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Power system restructuring & deregulation

Objective:

The objective is to introduce different **electrical energy trading models** and **mechanisms** and present technical and economical approaches designed to the **management of power systems** in the context of the **open electricity market**.

Key points of Electricity Market Liberalization

* What does it consist of? * Why competition? * What does it imply in power system operation & planning * How to move towards an unbundled structure & competition? * **Definition of the actors & components** * **Description of 4 paradigms** (vertically integration vs. unbundling) * Comments on privatization and competition * **Efficiency of the market (liquidity).**

Supply and demand modeling

* **Consumption modeling** (final consumers / retailer / Disco /…): definitions, typical profiles of demand or offer, gross surplus & net surplus, utility curve * **Generation modeling** (GENco/retailer/…): definitions, typical profiles of bid or supply, marginal cost & cost function, revenue and benefit, no load and startup costs, maximum benefit condition (perfect competition), complex bids for a multiple periods market.

Energy contracts & market mechanisms

* **Characteristics of a contract** (long term – day ahead – hour ahead,…) * **Spot market** vs. open energy market * Forward contract & market, futures contract & market * **Bilateral trading**: long term, over the counter (OTC), electronic trading * **Pool trading**: aggregated demand curve, aggregated supply curve, optimization formulation & market clearing price or equilibrium (marginal producer), impact of demand elasticity, definition of price CAP * Comparison pool/bilateral trading * Interactions of the spot market and the other markets * **Risk management**: price volatility, call & put options, contract for difference * Examples.

Bidding strategies

* What does it consist of and why? * **Perfect competition vs. imperfect competition** * **market power**: definition, HHI calculation, examples * Introduction to Game Theory (GT) and its variations: complete/incomplete information, cooperative/non cooperative game, static/dynamic games,…* Nash equilibrium & Pareto optima * Best response function, MinMax & MaxMin methods, dominant strategy method, …* Particular cases: Cournot model & Bertrand model * Examples.

System security & ancillary services

* Definitions and system security requirements* **Transmission facilities vs. system security** * **Ancillary services**: compulsory provision vs. provision through markets * Example of **balancing market mechanism** * Introduction to congestion management: market solution & technical solution (examples using FACTS devices or phases shifter transformers) * Examples.

Transmission pricing & congestion management

* What does it consist on? * The main components involved in **transmission pricing**: utilization of the infrastructure, power losses, congestions of transmission lines,… * Long run methods vs. short run methods * **Rolled-In methods**: postage stamp method – contract path method – MW mile method - … * Available Transmission Capacity calculation (ATC) * PTDF calculation * **Congestion management methods** dependences * TLR method * Willingness to pay method * Inc-Dec method (redispatching) * Counter-flow methods * auctioning method (cross-borders) * Zonal pricing: market splitting/coupling * Nodal pricing & Locational Marginal Prices (LMP) calculation: analysis of the appropriateness – application of market power – hedging (FTR, TTC,…) * Examples.

What does it consist on ?

Competition between electrical energy *providers* to supply *consumers* efficiently

Electrical energy as a product and its transportation as a service

Product and *transportation* managed commercially by different companies

Product traded on specific market(s) according to *transactions* or *contracts* (buyer, seller, quantity, price, time of delivery,…)

Moving from *vertically integrated* structure to *unbundled structure*

Vertically integrated structure (monopoly): same company produces, transmits and distributes (directly or not) the product to the consumers at a single imposed price

Unbundled structure: generation company and transportation company are different. The consumers choose the provider(s). Price components: product + transportation

<u>Transportation remains a monopoly</u>: it delivers the product in a *coordinated* and *non discriminatory* way

Why competition ?

To promote economic *efficiency* in electrical energy system operation & planning:

- Investments at right place and right time
- Avoid under or over investments
- Optimal operation of generators (efficiency)
- *Bids* should reflect marginal costs

To encourage the use of recent technologies to improve security and reliability of the whole electrical system (high *quality* of supply)

To induce the decrease (!!??) of electrical energy prices

What does it imply in power system operation & planning ?

Coordinated technical operation of generation and transmission/distribution

The following services must be guaranteed (*ancillary services*):

- frequency control: primary & secondary
- management of spinning reserve
- sufficient angular stability margins
- voltage control and reactive power support
- sufficient voltage stability margins
- availability of black start capabilities in case of blackouts
- transmission/distribution capacity management
- etc.

Needs for coordinated maintenance planning (short term) and coordinated investment planning (long term). No experience until now

How to move towards an unbundled structure & competition ?

Break up of large electrical generations companies into smaller ones

Allow implementation of new companies

Create ISO (Independent System Operator) to performs transmission/distribution in coordination with power plants operation (Europe: TSO / DSO)

Create appropriate trading infrastructures (market places)

Determine the eligibility of the consumers

Install appropriate metering devices to monitor the transaction performance

Create a regulating organism to ensure fair and efficient operations for both: electrical energy systems & markets

Definition of the actors & the components

GENco: Generating company (single plant or portfolio of plants). Sells electrical energy through competition in *wholesale* market. Could compete also to sell *ancillary services*

TRANSco: Transmission company. Operates its equipments according to ISO instructions

ISO: Independent system operator. Responsible to maintain the security of power system operation. Could also play the role of **MO** (market operator)

MO: Market operator. Matches generating bids (sellers) and consumption offers (buyers) and issues the contracts according to the mechanism used

DISco: Distribution company. It operates the distribution network. The sale of electrical energy to the consumers could be through the DISco itself (monopoly or partial deregulation) or *retailers* (*retail* markets in fully deregulated environment)

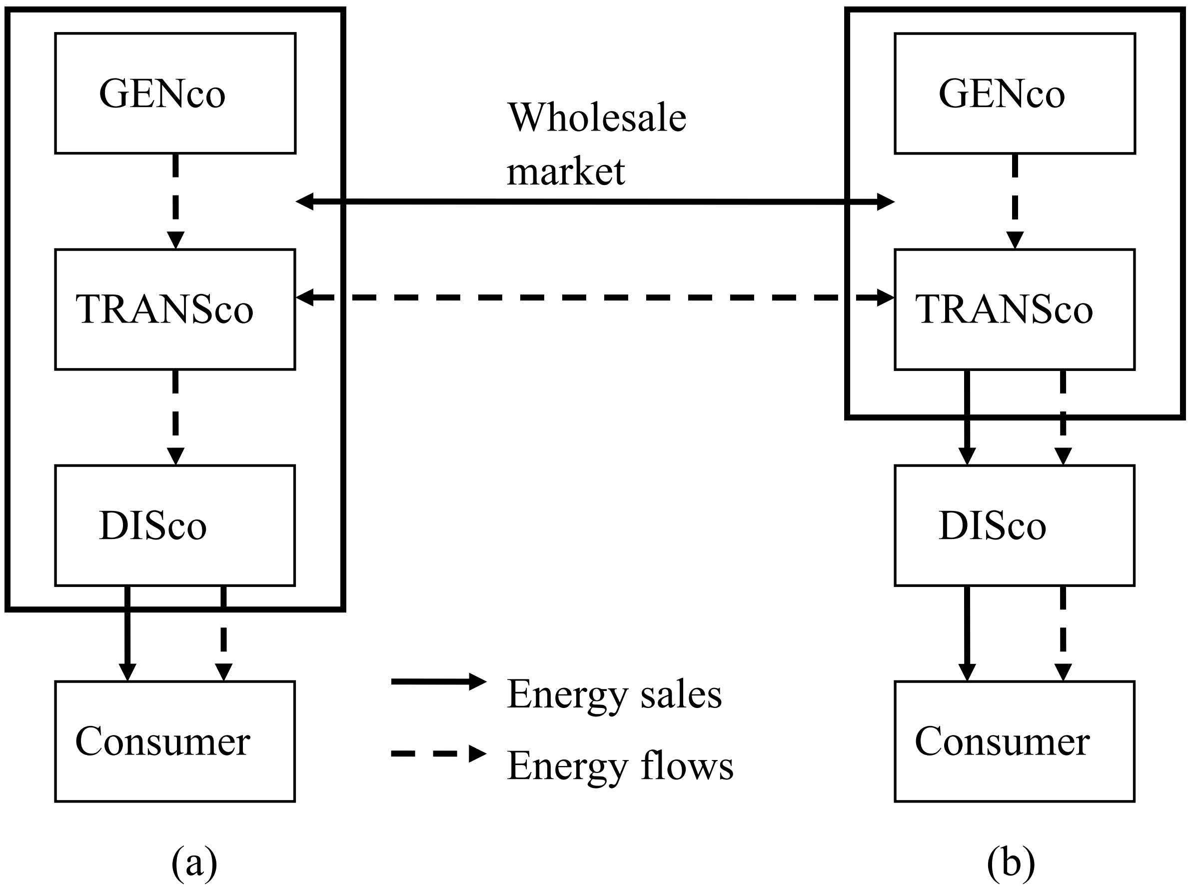
Key points of Electricity Market Liberalization

Retailer: buys electrical energy on *wholesale* markets. Resells it through a *retail* market to consumers not participating to the *wholesale* market. DISco is a particular retailer

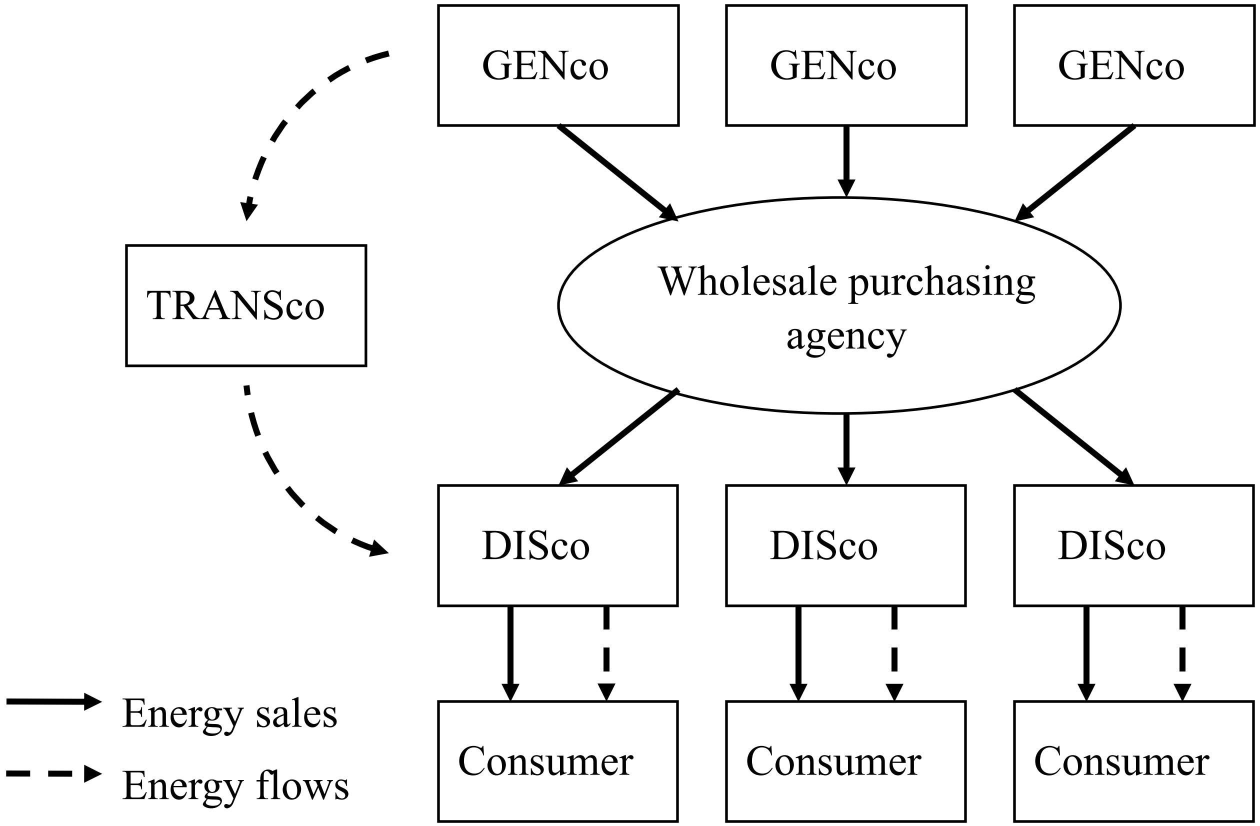
Consumer: *large* consumers buys the electrical energy through *wholesale* market. *Small* consumer buys the electrical energy through *retail* market or from the DISco to which it is connected

Regulator: determines or approves the electricity market rules and investigates the suspect cases of abuse (*market power*). Sets or controls the prices of products and services in the case of monopolies.

