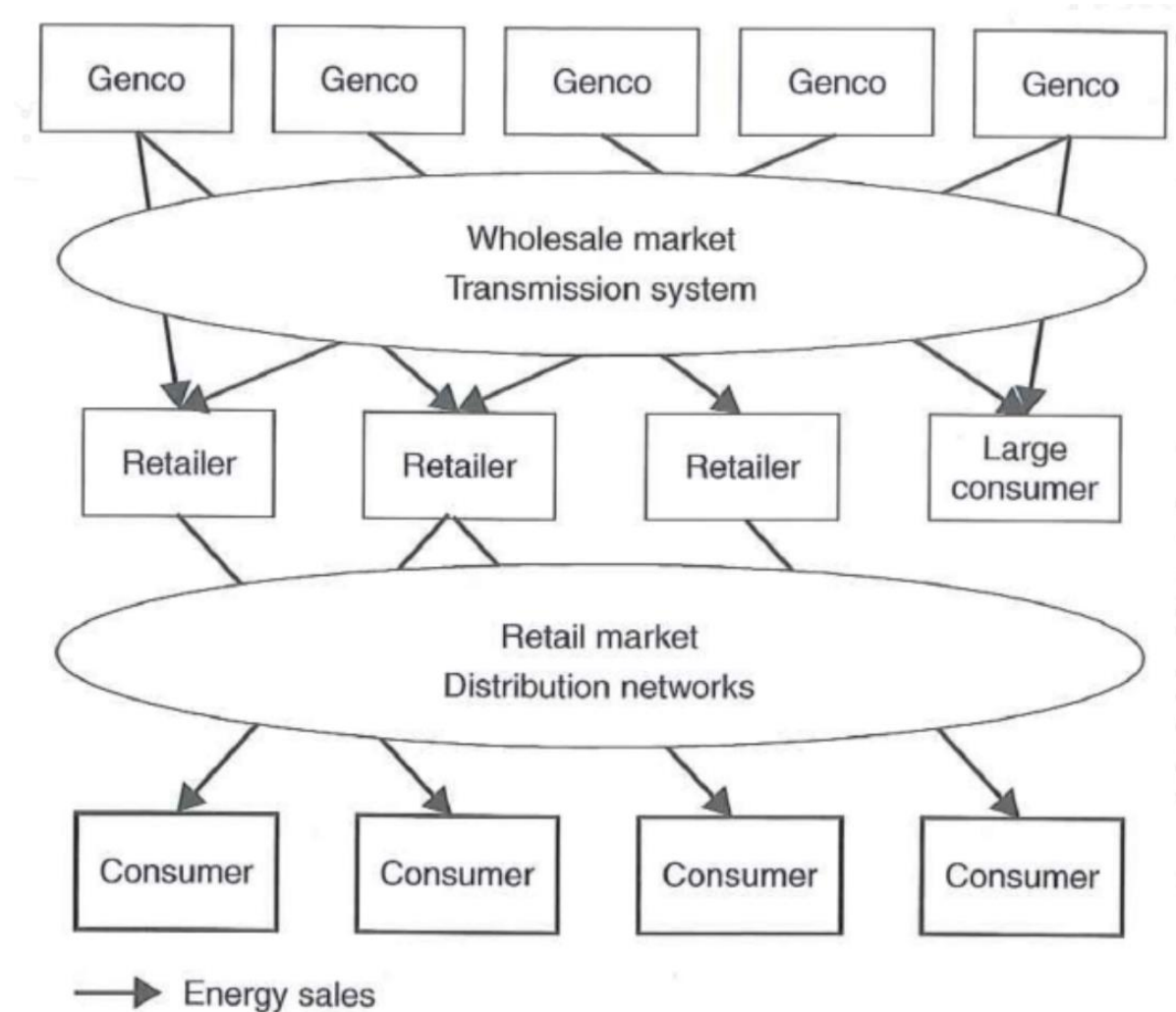


Market operator

Power exchange platform used by market players to negotiate purchases and sales of electricity., e.g., Nord Pool