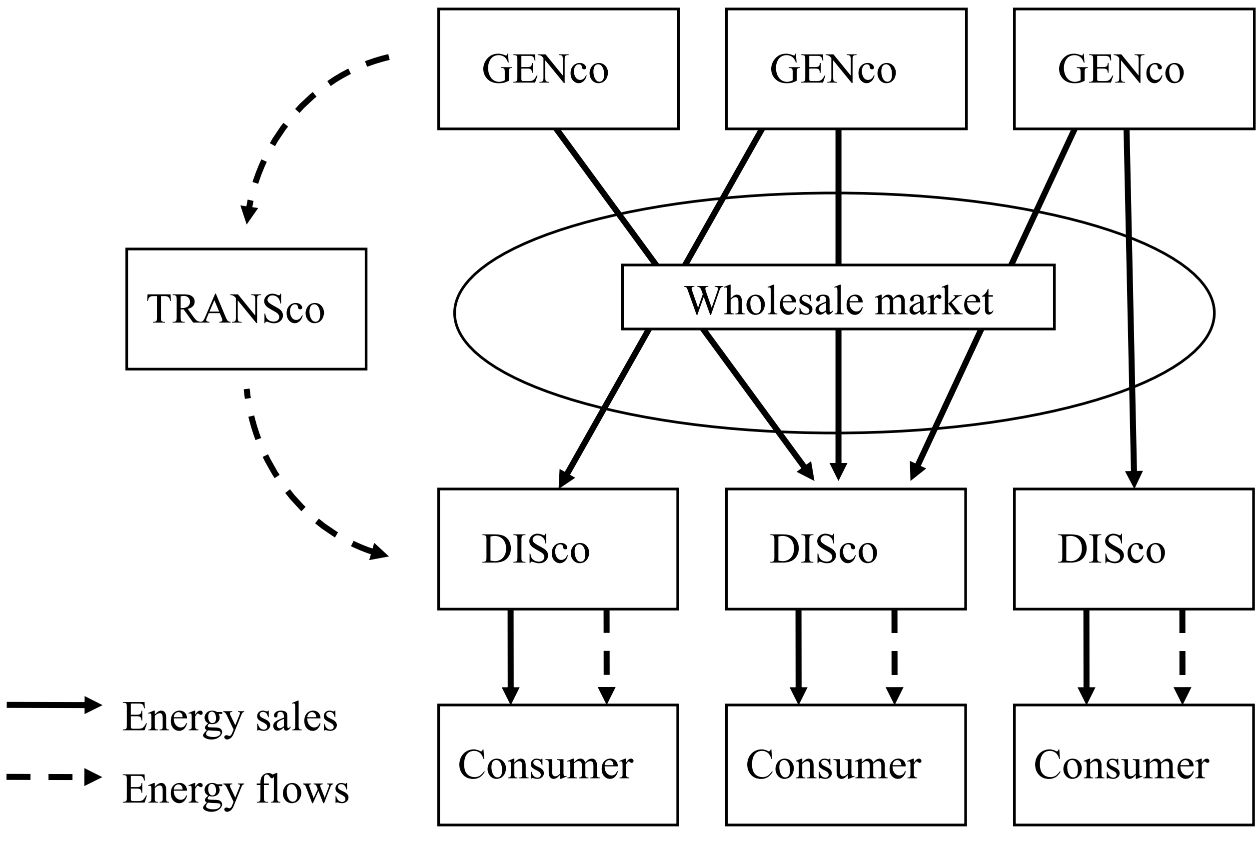
Monopoly (model 1)



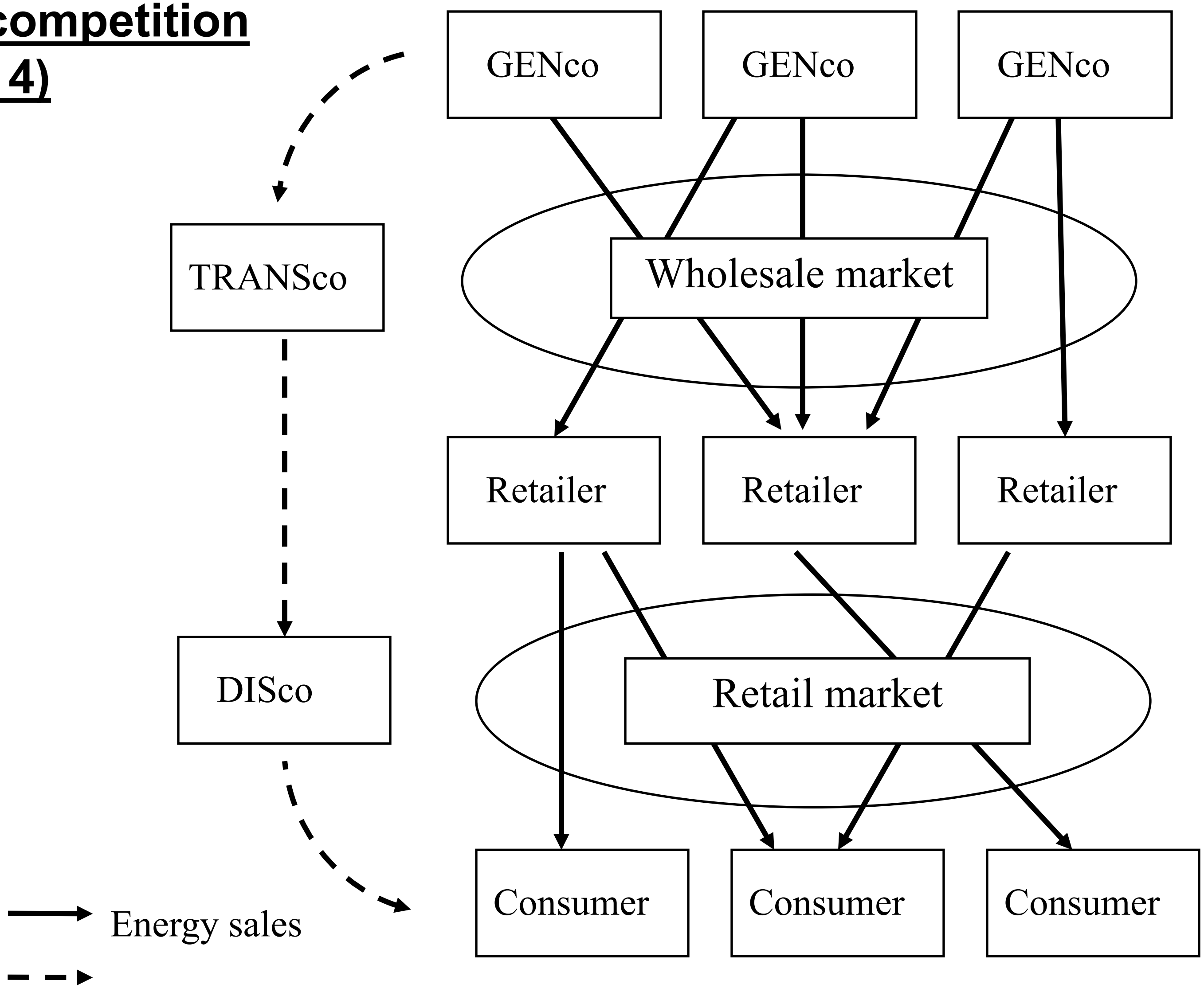
Purchasing agency (model 2)



Wholesale competition (model 3)



Retail competition (model 4)



Comments:

Gradual separation between transmission/distribution operation and market operation (**model 1 → model 4**)

Transmission/distribution remains a full monopoly. The fees or tariffs are regulated

Interaction between 2 types of network:

+ a physical network where the energy flows according to *Kirchhoff* laws

+ a trading network where the energy flows according to *auctioning* laws

Efficiency of the market:

Liquidity: always actors willing to sell or to buy electrical energy

Reliability of the market mechanism that determines prices and quantities

Transparency of market operation

Small trading costs (fees, administrative expenses,…)

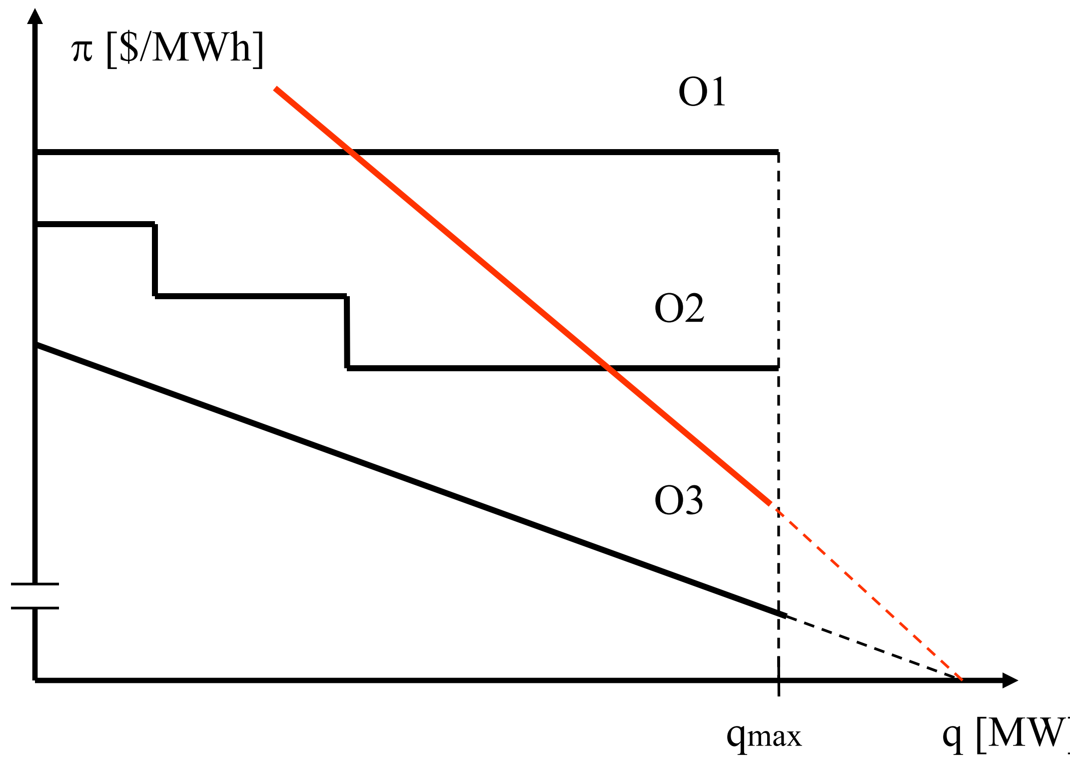
Hyp.: Hourly based market operation → Unit : MW (power) or MWh (energy)

Consumption modeling

Actors: (eligible) consumers, retailers, DIScos

Fixed or *variable offer* to buy (price, quantity)

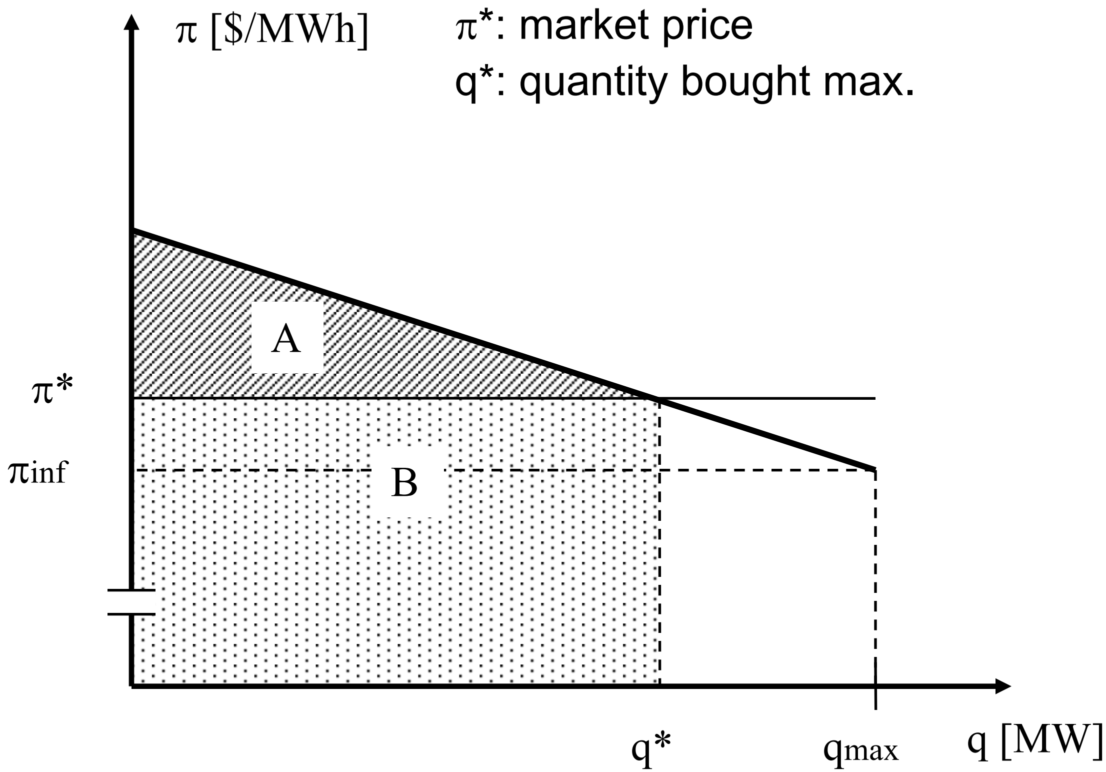
Inverse demand function



Offer price defined as a *marginal willingness to pay* price (max. price to be paid)

The slope of the inverse demand function defined as the *elasticity* of the demand

Consumer's revenue & profit:



A+B: *gross consumer's surplus* or *consumer's revenue*

Utility curve or *function U(q)* ($/h or $)

A: *net consumer's surplus* or *net consumer's profit/benefit*

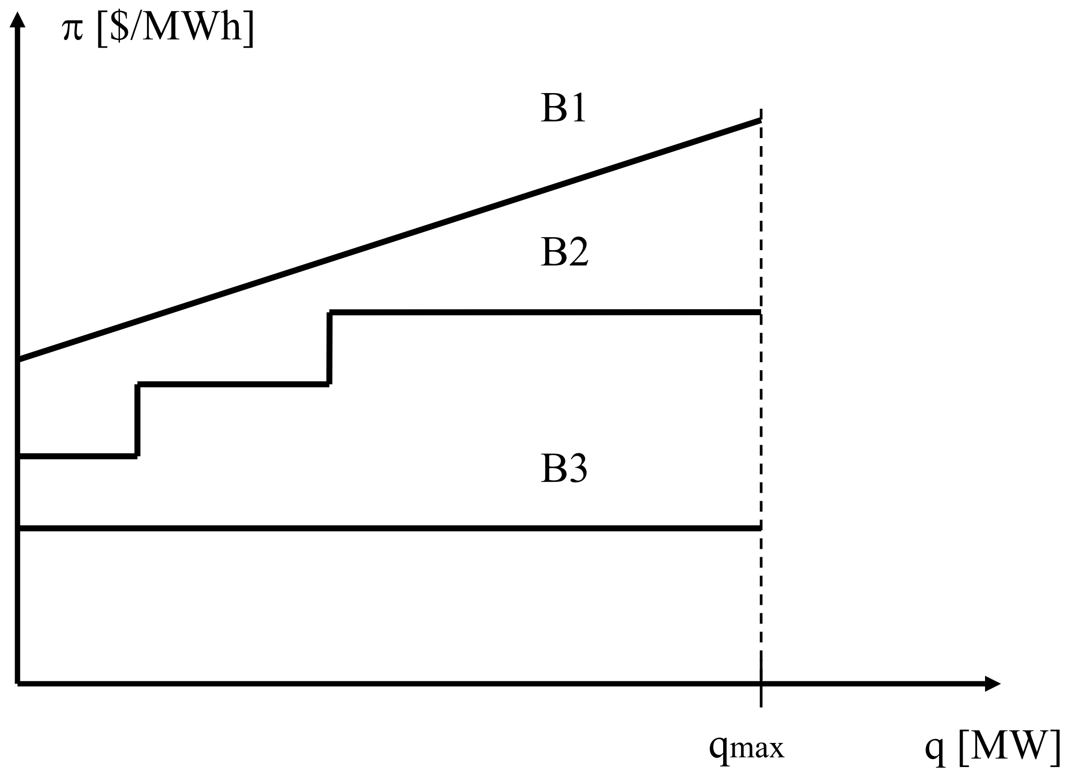
B: amount to be paid through the market to get q*