**NORD
POOL**

Relationship between market players

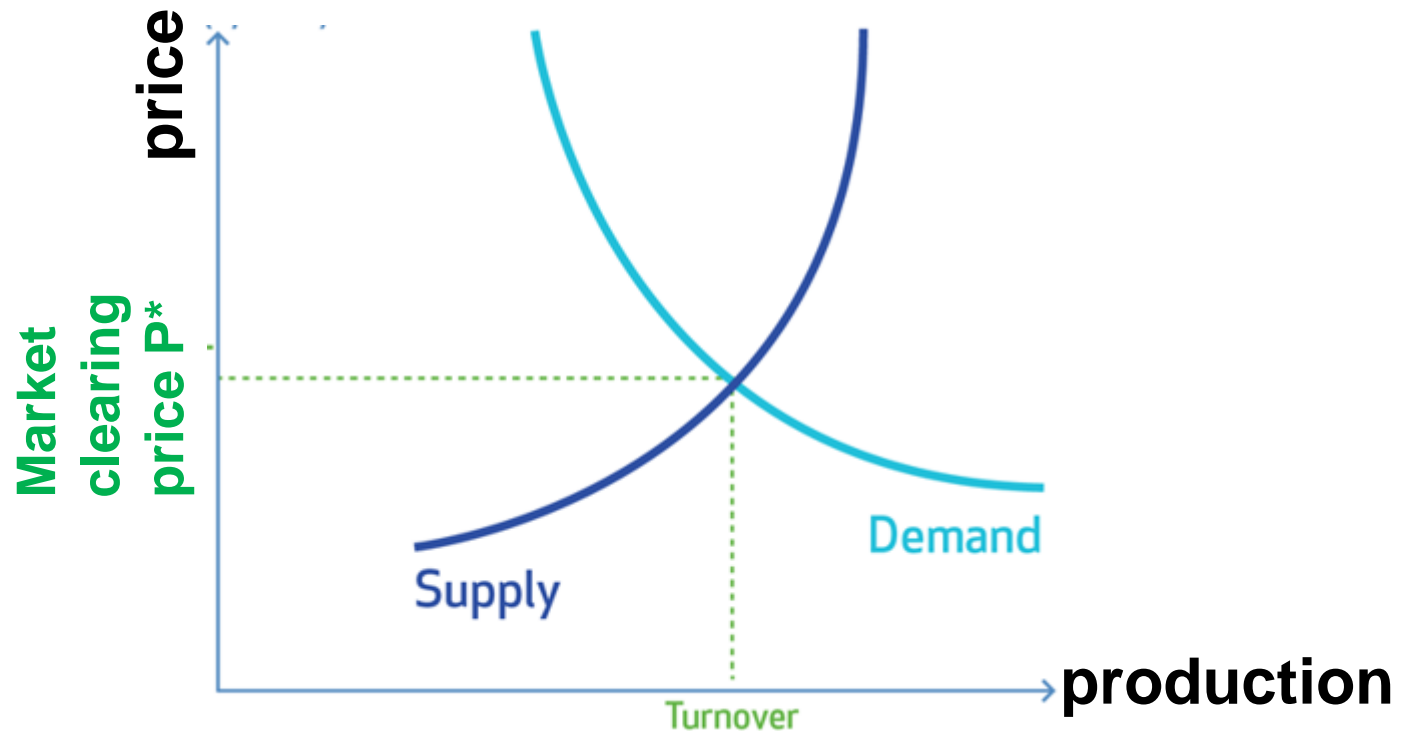


Market clearing price

Supply: power supply from generators

Demand: power demand from users

Market clearing price P^* when power supply is equal to power demand, i.e.,
Supply = Demand

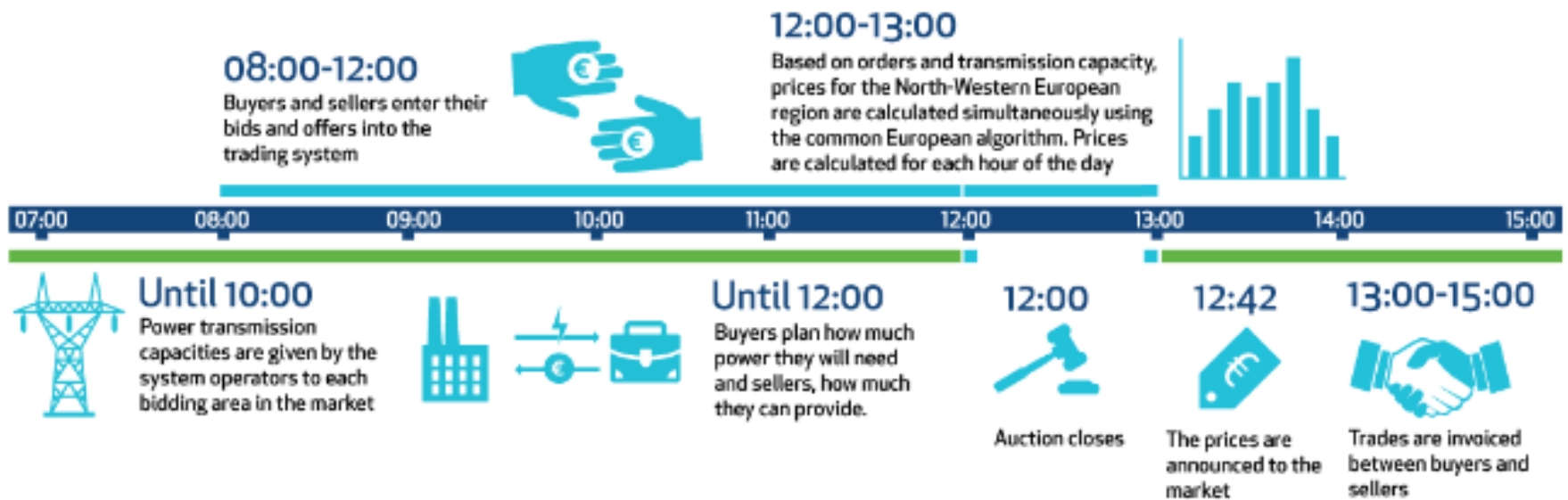


Nord Pool

Nordic Pool: power exchange platform used by market players to negotiate next-day purchases and sales of electricity.

Norway uses day-ahead trading system where buyers and sellers send orders.

The market price is important to establish equilibrium between supply and demand.



Day-ahead market

A buyer, typically a utility, needs to assess how much energy it will need to meet demand the following day, and how much it is willing to pay for this energy.

The seller, e.g., a power plant, needs to decide how much it can deliver and at what price.

Day-ahead market: contracts are made between seller and buyer for the power delivery the following day, the price is set and the trade is agreed.

The day-ahead market at Nord Pool becomes **a concrete visible hand** to create equilibrium. It is an auction based exchange for the trading of prompt physically delivered electricity.