Generation modeling

Actors: GENco, retailers

Fixed or *variable* <u>*bid*</u> to sell (price, quantity)

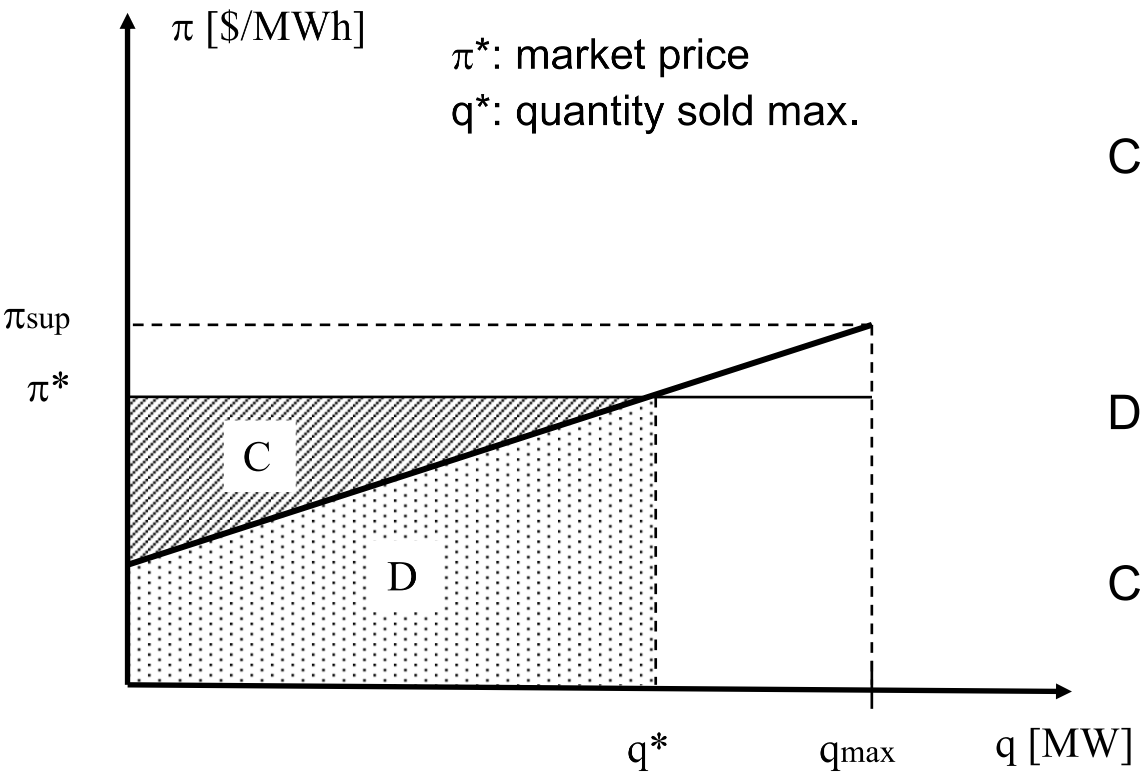
Inverse supply function



Bid price is the minimum price the seller is willing to accept for selling

In *perfect competition*, bid price reflects *marginal cost of production*

Producer's revenue & profit:



C+D: *producer's revenue*

amount received from the market to sell q*

D: cost to produce q*, assuming bid price = marginal cost of prod.

C: *producer's profit or benefit*

D corresponds to the *production cost function* or *curve* C(q) ($/h or $) if it includes the constant *no load* and the *startup* costs

The final benefit could be negative if we consider no load and starting costs

Market price vs. marginal cost of production:

Maximisation of the producer's profit Ω : max Ω = max [$\pi^*.q - C(q)$]

In perfect competition, the market price is not affected by the change of an individual quantity:

$$\frac{d\Omega}{dq} = \pi^* - \frac{dC(q)}{dq} = 0 \qquad \Rightarrow q = q^*$$

Selling price bids vs. power plant types:

Marginal production cost of nuclear power plant is lower than that of classical thermal or gas turbine power plant

Hydropower plant marginal production cost is practically negligible

In the case of hydropower, the bid prices account for the "*water value*"

"*Water value*" is correlated to the evolution of the market price and the availability of the rates of flows and the water in the reservoirs

Complex bids:

The market mechanism run is repeated consecutively for every delivery hour of a given period (ex.: 24 hours). Every run is generally independent from the previous one.

➔ the resulting generation schedules could not comply with some generation technical or economical constraints

Therefore the simple bid is completed with the following constraints that depend on the power plant type:

+ *Minimum output power (thermal)*
+ *Up / down ramp rates (thermal)*
+ *Minimum up / down time (thermal)*
+ *Minimum revenues or benefits*
+ *Energy availability (hydro)*
+ *Environmental constraints such as CO2 emissions (classical thermal units)*

The market mechanism operating with complex bids is based on multi-period constrained optimization calculation (*units commitment problem*)

Characteristics of a contract (hourly basis)

Common specifications:

+ a buyer and a seller
+ a quantity to be traded
+ a price to be paid (respectiv. received) on delivery
+ a place of delivery
+ duration (long/short term)

Type dependencies:

+ Time of delivery: immediate (*spot contract*) – specified time in the future (*forward* or *futures* contract)
+ Condition of delivery: in any circumstance (*forward* or *futures* contract) – on request (*call option* / buyer, *put option* / seller)
+ Method of settlement: physical delivery – in cash (only for *Contract of differences*)

Every contract is concluded in the corresponding market (spot, forward,…) operated at an appropriate time before delivery

Spot market vs. open electrical energy market

This is a real time market (1 to 24 hours max. before delivery) where the delivery is “immediate” and unconditional

Spot market prices tend to change quickly due to:

+ sudden increase of the demand whereas the energy availability is limited for immediate delivery

+ glut in production whereas the demand is low

The consequences of a such price volatility are mitigated using:

+ open electrical energy markets (*forward* or *futures* markets)

+ hedging price volatility methods (*risk management*)

Forward contract & market

Forward contract is a contract of delivery of a quantity at an agreed price at a specified time in the future (ex: 1 week, 3 months since the issue)

It is generally concluded on *bilateral basis* through a *broker* (ex: long term contract)

At the date of delivery, with regard to the spot price, it could represent a benefit or a loss for the buyer respectively the seller

Futures contract & market

Similar to a forward contract but issued from *a centralized* or *exchange* market only

When issued its value is negotiated every day until the delivery => benefit or loss (/initial value) added or withdrawn from a so called *margin account*

The aim is to induce a convergence between the spot price and the contract price at the delivery time

At the delivery date, the money available in the margin account should guaranty the initial value recovering

Bilateral trading mechanism

It involves 2 parties, i.e. a buyer and a seller, sometimes through a broker

Contracts are negotiated independently so no reference or historical prices exist

Customized long term contracts:

it involves the delivery of a large amounts of power
(ex: 100 MW or 1000 MW) over long periods of time (several months/year)

Trading "over the counter" (OTC):

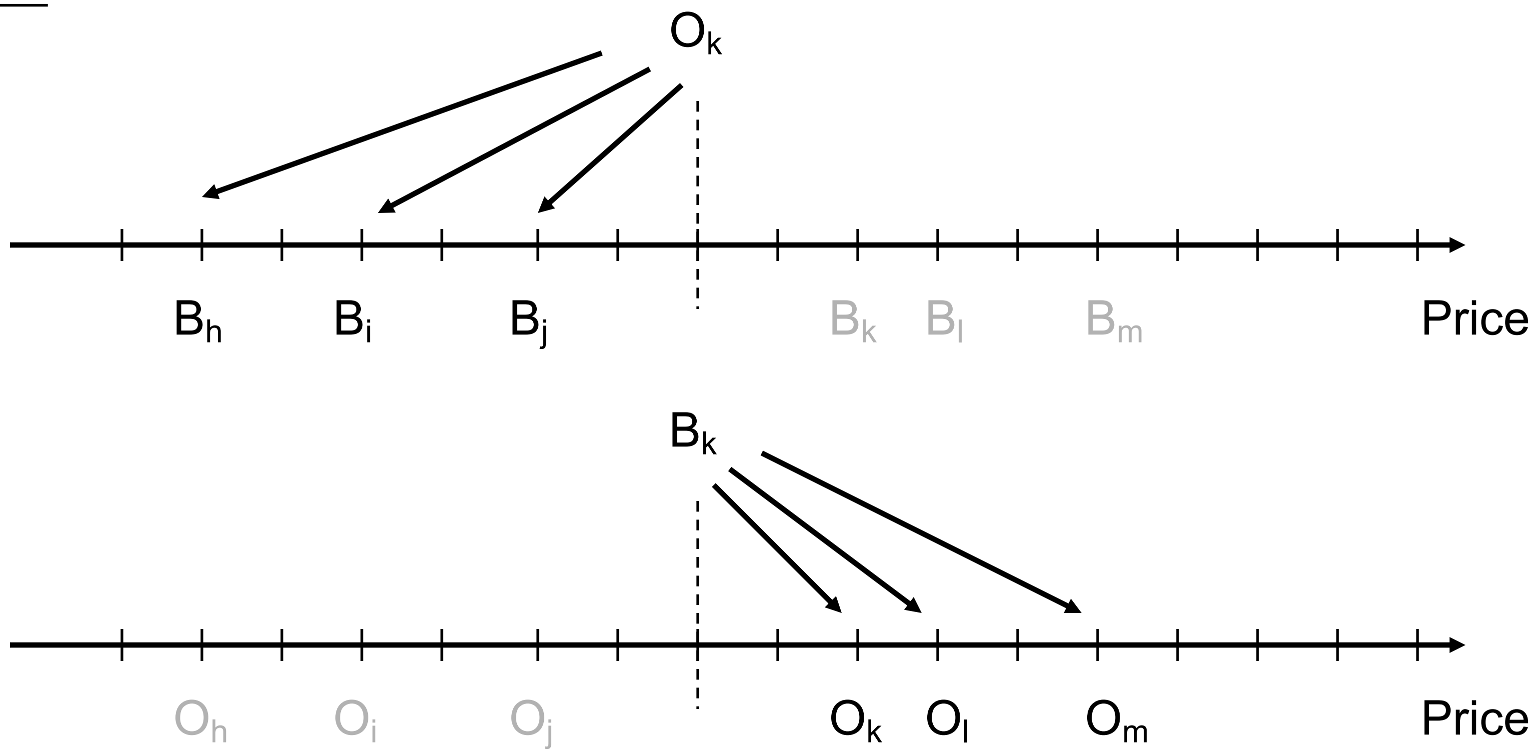
smaller amounts of power/energy are delivered during different periods of the day or the week.

Used by buyers/sellers to refine their position as delivery time is approaching

Electronic trading:

Computerized market place where offers to buy and bids to sell are entered *anonymously.* Identities are disclosed only in a case of contract conclusion

Examples:



Settlement example: π^* = (Bid price + offer price)/2 ; q^* = min [bid q, offer q]

Coordination procedure is necessary to make electronic market works properly

Pool trading mechanism

It is designed for a *centralized* or *exchange* market

The operator collects bids and offers and determine a market price that is unique

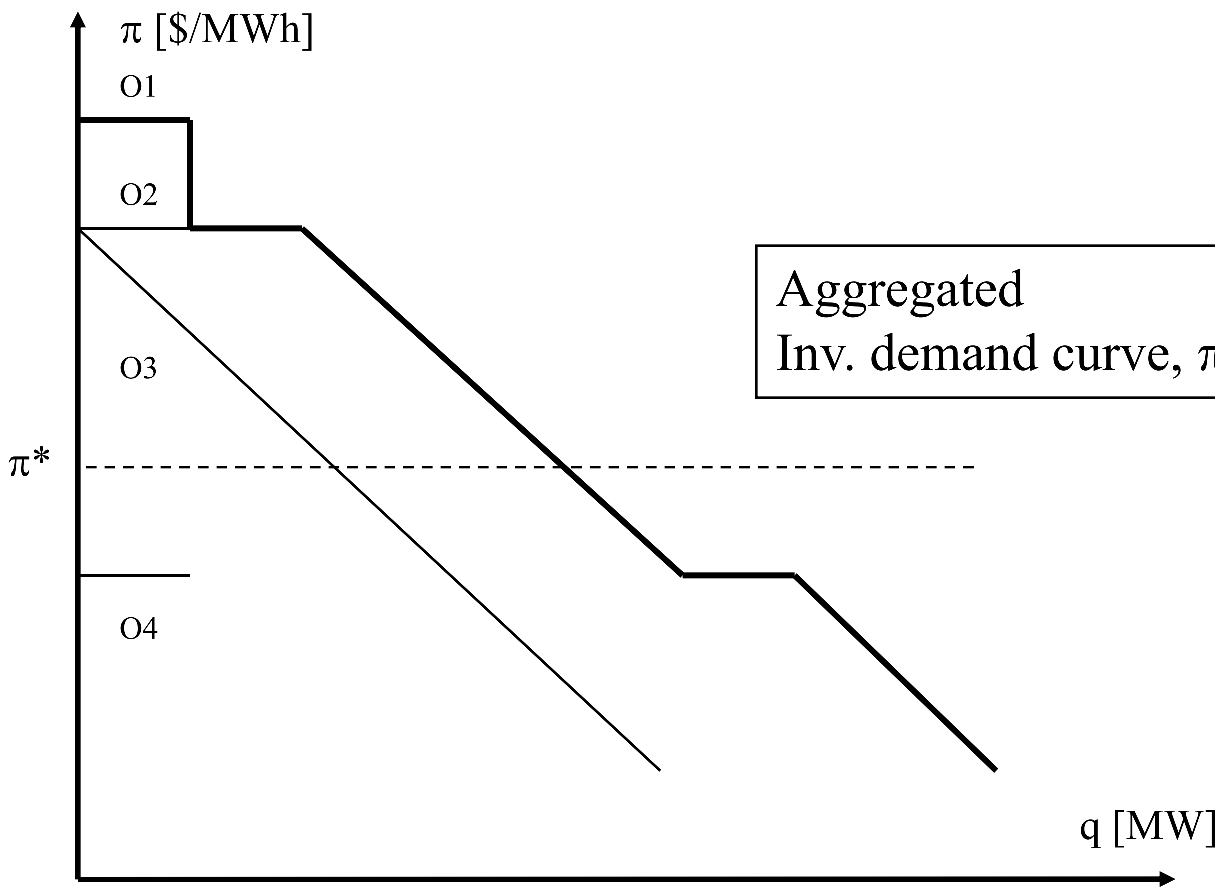
This price is called *market clearing price* (MCP) or *system marginal price* (SMP)

The bids whose the prices are lower or equal to MCP are selected. The bid quantities are sold at MCP

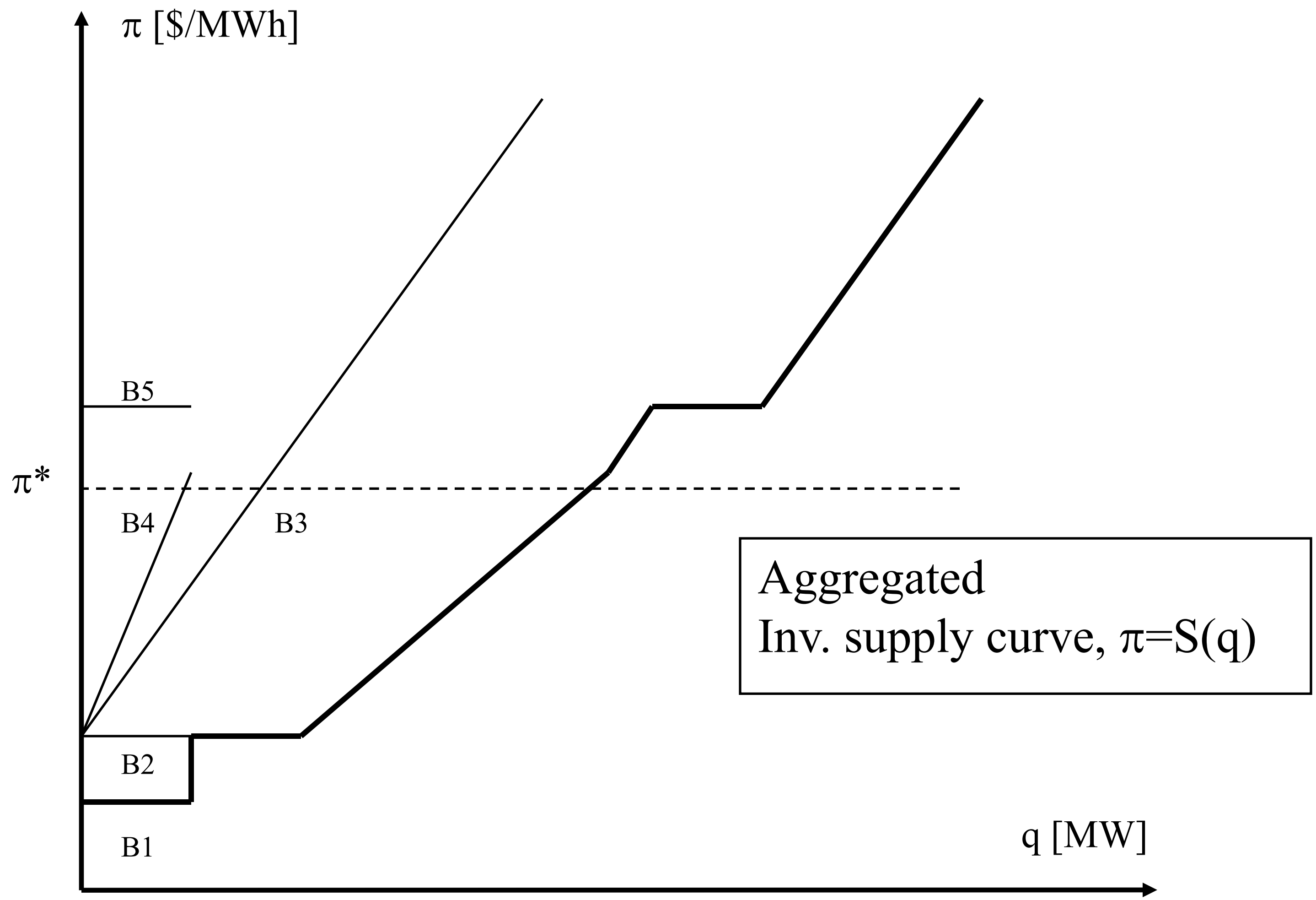
The offers whose the prices are greater or equal to MCP are selected. The offer quantities are bought at MCP

How MCP is determined?

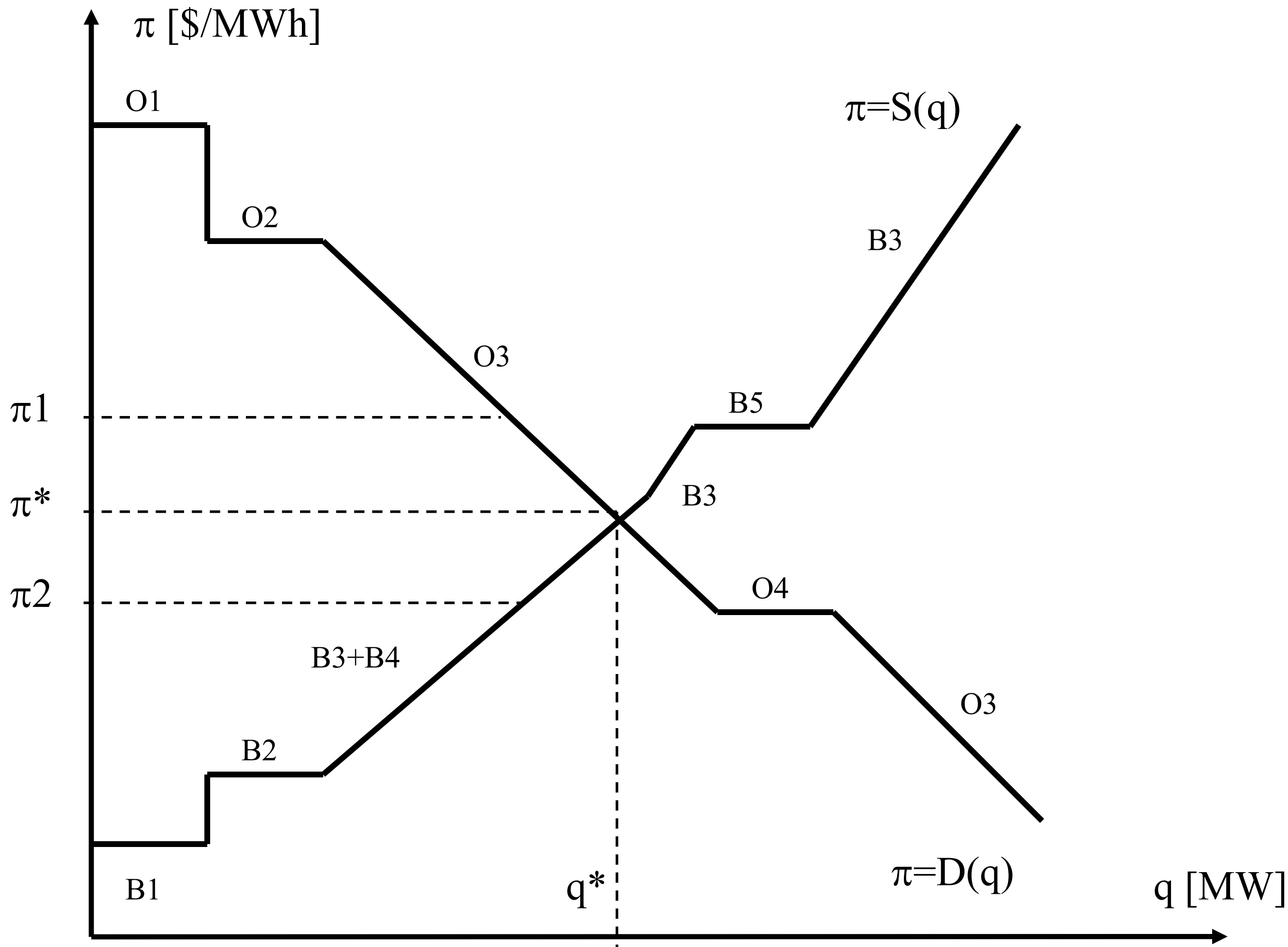
- Submitted offers are ranked in decreasing price order. It leads to build a cumulative quantities curve following this ranking (*aggregated inverse demand* function)



- Submitted bids are ranked in increasing price order. It leads to build a cumulative quantities curve following this ranking (*aggregated inverse supply* function)



- The intersection of S(q) and D(q) gives π^* (SMP). q* is the total quantities sold and bought respectively



B3 and B4 are *marginal producers* and O3 is a *marginal consumer* since any MWh added in the market will be produced by B3 + B4 and consumed by O3

The MCP results from the maximization of the *social welfare*:

Find q=q* such as **∫(D(q) – S(q)). dq** is **maximum**

or

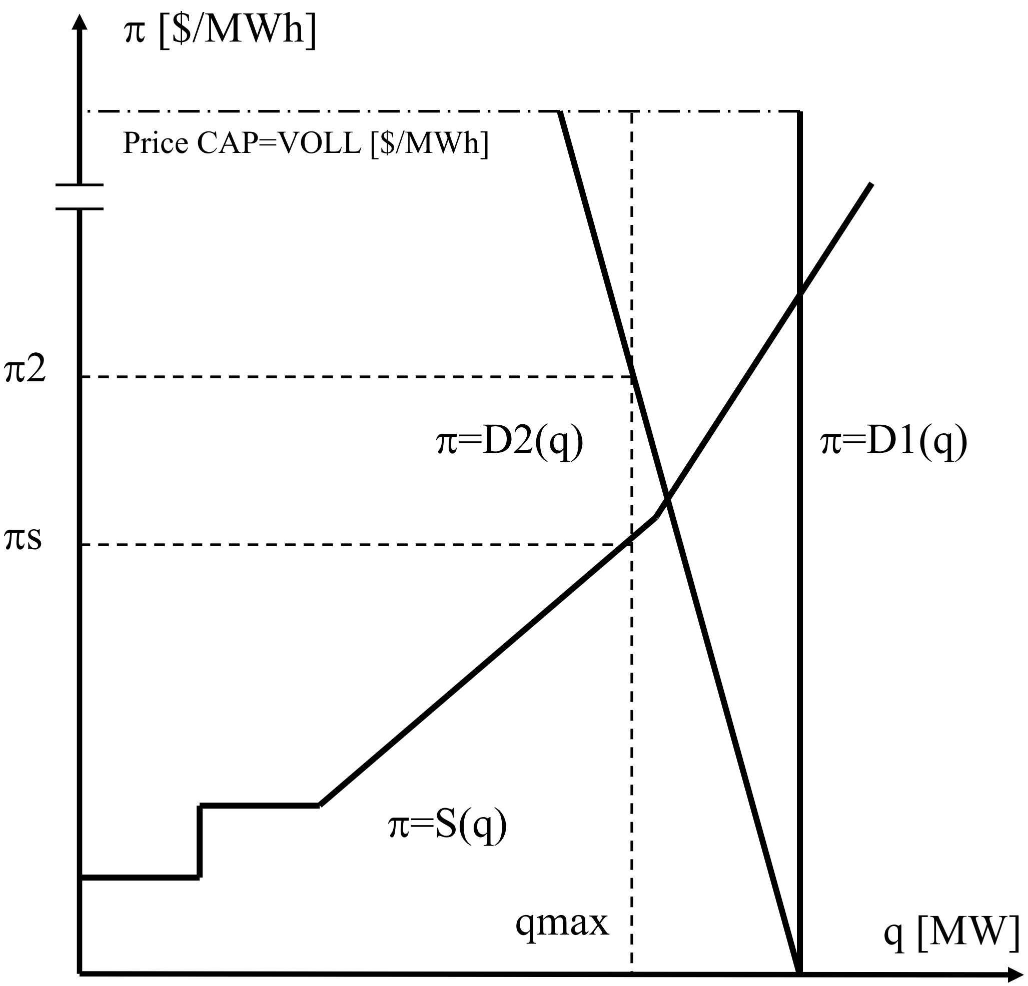
Find qi* & qj* such as **Max** $\sum_j U_j(q_j) - \sum_i C_i(q_i)$ **s.c.:** $\sum_i q_i = \sum_j q_j$

The solution is given by the *Lagrangian multiplier* method:

Find q_i* ,q_j* & **π*** such as **Max** $\sum_j U_j(q_j) - \sum_i C_i(q_i) + \pi.(\sum_i q_i - \sum_j q_j)$

The MCP is a *Pareto optimal* solution. At this point any MCP increase (decrease) leads to an increase (decrease) of producer benefits and a decrease (increase) of consumer benefits. So the social welfare decrease anyway (*deadweight loss*)

Impact of elasticity:



Inelastic offer D1(q): consumers are willing to pay any price fixed by S(q)