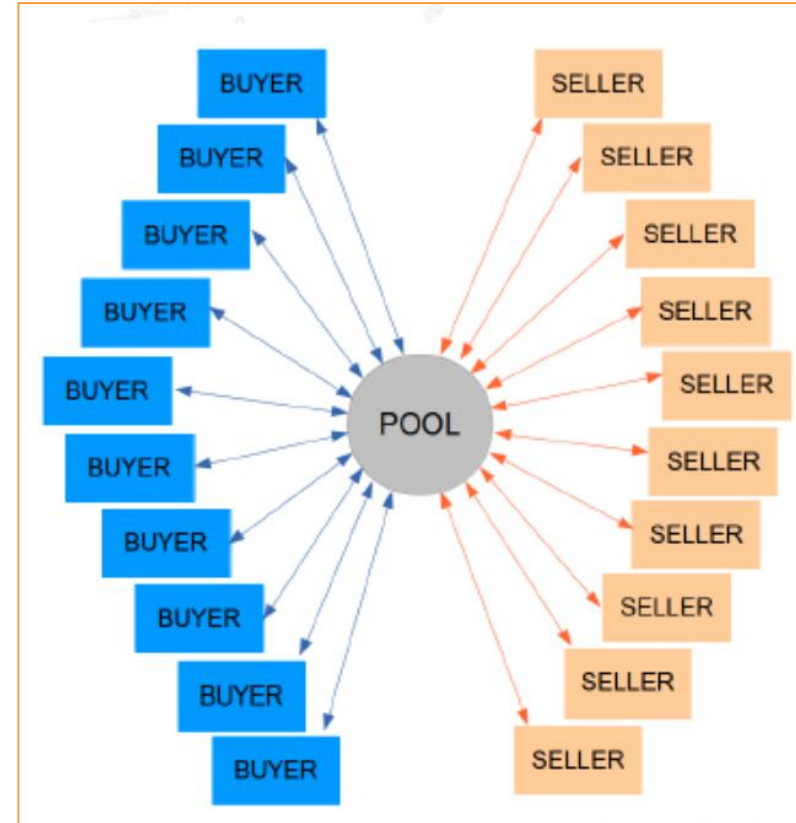
Auction in electricity pool

All generation bids and consumption offers are placed at the same time

No-one knows about others' bids and offers

An algorithm decides about bids and offers that are retained

Eventually, the system operator is informed about the trades that occurred



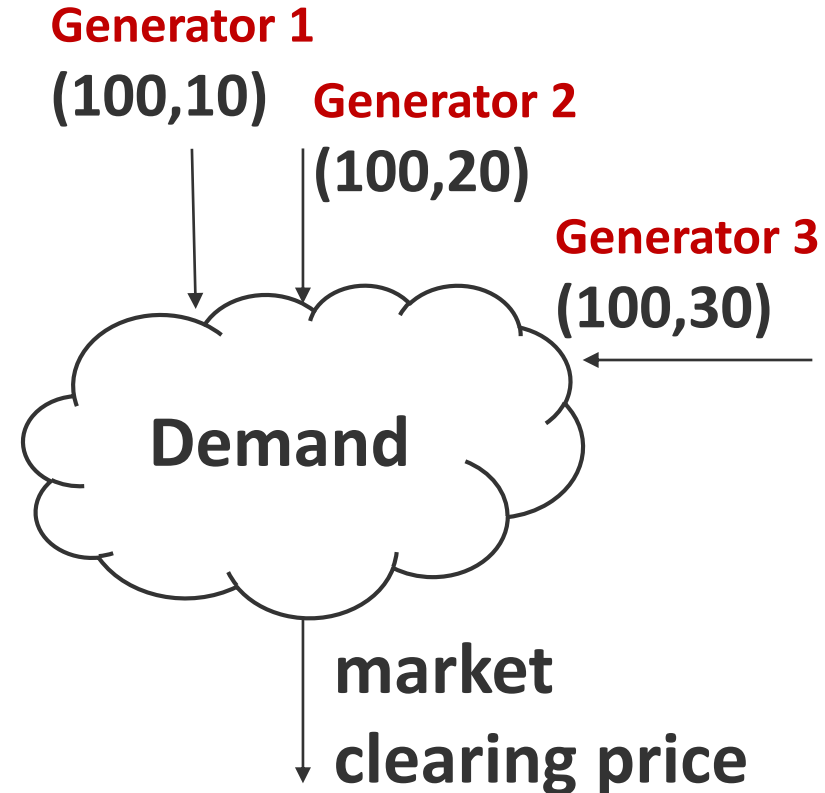
How does electricity market work? – an example

An electricity generator bids an amount of production and a price they will sell

Generators submit their bids simultaneously to the market in the form:
(production, bid price)

Example: Generator 1 with bid (100, 10)