Elastic offer D2(q): MCP is limited but the quantity bought as well

Quantity to be sold shortened to qmax:
-D2(q): price between πs and π2
-D1(q): price between πs and VOLL

VOLL: *value of loss of load*. Would be paid by consumer to not be shed

Comparison of pool and bilateral trading

In bilateral trading, it is not common to know the historical practiced prices. This Could lead to a lack of transparency that would prevent global market efficiency

In pool trading, historical MCP profile are disclosed to every actor who can define pertinent bids or offers respectively

The pool trading is capable to tackle more efficiently the problem of multi-period trading:

Find q_i^{t*} & q_j^{t*} such as **Max** $\sum_t \left(\sum_j U_j^t(q_j^t) - \sum_i C_i^t(q_i^t) \right)$

s.c.: + $\sum_i q_i^t = \sum_j q_j^t$ t=1,..,T

\+ Complex bids constraints

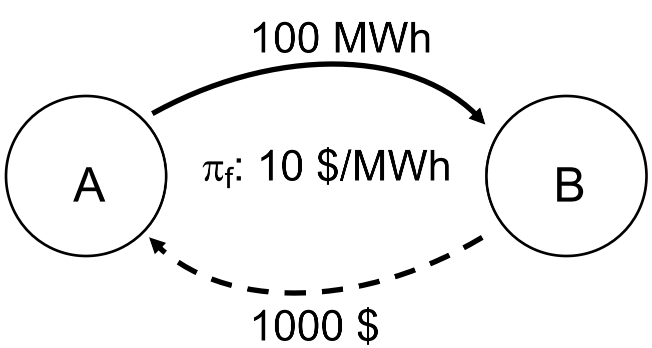
Interaction between spot and open electrical energy markets

Spot market is market of last resort when contracts issued in other markets suffer from energy availability at the delivery time

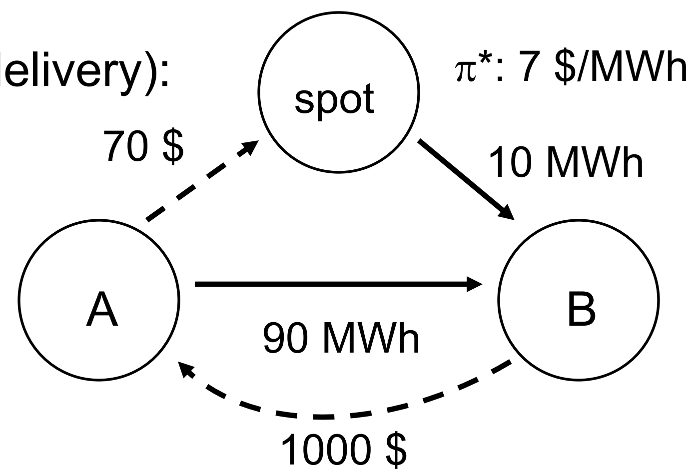
This could lead to some arbitrage that would increase the benefice of the seller or the buyer beyond what it is specified in the contract

Example:

date **J-N**: contract forward



date **J** (delivery):



Expected revenue: 1000/100=10 $/MWh

Effective revenue: 930/90=10.33 $/MWh

Risk management

Price volatility phenomenon:

- Large, sudden and frequent variations of spot prices over a specified time period
- It predicts uncertainty in future price movements
- It is measured in term of *standard deviation* using historical data
- Volatility analysis would permit appropriate hedging strategies

The main driving forces causing spot prices volatility:

- **Electricity as non (or limited) storable commodity**: difficulties to smooth out spot prices between peak and off peak periods
- **Load uncertainty**: related to the correlation between load forecast and weather conditions which are sometimes unpredictable

- **Fuel prices:** related to marginal generator units using fuel with fluctuating price

- **Irregularity in hydro-electricity production**: unpredictable dry period would lead to the utilization of more or less large number of thermal units that are costly

- **Unplanned outage**: replacement of a large and cheap production unit with several small but expensive ones

- **Constrained transmission system**: low cost generation could not be transmitted to the loads during hour when congestions exist

- **Market power**: strategic bidding of producers to increase their expected benefits beyond the competitive level

In order to prevent risk exposures, only small quantities are normally traded in the spot market

Hedging price volatility methods:

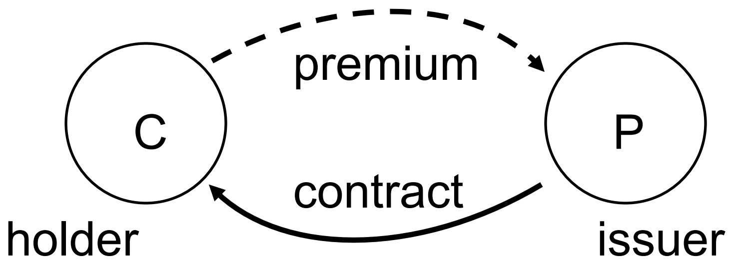
Specific instruments that respectively:

- do not necessitate *any obligation* to buy (*call option*) or to sell (*put option*)

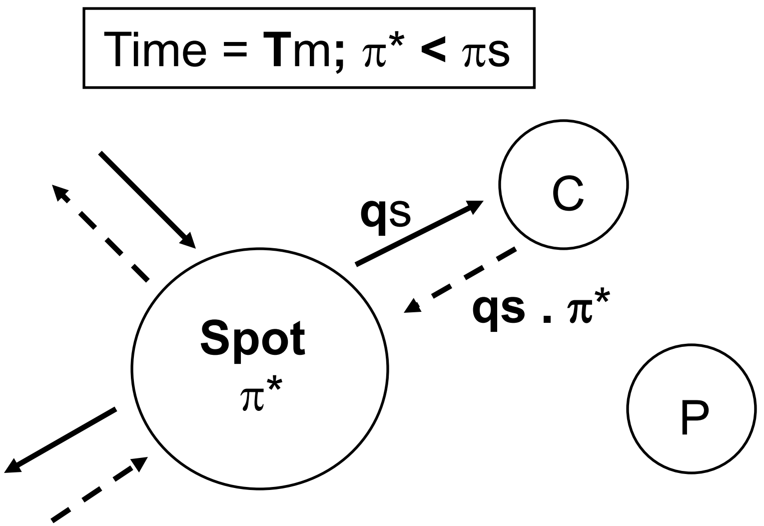
- are based on sharing the price risk exposures (*contract of differences*) providing financial compensations

Call option

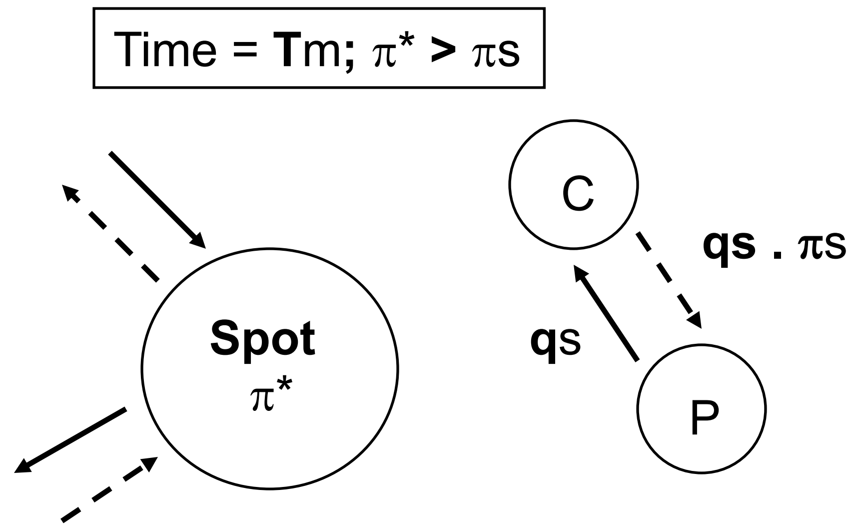
qs: specified quantity; **T**m: *maturity/expiration* time; πs: *strike/exercise* price



- It gives to the holder the right to **buy**, *without any obligation*, **qs** at πs at **T**m



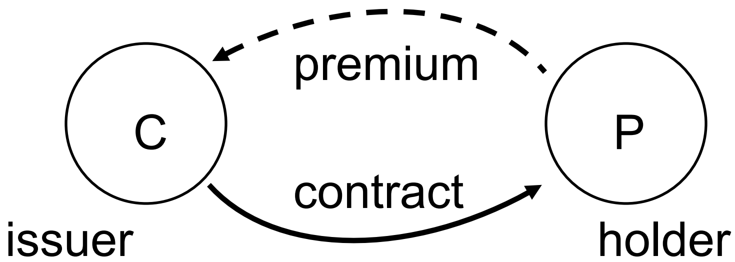
Call option *out of the money*



Call option *in the money*

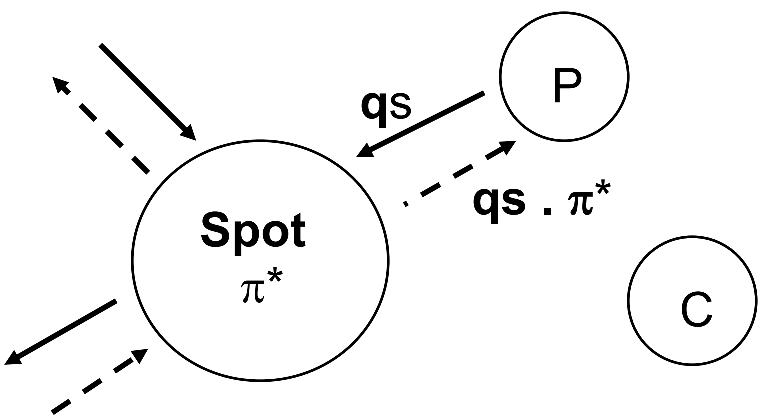
Put option

qs: specified quantity; **T**m: *maturity/expiration* time; πs: *strike/exercise* price



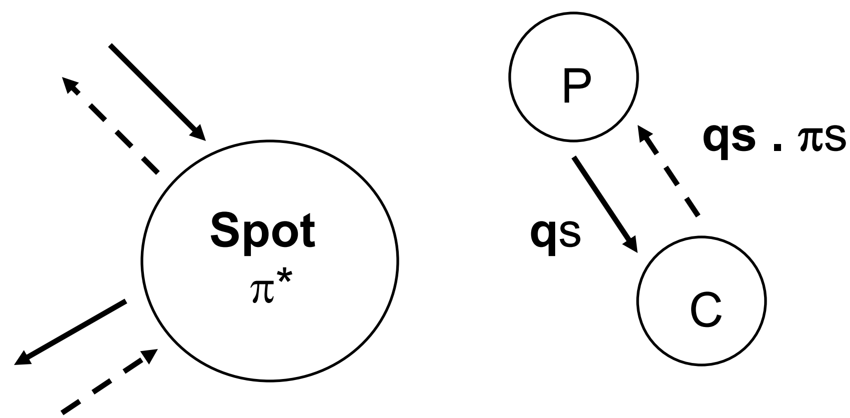
- It gives to the holder the right to **sell**, *without any obligation*, **qs** at πs at **T**m

Time = **Tm;** π^* **>** πs



Put option *out of the money*

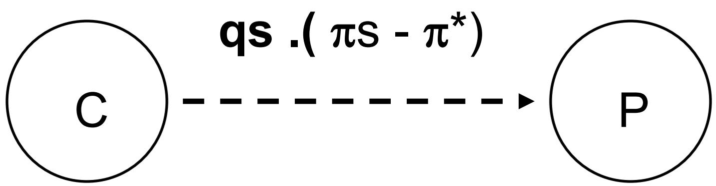
Time = **Tm;** π^* **<** πs



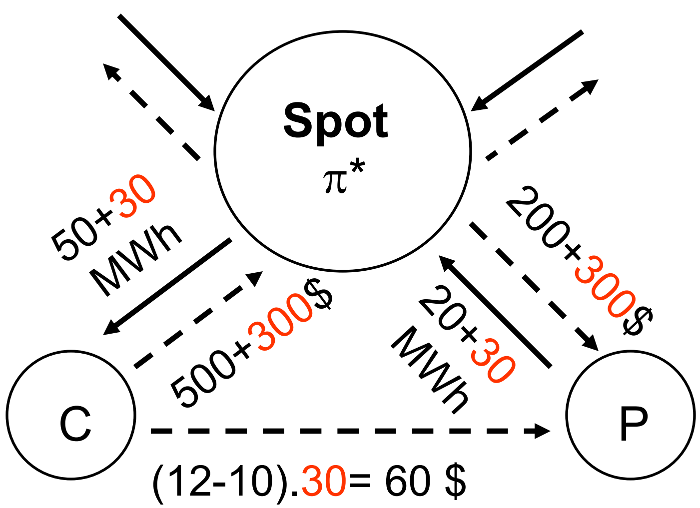
Put option *in the money*

Contract for differences (CfD)

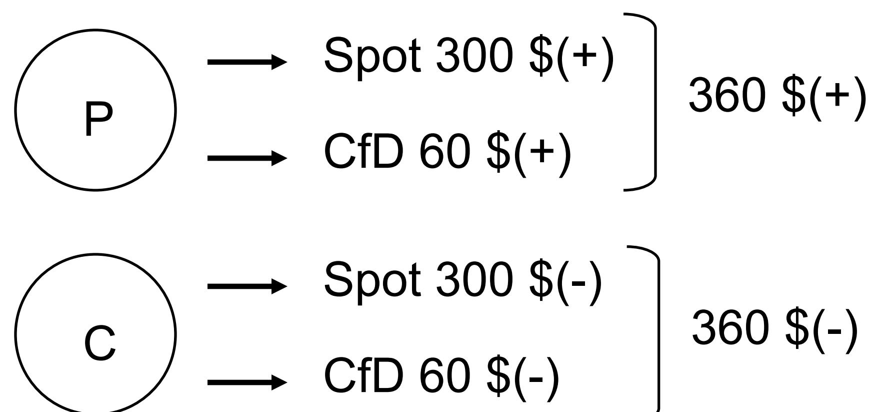
qs: specified quantity; **T**m: period of time; πs: *strike* price; π*: spot price



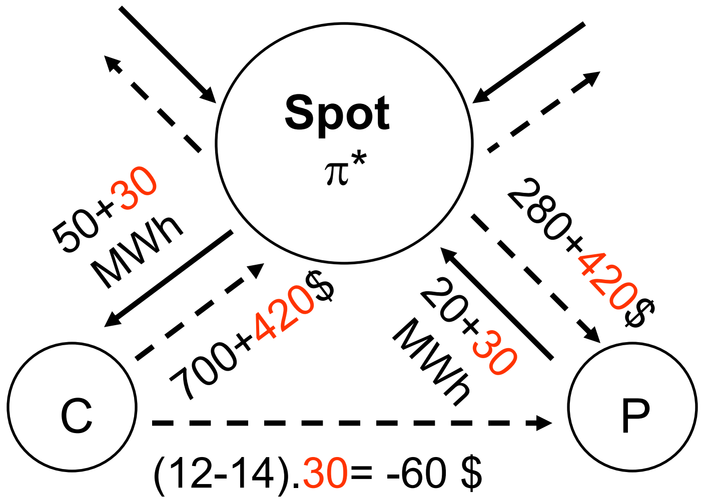
<u>Example 1</u>: **qs**= 30 MWh; πs = 12 $/MWh; π* =10 $/MWh



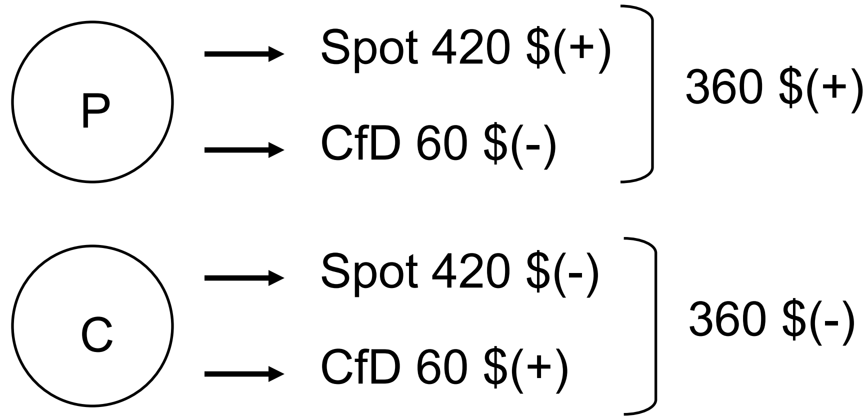
- Bilan financier pour 30 MWh:



Example 2: **q**s= 30 MWh; πs = 12 $/MWh; π* =14 $/MWh



- Bilan financier pour 30 MWh:



What does it consist of and why?

A generating company can utilize *strategic bidding* to increase its benefits while exploiting the *imperfection* of the market

It consists on bidding other than the marginal cost and the corresponding quantity

A generating company exercise *market power* if it increases successfully its profits using strategic bidding

It could be based on historical market data, load forecasting, generating units type participating in the markets, etc.

Optimal bidding strategies can be handled by *game theory*

Perfect competition vs. imperfect competition

Modeling and analysis according to the *Cournot model*: maximization of the individual profits of the GENcos

Let's assume n GENcos. The total quantity produced and supplied is noted:

$$Q = q_1 + q_2 + \dots + q_n$$

Maximization of GENco i profit is stated as:

$$\textbf{Find } q_i \text{ such as } \textbf{max } (q_i \cdot \pi(Q) - C_i(q_i))$$

It leads to:

$$\pi(Q) + qi \cdot \frac{d\pi(Q)}{dq_i} = \frac{dC_i(q_i)}{dq_i}$$

And:

$$\pi(Q).\{1 + \frac{q_i}{Q}\frac{Q}{dq_i}\frac{d\pi(Q)}{\pi(Q)}\} = \frac{dC_i(q_i)}{dq_i}$$

Defining:

$s_i = \frac{q_i}{Q}$ as *market share* of GENco i; $\varepsilon_i(Q) = \frac{\pi(Q)}{Q}\frac{dq_i}{d\pi(Q)}$ as demand elasticity (<0)

Then:

$$\pi(Q).\{1 - \frac{s_i}{|\varepsilon_i(Q)|}\} = \frac{dC_i(q_i)}{dq_i}$$

Perfect competition occurs when s_i is negligible for every GENco i.
GENco i is a *price taker*

Otherwise, the market price is higher than the marginal cost of GENco i. So electricity market is intrinsically imperfect

Market power phenomenon

Ability for GENcos to drive the prices over a *competitive level* to increase their profits or to prevent the profit expectations of other competitors

Market power can be *intentionally* or *accidentally* and appears under 2 types: *vertical or horizontal* market power

Vertical market power: capability of GENcos to control bottlenecks in the system such as congested paths to get preference to themselves or their affiliates

Horizontal market power: capability of GENcos with high market share to control production availability and thereby raising the prices

Market power can be assessed using the *Herfindhal-Hirshman Index* (HHI). It reflects the number of participants and the inequality of their market shares:

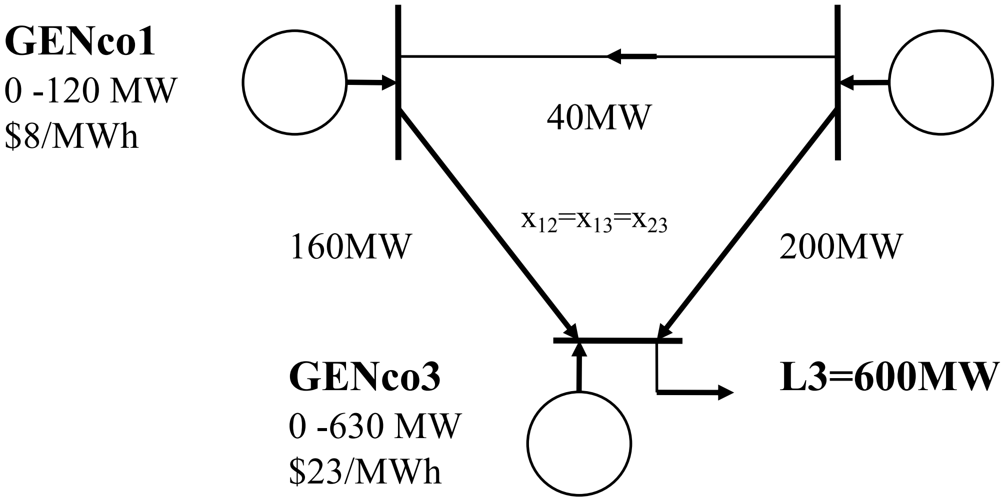
$$HHI = \sum_{i=1}^{N} s_i^{\,2}$$

s_i is the contribution of GENco i divided by the total contribution of all GENcos

HHI tending to 1 (maximum value) means an important market power (monopoly)

HHI tending to 0 means a weak market power (perfect competition)

Example:



- GENco3 (marginal generator) can exercise *horizontal* market power asking any price since L3 is higher than Genco1 + GENco2 max. production

- If line 1-3 and 2-3 are limited to 150 MW of capacity, GENco1 & 2 can not simultaneously sell their max. output. So GENco3 can exercise *horizontal* market power

Bidding strategies

- In both cases, the market power is said *accidental*

- Assuming a bilateral contract of 90 MW between GENco3 and loads at node 2, the flows in lines 1-3 and 2-3 would decrease to 130 and 140 MW respectively (*counter flow* of -30 and -60 MW respectively)

  Then GENco1 & 2 can sell more power until the occurrence of a new congestion

  GENco3 would exercise an *intentional vertical* market power since it would have the capability to control the physical bottleneck

Introduction to Game Theory (GT) and its variation

GT is an optimization method for solving interacting decision problem where each GENco (*player*) has to consider in the solution approach simultaneously the problem faced by each of the other GENcos

The aim is to bid strategically in order to maximize its profit (*payoff*) that depends on the bidding of the others players

Each player is supposed to bid *rationally* (*rational choice*)

A game is based on the following three elements:

- the set of players, i=1,..,n
- the strategy/bidding space $S_i = \{S_i^1, S_i^2, \ldots, S_i^p\}$ for each player i, and
- payoff function $B_i(S)$ that gives the profit of player i for each collection of S of S_j^k, j=1,..,n. It leads to the *payoff table*

Example of payoff table in the case of 2 players:

Strategies	S_2^1	S_2^2	S_2^3
S_1^1	$B_1(S_1^1, S_2^1); B_2(S_1^1, S_2^1)$	$B_1(S_1^1, S_2^2); B_2(S_1^1, S_2^2)$	$B_1(S_1^1, S_2^3); B_2(S_1^1, S_2^3)$
S_1^2	$B_1(S_1^2, S_2^1); B_2(S_1^2, S_2^1)$	$B_1(S_1^2, S_2^2); B_2(S_1^2, S_2^2)$	$B_1(S_1^2, S_2^3); B_2(S_1^2, S_2^3)$

Every player can analyze this table using different methods to find the solution sought after

GT can appear according to different variations

Game of complete/incomplete information:

- complete information means each players knows the strategies and the payoff functions of the others

- incomplete information means this common knowledge is uncertain. Uncertainty is modeled in GT using *probability distribution*

Static/dynamic game:

- in a static game, all the players bid simultaneously

- in a dynamic game, a first player bids then a second player observes this first bid and choose his bid consequently

Cooperative/non cooperative approach:

- in a cooperative approach, a coalition between players leads them to bid strategically together increasing even more their profits

- In a non cooperative game, we seek for and analyze the *Nash equilibrium* solutions of GT

Pure/mixed strategy:

- mixed strategy is the interpretation of one player's uncertainty about what another player will bid

- a probability distribution $\{p_i^1, p_i^2, \ldots, p_i^p\}$ is associated to the strategies in S_i

  with $\sum_k p_i^k = 1$. p_i^k is the probability to play S_i^k

- if $p_i^k = 1$ the S_i^k is defined as a pure strategy

- in case of mixed strategy, complete information and non cooperative game, it exists at least one Nash equilibrium solution

- this solution gives the optimal distribution probability over the strategies of each player and the corresponding expected average payoffs

Definition of Nash equilibrium & optimum of Pareto

When a Nash equilibrium of GT is reached, no player has an incentive to deviate from his decision. If he does, automatically his payoff will decrease

When an optimum of Pareto is reached, if any player deviates from his decision and increase his payoff then the payoff of at least one other player will decrease

A Nash equilibrium is a *stable* solution whereas an optimum of Pareto is *unstable*

Solution methods of Game Theory

Iterated elimination of strictly dominated strategies method:

A strategy S_i^k is strictly *dominated* by a strategy S_i^m if $B_i(S^k) < B_i(S^m)$ with $S_i^k \in S^k$ and $S_i^m \in S^m$. S^k and S^m are collections of strategies played by the n players

Example:

Strategies	S_2^1	S_2^2	S_2^3
S_1^1	20,40	30,70	20,50
S_1^2	40,60	60,50	30,70
S_1^3	50,40	20,30	40,20

(*the payoff unit is in k$)*

The solution is a Nash equilibrium !

Best response function method:

We mark the cell indicating the best payoff for each player while considering every combination of the strategies of the other players

The cell(s) marked n times gives the collection of strategies solution of the game

Example:

Strategies	S_2^1	S_2^2	S_2^3
S_1^1	20,20	10,60	40,40
S_1^2	30,30	20,20	20,00
S_1^3	20,10	70,50	20,70

(*the payoff unit is in k$)*

The solution is a Nash equilibrium !

MinMax & MaxMin methods:

In Minmax, we mark for every player its best response for every combination of the strategies of the other players. We select then the worst response over them

In Maxmin, we mark for every player its worst response for every combination of the strategies of the other players. We select then the best response over them

Example:

Strategies	S_2^1	S_2^2	S_2^3
S_1^1	20,40	70,40	20,50
S_1^2	40,60	60,50	30,70
S_1^3	50,40	80,30	40,20

(the payoff unit is in k$)

The Minmax solution is a Nash equilibrium !

The Maxmin solution is a Pareto optimum !

Particular cases of GT: Cournot and Bertrand models

In Cournot model, the players *bid strategically only in quantities* whereas in Bertand model, the players *bid strategically only in prices*

Cournot model:

The price is determined by the inverse demand function:

$$\pi(q_1,..,q_n) = D(\sum_i q_i),\ i=1,..,n$$

q_i is the output of producer i and $\sum_i q_i$ is the total demand

The benefit of each producer is:

$$B_i(q_1,..,q_n) = \pi(q_1,..,q_n) \,.\, q_i - C_i(q_i), \quad i=1,..,n$$

Cournot model propose to maximize individually each B_i with respect q_i while keeping all q_j (j=1,..,n and j=i) constant

This leads to solve the following system of n equations:

$$\frac{dB_i}{dq_i} = \pi + q_i . \frac{d\pi}{dq_i} - \frac{dC_i}{dq_i} = 0 \qquad i=1,..,n$$

The solution $q_1^*,..,q_n^*$ and the corresponding price π^* correspond to a Nash equilibrium solution

Definition and system security requirements

Ancillary services must be available to ensure at anytime an appropriate functioning of the power system (*system security*) while accounting for credible contingencies

It is managed by ISO (or TSO/DSO)

System security means:

- **voltage** drop kept in specified ranges (i.e., ±10%)
- transmission line **currents** under their thermal limits
- **frequency** maintained very close to the reference value (50 Hz) everywhere
- rotor **angle** differences between any 2 generators (with respect a synchronous frame) kept constant or limited (**synchronism** condition)

Degradation of these variables could lead to specific *phenomena*, then a *blackout*

Angular instability phenomena:

- Any sudden perturbations in a power system leads to rotor oscillations around their *synchronous equilibrium point*
- The difference of rotor angles of any 2 generators oscillates either with increasing amplitude (instability or loss of synchronism) or decreasing amplitude (stability)
- It depends on: severity of the perturbation, its location, its duration, generators inertia, AVR characteristics, transfer impedances between generators, load amplitude, etc.