- Generator 1 wants to sell 100MW with price 10\$/MW



Market Clearing Price

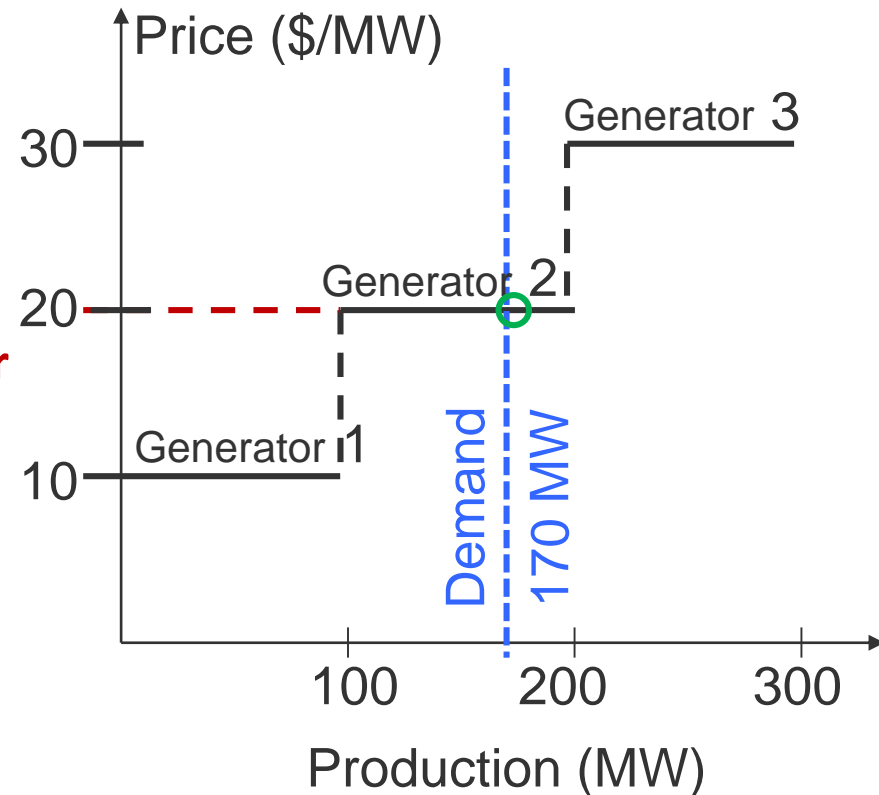
Three generators send bidding proposals.

- Generator 1 bid (100; 10)
- Generator 2 bid (100; 20)
- Generator 3 bid (100; 30)

The Market Operator (e.g., Nord Pool) organizes the proposals by **ascending order of prices**

The market operator finds the intersection between the demand line and the supply curve. This intersection gives the market clearing price.

Then, market clearing price is **20\$/MW**. This price is same for all generators when they are accepted and sell electricity.



Profits

The accepted bids are the ones in the left side of demand line:

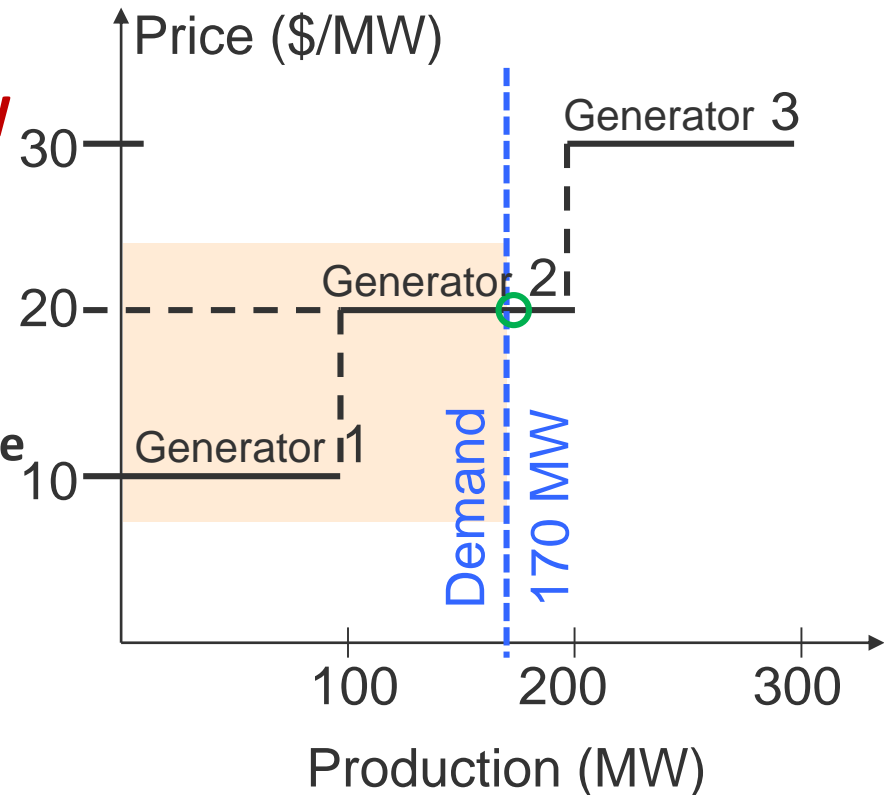
- **Generator 1 produces 100MW**
- **Generator 2 produces 70MW**
- **Generator 3 is not accepted**