Voltage instability phenomenon:

- It occurs when a decrease of electrical power responds to an increase of a requested load at a given node and when the voltage decreases monotonically at that node
- Transformers with automatic tap changers typically exacerbates the phenomena leading to a *voltage collapse*
- Preventive actions consist of appropriate coordination of reactive power compensation and curative actions consist of load shedding

<u>*Congestion phenomena*</u>:

- It occurs when a line/transformer current exceeds its thermal limits (overload)
- The protective relays disconnect the component and the corresponding flow takes another path according to the Kirchhoff laws
- It could lead to a new congestion and consequently to a cascading outage of lines or transformers until a complete blackout

<u>*Frequency variations*</u>:

- When power system load increases (decreases) the frequency decreases (increases). Energy is taken from (added to) the kinetic energy of the rotating machines
- Speed governors of generators stop this variation increasing (decreasing) mechanical power until a new equilibrium is reached or the new load is fully covered (*primary control*)
- *Secondary control* or *load following* moves appropriately the speed droop lines of <u>parti-cular</u> generators to recovers the reference value of the frequency
- With no such controls, the frequency would increase or decrease continuously

- Loads or powers generated deviate continuously but slightly (in general) from the values resulting from the energy market

Transmission system facilities & system security

ISO determines a priory all the necessary resources (type, number, quantities) to ensure the physical feasibility of the energy market transactions and the appropriate operation margins

ISO uses different simulation tools to assess static (or dynamic) behaviors of the power system. It accounts for the facilities owned by TRANSco

These facilities are: reactive compensation devices, transformer with tap changer, phase shift transformers, FACTS devices, grid topology changes, etc.

It helps to control the voltage profiles and to reroute the active/reactive power flows enhancing for some extent angular/voltage stability and transmission capacity margins

It can not help to control the frequency due to load variations

More effective resources are provided from generation side or from demand side. It reinforces and complements the above-mentioned facilities

In general, theses resources must be purchased on a commercial basis (*ancillary services*)

Ancillary services are dedicated either to *preventive* or *curative* issues

Ancillary services: compulsory provision vs. provision through markets

Compulsory provision:

Basic security requirements fulfilled through agreements between ISO and particular generating companies. The latter must provide certain type of ancillary services as condition for being connected to the grid

Examples: primary frequency control and primary voltage control

Primary frequency control:

- Generator with speed governors ensure continuously the equilibrium between MW powers generated and the loads. Therefore, it prevents frequency collapse

Primary voltage control:

- Generators with AVR (*automatic voltage control*) and possibly PSS (*power system stabilizer*) contributes to the voltage control and stability
- It contributes strongly to maintain the synchronism of the generators (AVR => synchronism torque, PSS => damping torque)

<u>Provision through market</u>:

ISO is the unique buyer. GENcos and particular consumers (*interruptible loads*) are the sellers

ISO pays the provider for the ancillary services and then it recovers this cost from the users

Long term contracts (bilateral trading mechanism):

It concerns ancillary services in which the amount needed change very little over the time such as:

- **primary frequency control**
- **primary voltage control (+PSS)**
- **intertrip schemes**: to mitigate angular stability problems by disconnecting some generators or loads
- **black start capability**: ISO is responsible for a fast restoration after a blackout – contribution of hydro-plants, diesel/gas turbine generators providing flexibility to control the voltage profile and the frequency – limited contribution of thermal units

Short term contracts (bilateral trading mechanism):

It concerns ancillary services in which the amount needed change substantially over the time due to the interaction with energy market

- **Secondary voltage control**: centralized and coordinated control to ensure an appropriate voltage profile for the whole system (provide by generator with AVR)

- **Reactive power**: ISO must guaranty its provision and delivery. It is linked to voltage control

- **Secondary frequency control**: on commercial basis, some generators with speed governors are defined to cover the load variation and to recover the nominal frequency (*balancing market*)

- **Energy reserve**: designed to handle the large and unpredictable power deficits. Provision can be negotiated in specific market or simultaneously through energy market. The prices of this service are normally lower than MCP's

The reserve is assumed to be a *spinning reserve* (generators in). *Cold energy reserve* (generators out) is another ancillary service

Example of balancing market mechanism (*load following case*)

Generators bid before every hour delivery (ex: up to 30 mn before) both quantities and prices. The bidders should be able to *regulate up* or *down* their production within few minutes when called upon

The reference price for bidding is generally MCP or π^* (i.e. spot market price)

Bid for *regulating up* (GENco i): Δq_i^+ and $\pi_i^+=\pi^*+\Delta\pi_i^+$ paid by ISO to GENco i

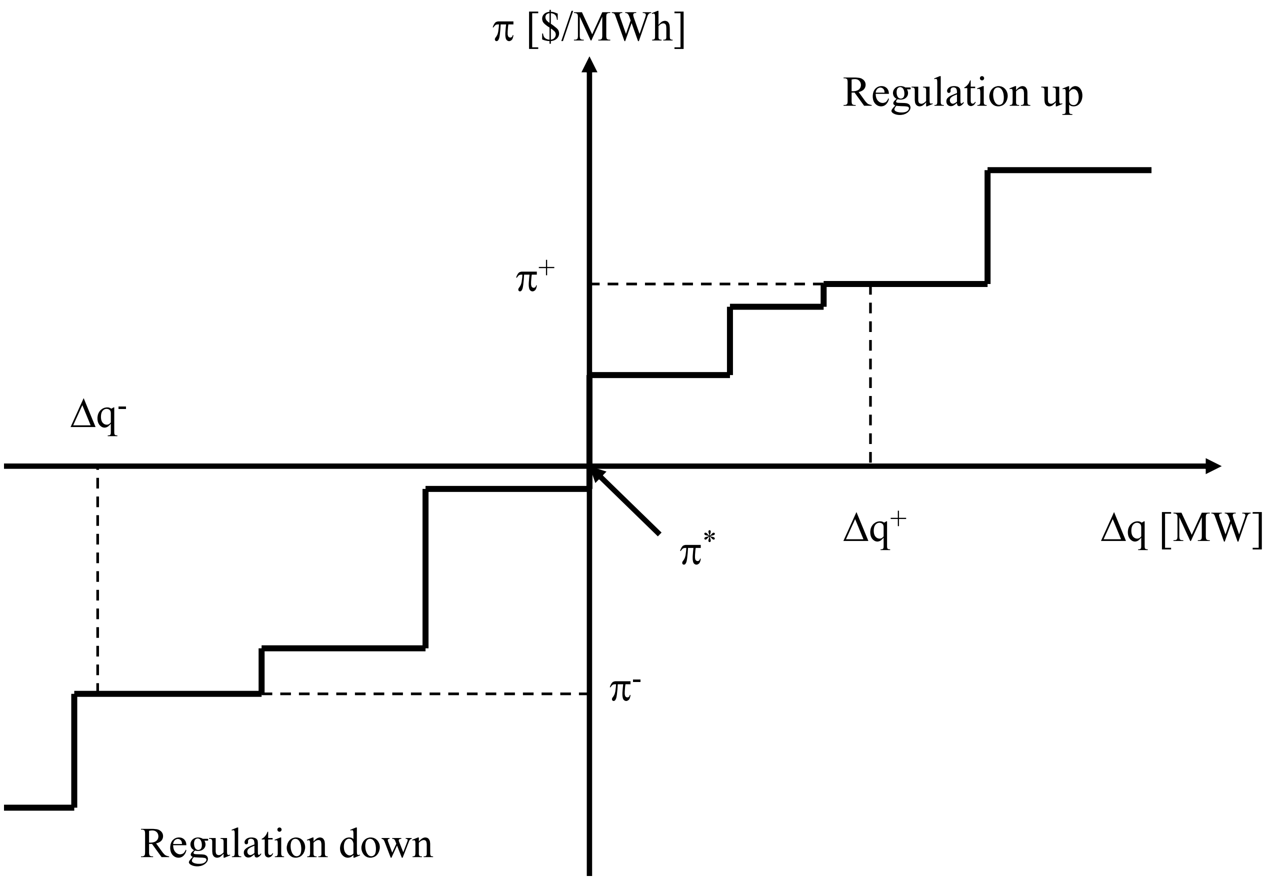
Bid for *regulating down* (GENco i): Δq_i^- and $\pi_i^-=\pi^*-\Delta\pi_i^-$ paid by GENco i to ISO

q_i is the quantity cleared in the energy market

The bids are sorted in the merit order of the price in order to build the cumulative bid curve. The balancing market is cleared according to:

- *ex ante*: the maximum Δq^+ and Δq^- are determined *a priori* then the corresponding clearing prices π^+ and π^- are derived

- *ex post*: during the hour, the called generators with respectively the highest price for regulating up and the lowest price for regulating down define these variables (marginal regulating generators)



What does it consist on ?

In addition to the ancillary services charge, the transmission/distribution users have to pay for the use of the infrastructures, the power losses and congestion managements if any. The users concerned are generally the consumers

The infrastructures involve: connection, metering, billing, maintenance, operation,…

The pricing of the transmission service must meet the following requirements:

- promote economic efficiency
- compensate ISO (TRANSco) fairly for providing transmission services
- allocate transmission costs reasonably and equitably over all the users
- maintain the security of the transmission grid
- must be practical

Rolled-In methods

All the cost components are summed up into a single number TC (except congestion management cost)

Postage Stamp Method:

- TC is divided by the system peak demand to get a flat charge rate Rt [$/MW] for every user (mainly the consumers)

- Rt times the quantity contracted is paid by every user

This method does not account for the distances between injection and receipt nodes. Easy to calculate and often used

Contracted path method:

- For a given transaction, the supposed used path is defined between the injection and the receipt nodes
- A global transmission TC' cost is assessed for this path
- TC' is allocated according to the postage stamp approach over the consumers involved in the transactions related to this path

Parallel paths should normally be accounted for!

MW-Mile method based on distance:

- For every transaction, the airline distance between the injection node and receipt node is defined
- The MW-Mile value is defined then as the quantity contracted times this distance
- The consumer pays TC times MW-Mile divided by the sum of all the MW-Mile values

The network technical conditions are not considered

MW-Mile method based on power flow:

- For every transmission line k we determine an utilization cost C_k

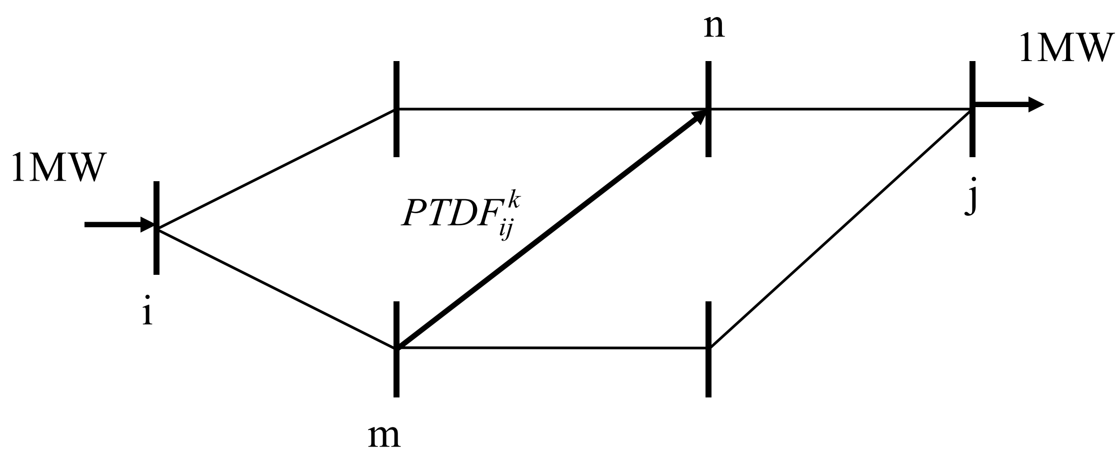
- For every transaction, the flow contribution in line k is determined

- The price paid is C_k times that flow contribution divided by the max. capacity of k

- For the same transaction, the process is repeated for all the lines, k=1,..,n

Most appropriate method but very heavy from implementation point of view!

PTDF & ATC calculation



$PTDF_{ij}^{k}$ is defined as the fraction of MW flowing in line k (or m-n) resulting from 1 MW injected in node i and consumed in node j

Assuming the DC-Flow model:

$$\Delta P_{mn} = PTDF_{ij}^{k} \, . \, q_{ij}$$

- ΔP_{mn} is the flow increase in line k due to the transaction T_{ij}
- q_{ij} is the quantity contracted in T_{ij}

The DC-Flow model can help to determine any PTDF needed based on:

$$P_{mn} = \frac{1}{x_{mn}} \cdot (\theta_m - \theta_n) \;;$$ where $(\theta_m - \theta_n)$: voltage angle difference

x_{mn} : reactance of the line

The injected power in node i is given by:

$$P_i = \sum_j P_{ij} = \sum_j \frac{1}{x_{ij}} \cdot (\theta_m - \theta_n)$$

The set of the DC-Flow equations is defined by (grid of s nodes):

$$\begin{bmatrix} P_1 \\ \vdots \\ \vdots \\ P_s \end{bmatrix} = \begin{bmatrix} & & \\ & B_x & \\ & & \end{bmatrix} \cdot \begin{bmatrix} \theta_1 \\ \vdots \\ \vdots \\ \theta_s \end{bmatrix}$$

Accounting for the B_x singularity, we derive the angles as (i.e, θ_s=0):

$$\begin{bmatrix} \theta_1 \\ \vdots \\ \vdots \\ \theta_{s-1} \end{bmatrix} = \begin{bmatrix} & & \\ & X & \\ & & \end{bmatrix} \cdot \begin{bmatrix} P_1 \\ \vdots \\ \vdots \\ P_{s-1} \end{bmatrix}$$

The effect of adding the transaction T_{ij} will lead to:

$$\begin{bmatrix} \Delta\theta_1 \\ \vdots \\ \Delta\theta_m \\ \vdots \\ \Delta\theta_n \\ \vdots \\ \Delta\theta_{s-1} \end{bmatrix} = \begin{bmatrix} & & \\ & X & \\ & & \end{bmatrix} \cdot \begin{bmatrix} 0 \\ q_{ij} \\ 0 \\ -q_{ij} \\ 0 \\ \vdots \\ 0 \end{bmatrix} \begin{matrix} \\ \text{node} \rightarrow i \\ \\ \text{node} \rightarrow j \\ \\ \\ \\ \end{matrix}$$

Since: $$\Delta P_{mn} = \frac{1}{x_{mn}} \cdot (\Delta\theta_m - \Delta\theta_n)$$

We derive: $$PTDF_{ij}^{mn} = PTDF_{ij}^{k} = \frac{X_{im} - X_{jm} - X_{in} + X_{jn}}{x_{mn}}$$

ATC_{ij} (*Available Transfer Capacity*) is the maximum quantity we can still contract from node i to node j without any violation of transmission line thermal constraint.