Generator 1 will produce 100MW with price 20\$/MW

- The profit is: $100 \cdot (20 - 10) = 1000$

Generator 2 will produce 70MW with price 20\$/MW

- The profit is 0



Electricity Market Strategies

Electricity producers play the game using their price and production. By changing these two parameters, the market sharing changes.

Cournot strategy: Two firms compete simultaneously on the quantity of output they produce of a homogeneous good.

Bertrand strategy: Two firms compete simultaneously on the price of a homogenous good.



Antoine Augustin Cournot (1801-1877)



Joseph Louis François Bertrand (1822-1900)

Cournot Model

Non-cooperative: Generators are **non-cooperative**, independently decide their production (simultaneously).

Rational and selfish: A generator should decide how much electricity to produce in order **to maximize its profit** without knowing the decision of the others.

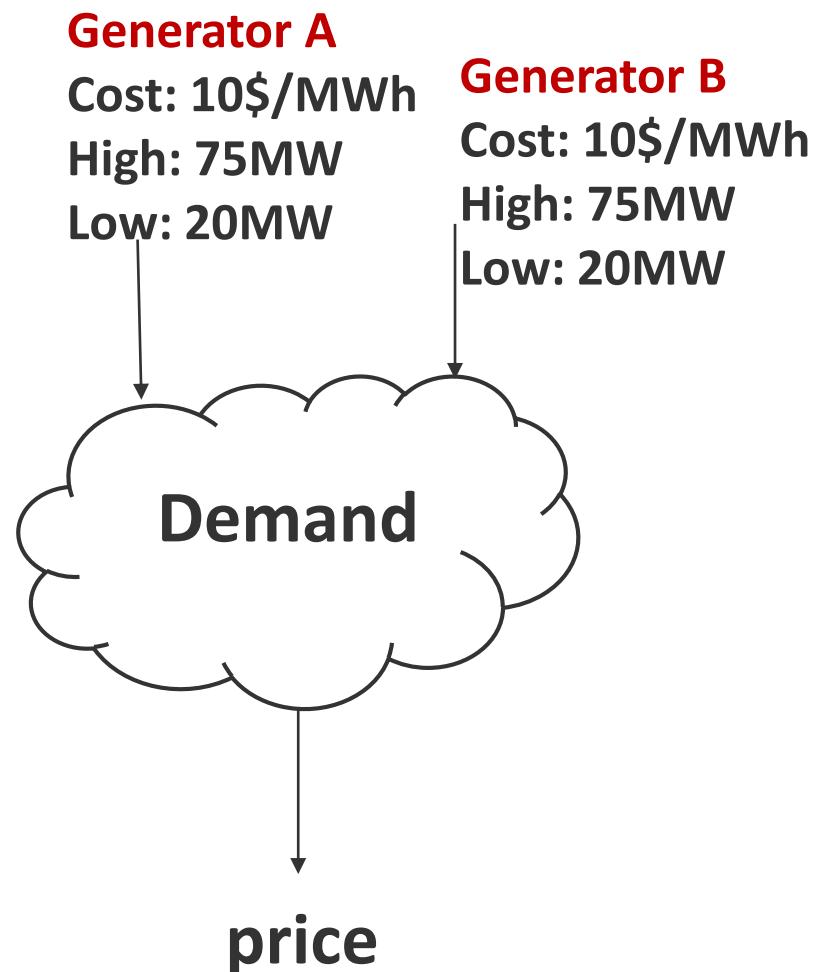
Electricity price will be determined by the demand curve and supply curve where the total supply is equal to the total demand.

Cournot Game with Two Generators

Each generator chooses only between two levels of production

- High production: 75MW
- Low production: 20MW

The low production may be interpreted as withholding of capacity with a motivation to increase prices. If prices increase sufficiently, the generator can make a higher profit at the low production.



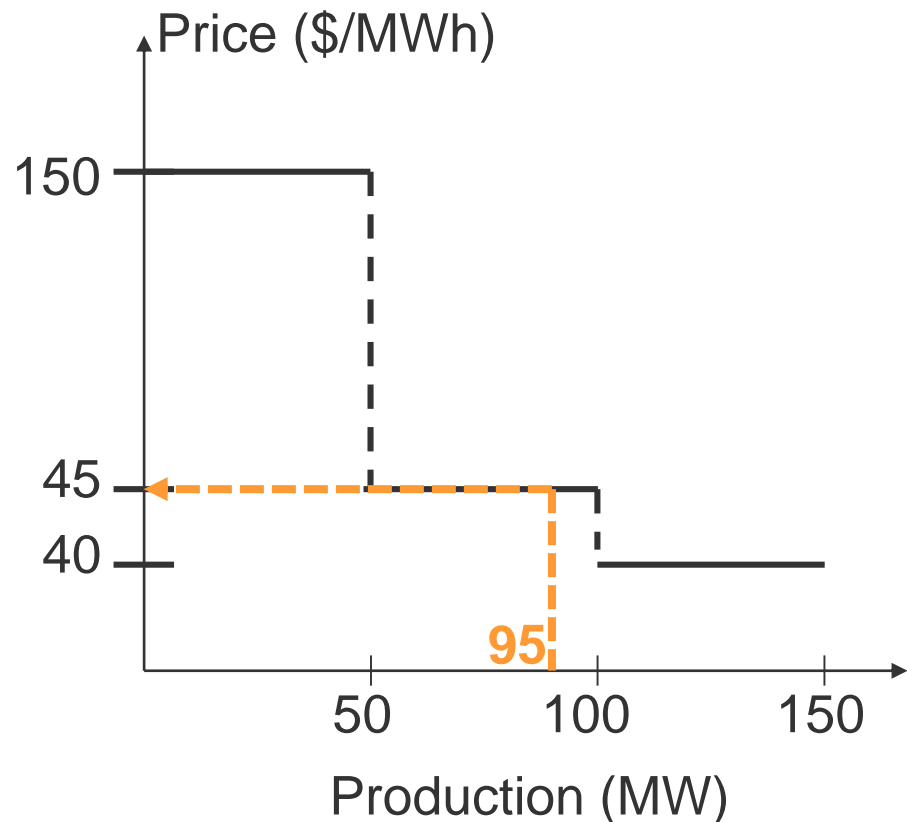
Cournot Game with Two Generators

Market price is set by the Market Operator

- If total power demand $< 50\text{MW}$, the price will be set as $150\$/\text{MWh}$
- If $50 < \text{power demand} < 100$, the price will be set as $45\$/\text{MWh}$
- If $100 < \text{power demand} < 150\text{MW}$, the price will be set as $40\$/\text{MWh}$

For example, when the total power demand is **95MW**, the price is set as **45\$/MWh**

Goal: to choose the power production level (either High or Low production) that maximizes their profits.



Power Production Matrix

PRODUCTION	<u>Generator B</u>	
<u>Generator A</u>	High	Low
High	(75, 75)	(75, 20)
Low	(20, 75)	(20, 20)

For (High, High) = (75, 75), the total production is **75+75=150**. According to the price curve, the price is **\$40**.

For (High, Low) = (75, 20), the total production is **95**. According to the price curve, the price is **\$45**.

For (Low, High) = (20, 75), the total production is **95**. According to the price curve, the price is **\$45**.

For (Low, Low) = (20, 20), the total production is **40**. According to the price curve, the price is **\$150**.