For every line k, we determine how much quantity we can transfer from node i to node j until the capacity limit $P_k^{\,max}$ is reached:

$$q_{ij}^{k,max} = \frac{P_k^{max} - P_k^0}{PTDF_{ij}^k}$$; P_k^0 is the actual flow in line k

Then: $$ATC_{ij} = \min_k q_{ij}^{k,max}$$

Congestion management dependencies

The methods depend on:

- the energy trading mechanism: pool or bilateral,

- the structure of the system: inter-zone (cross border) or intra-zone,

- the auctioning mechanism: implicit or explicit,

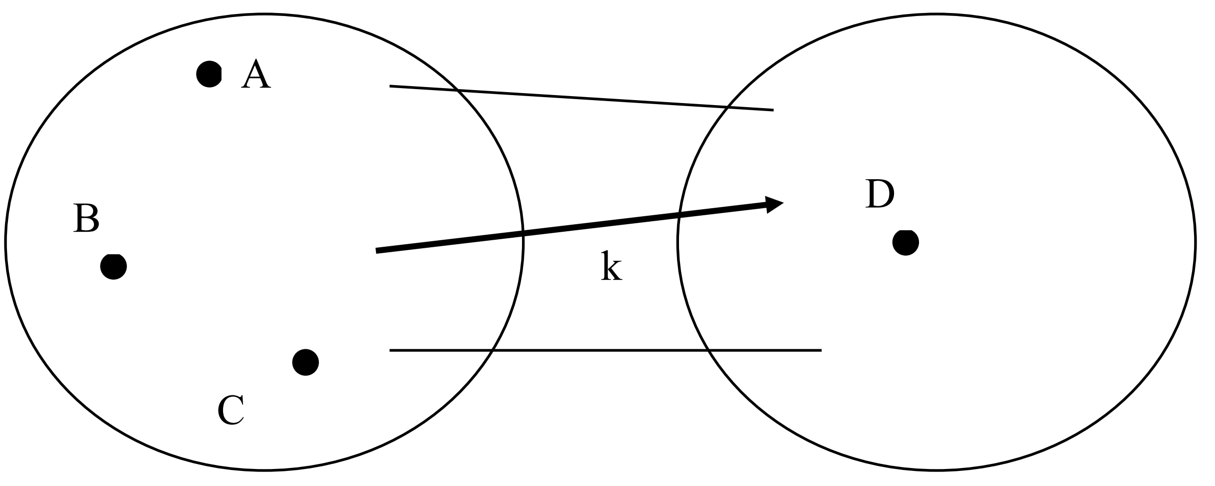
- the settlement mode: free of charge or charged

Transmission Load Relief (TLR) method

We consider inter-zone congestion and bilateral trading mechanism. What is the minimum quantity to be curtailed over all the inter-zone transactions?

Criteria: congestion relief and fairness to all the transactions

Example: a case with 3 transaction T_{AD}, T_{BD} et T_{DC}



q_{AD}= 900 MW, $PTDF^k_{AD}$ =0.1; q_{BD}= 300 MW, $PTDF^k_{BD}$ =0.3, q_{DC}= 100 MW, $PTDF^k_{DC}$ =-0.2

The flow in line k is:

$$q_{AD} \cdot PTDF^{k}_{AD} + q_{BD} \cdot PTDF^{k}_{BD} + q_{DC} \cdot PTDF^{k}_{DC} = 160 \text{ MW}$$

The capacity of the line being 80 MW, the overload is of 80 MW

Find minimum curtailment of T_{AD} and T_{BD} while fulfilling the constraint:

$$\Delta q_{AD} \cdot PTDF^{k}_{AD} + \Delta q_{BD} \cdot PTDF^{k}_{BD} = \Delta F = 80 \text{ MW}$$

*The **Min** and **Max** curtailment schemes:*

Min: $\Delta q_{AD} = 0$ and $\Delta q_{BD} = \Delta F / PTDF^{k}_{BD} = 266.7$ MW

Global minimum curtailment but unfair with regard T_{BD}!

Max: $\Delta q_{AD} = \Delta F / PTDF^{k}_{AD} = 800$ MW and $\Delta q_{BD} = 0$

Unfair and far from the required minimum curtailment!

<u>NERC's curtailment scheme</u>: (NERC:North American Reliability Council)

Find Δq_{AD} & Δq_{BD} that Min. $\Delta q^2_{AD} \cdot \dfrac{1}{q_{AD}} + \Delta q^2_{BD} \cdot \dfrac{1}{q_{BD}}$

under: $\Delta q_{AD} \cdot PTDF^k_{AD} + \Delta q_{BD} \cdot PTDF^k_{BD} = \Delta F$

It gives:

$$\Delta q_{AD} = \Delta F \cdot \frac{PTDF^k_{AD} . q_{AD}}{(PTDF^k_{AD})^2 . q_{AD} + (PTDF^k_{BD})^2 . q_{BD}} = 200 \text{ MW}$$

$$\Delta q_{BD} = \Delta F \cdot \frac{PTDF^k_{BD} . q_{BD}}{(PTDF^k_{AD})^2 . q_{AD} + (PTDF^k_{BD})^2 . q_{BD}} = 200 \text{ MW}$$

The total curtailment is 400 MW. Equal reductions on T_{AD} and T_{BD} but the respect. impacts on the congestion are different (20 and 60 MW)

Improved NERC's curtailment scheme:

Find Δq_{AD} & Δq_{BD} that Min. $\Delta q^2_{AD} \cdot \dfrac{1}{q_{AD}.PTDF^k_{AD}} + \Delta q^2_{BD} \cdot \dfrac{1}{q_{BD}.PTDF^k_{BD}}$

under: $\Delta q_{AD} \cdot PTDF^k_{AD} + \Delta q_{BD} \cdot PTDF^k_{BD} = \Delta F$

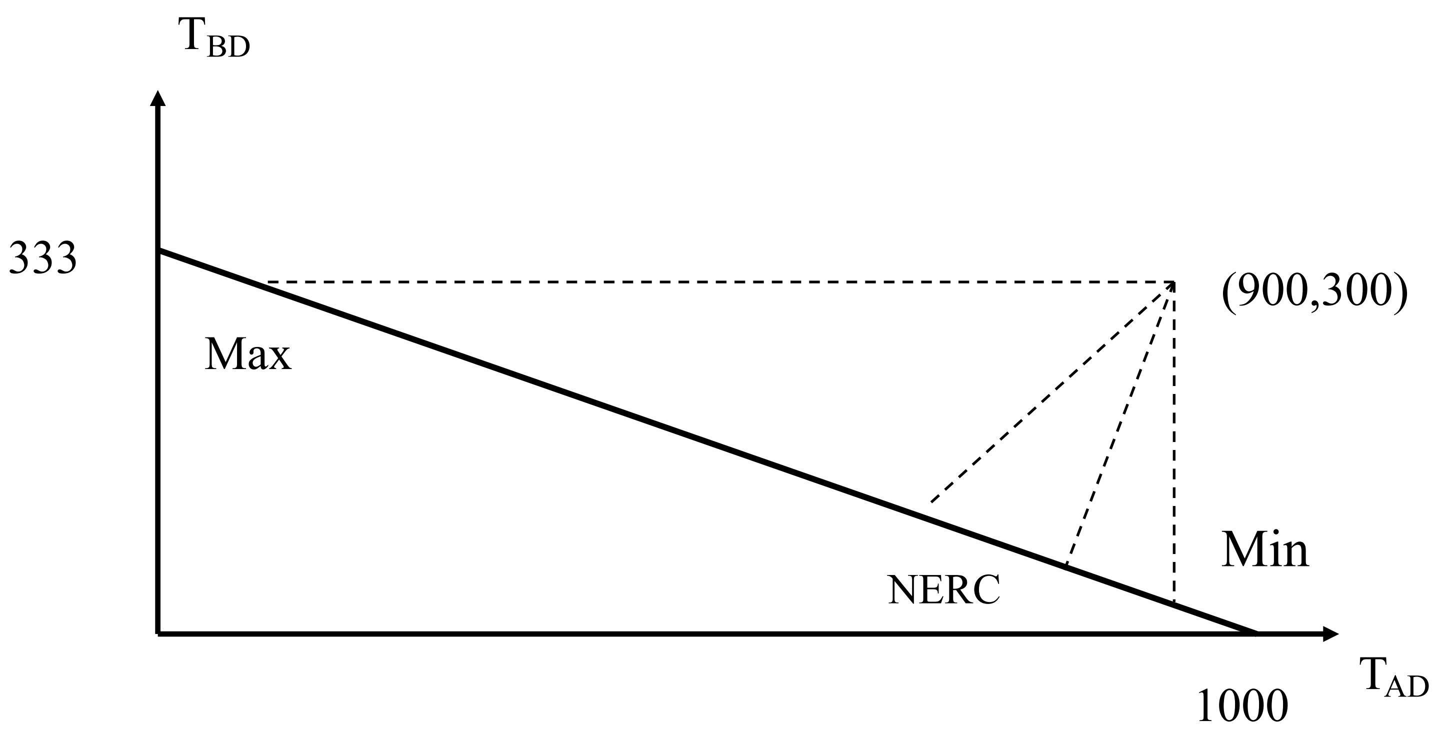
It gives:

$$\Delta q_{AD} = \Delta F \cdot \frac{(PTDF^k_{AD})^2.q_{AD}}{(PTDF^k_{AD})^3.q_{AD} + (PTDF^k_{BD})^3.q_{BD}} = 80 \text{ MW}$$

$$\Delta q_{BD} = \Delta F \cdot \frac{(PTDF^k_{BD})^2.q_{BD}}{(PTDF^k_{AD})^3.q_{AD} + (PTDF^k_{BD})^3.q_{BD}} = 240 \text{ MW}$$

The total curtailment is 320 MW. T_{AD} is curtailed 3 times less than T_{BD}.
It seems fair with regard to the respect. impact on the congested line k

Summary of TLR example:



Willingness to pay method

In the bilateral trading mechanism, consumers are willing to pay a fee in order to avoid or to limit, in case of congestion(s), the curtailment of the transaction where they are involved

Find q_i **such as Min.** $\sum_{i} (q_i - q_{i0}) \cdot w_i \cdot (q_i - q_{i0})$

Subject to:

$f(\mathbf{q},\mathbf{u}) = 0$, load flow (LF) equations

$g(\mathbf{q},\mathbf{u}) < 0$, thermal capacity constraints of lines

q ($=q_1,..,q_n$) : contracted quantities
u : state variables (voltage modules and angles)
wi : weight proportional to the paid fee

Inc-Dec method (redispatching)

Compatible with bilateral and pool market mechanisms

The congestions are relieved by increasing the production at certain nodes and decreasing the production at other ones while deserving continuously the same load

Every generator bids for increase and decrease its production

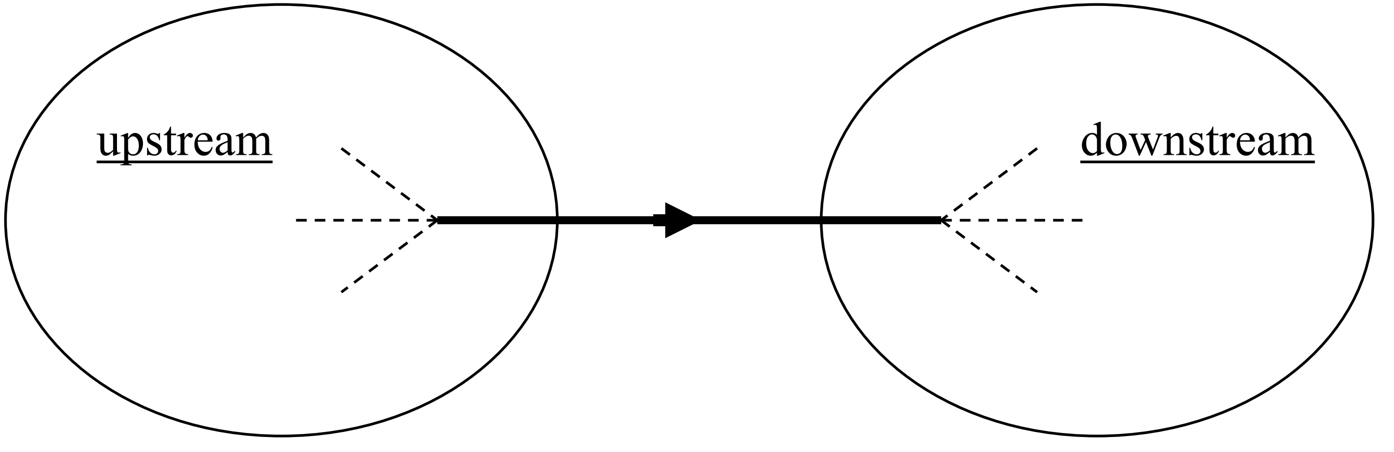
The bid price for increase will be paid to the generator by ISO; the bid price for decrease will be paid to ISO by the generator (spot price as reference)

Optimization problem where the total cost (sum of bids times prices) for the redispatching is to be minimized while observing the LF equations and the thermal capacity line constraints

Counter-flow method

Particular Inc-Dec method where the participating generators are chosen such as they impact significantly the congested line (PTDF's)

2 sets: – generators *upstream* to the congested line – generators *downstream* to the congested line



When one or several downstream generators increase their generation output then one or several upstream generators decrease their generation output by the same global quantity (congestion relief rule)