Nash equilibrium

PRICE	<u>Generator B</u>	
<u>Generator A</u>	High	Low
High	40	45
Low	45	150

PROFIT	<u>Generator B</u>	
<u>Generator A</u>	High	Low
High	(2250, 2250)	(2625, 700)
Low	(700, 2625)	(2800, 2800)

Nash Equilibrium

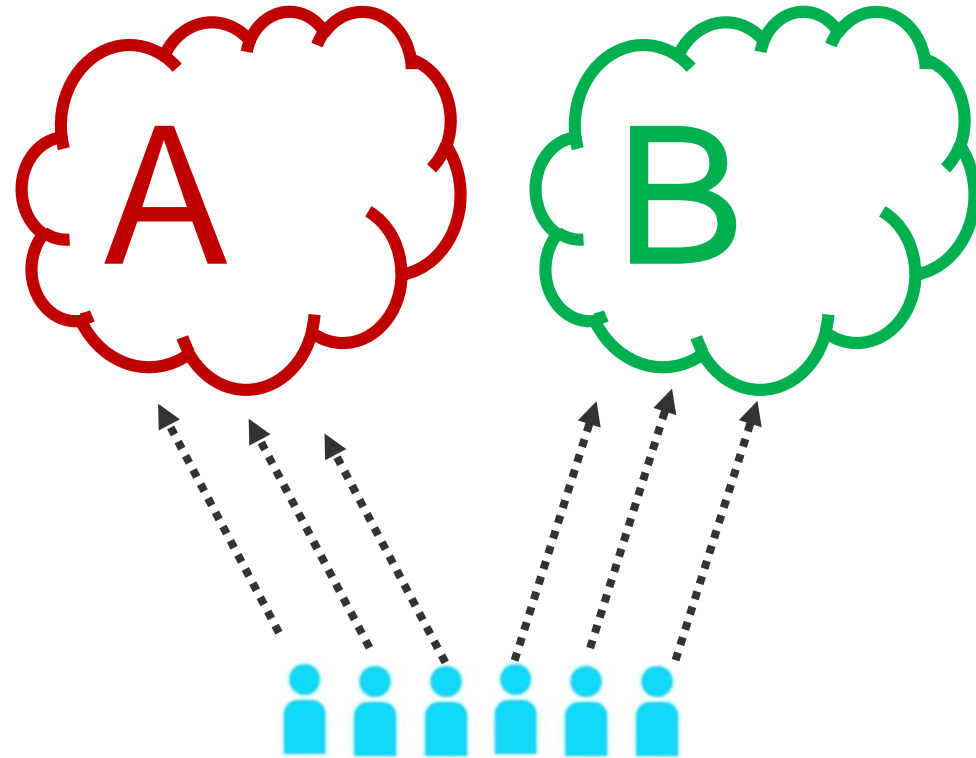
NE

When both generators choose low levels of production to maximize their profits. No one has an incentive to change strategy, given the other player's choice (mutual best response).

MORE CONSIDERATIONS...

Setting Electricity Price

- Oslo has two power companies **A** and **B** to provide electricity
- A and B set different electricity price to attract customers
- Any user can freely use either A or B
- **Q:** how can A or B decide the electricity price?



- If both generators cooperate, they can both charge the monopoly price. However, each generator has an incentive to reduce its price slightly and capture more market share, even though it knows that both generators will be worse off if they both cut price. - **Structure similar to that of the prisoner's dilemma.**

The Prisoner's Dilemma: application

- You and your partner are working on a project assignment
- You can choose to either stay up late and work hard, or slack off and hope your partner does most of the work.
- **Q:** Should you work hard?



<u>You</u>	<u>Your partner</u>	
	Work hard	Slack off
Work hard	(12, 12)	(7, 7)
Slack off	(7, 7)	(2, 2)

NE

Conclusion: you should work hard!

References

- <https://www.youtube.com/watch?v=t9Lo2fgxWHw>
- H. Singh, “Introduction to game theory and its application in electric power markets”, *IEEE Comp. Applicat. in Power*, vol. 12, pp. 18-22, Oct. 1999