Market for electricity

Smart Electricity Systems

A.Y. 2025- 2026

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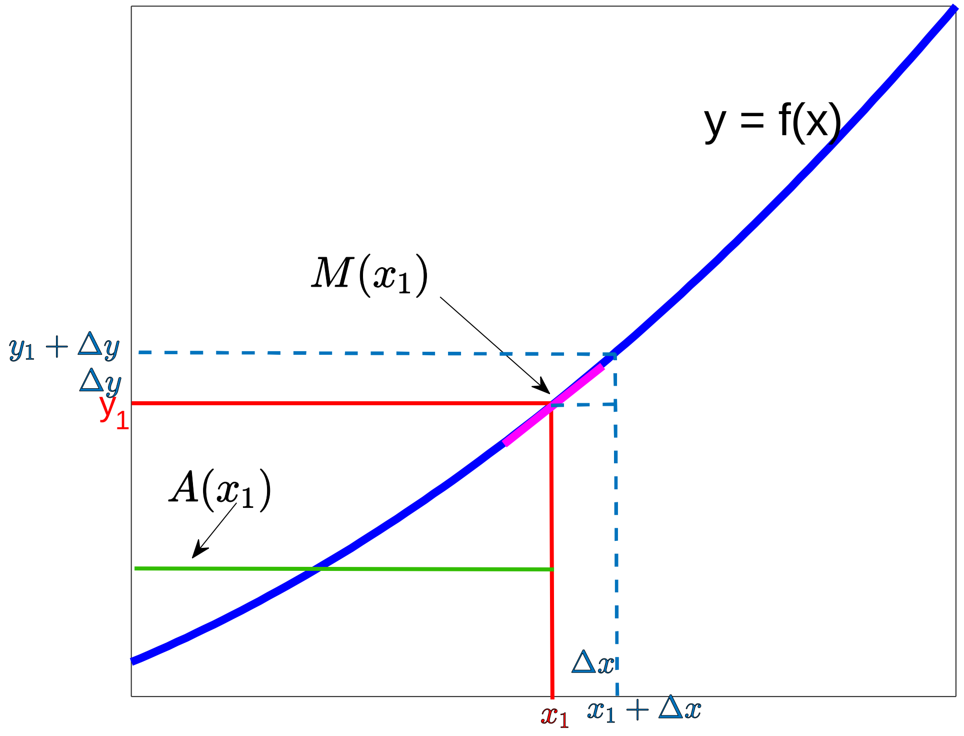
[recall math.] average and marginal

- The function $f(x)$ represents the value of a quantity y as a function of the variable x.
- Consider a value x_1 corresponding to the quantity y_1, we can define at x_1:

$$A(x_1) = \frac{f(x_1)}{x_1}$$

$$M(x_1) = \left.\frac{df(x)}{dx}\right|_{x=x_1}$$ corresponds to:

- the slope of function $f(x)$ at $x = x_1$.
- the straight angle coefficient of the tangent to $f(x)$ at $x = x_1$
- For a small increase of the value x : $x_1 \rightarrow x_1 + \Delta x$ the increase of the quantity y_1 is $y_1 \rightarrow y_1 + \Delta y$, i.e.



$$\lim_{\Delta x \to 0} \left.\frac{\Delta y}{\Delta x}\right|_{x=x_1} = \left.\frac{dy}{dx}\right|_{x=x_1} = M(x_1)$$

Scarcity

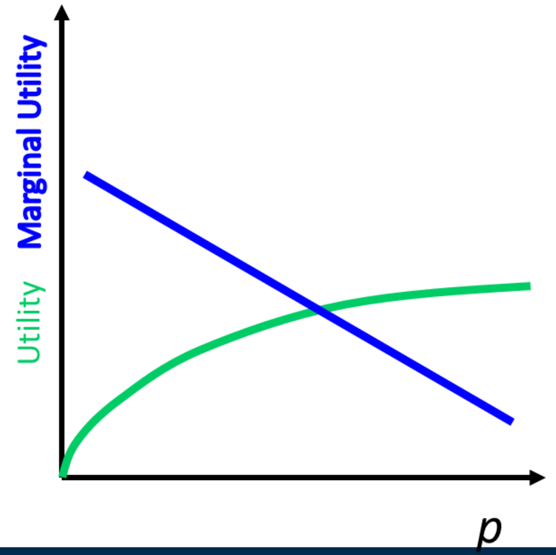
- Desirable *goods* (natural resources, product, material and immaterial assets, services) are *limited* in their availability/quantities and cannot be procured by all the interested subjects in the eventually desired quantities
- The problem of having *finite resources* while *infinite* society's *demand* for goods is the problem of scarcity.
- From scarcity arises the problem of how and to whom allocate resources and in which ways
- Economics is focused on *how to allocate scares goods* in an efficient way

Law of diminishing marginal utility

- Utility is the degree of removed discomfort or perceived satisfaction that an individual receives from a good or service
- It is very difficult to measure as it is individual, relative, psychological
- It has no ethical or moral significance, and it is not necessarily requiring “usefulness” (e.g. alcohol)
- Utility is highly depended on the intensity of the desire, thus for the same good or service, the utility will change according to the urge or need.
- The extra utility added by the last unit consumed of a good diminishes as more of the good is consumed.
- The diminishing marginal utility results from the fact that your appreciation or taste for a good drops off as more of the good is consumed.

Demand curves

- Utility always increases with consumed quantity
- The utility of last consumed unit is decreasing (marginal utility decreases).
- The utility is reflected by the price the consumer is willing to pay
- The demand curve of a good in the market is represented by the marginal utility

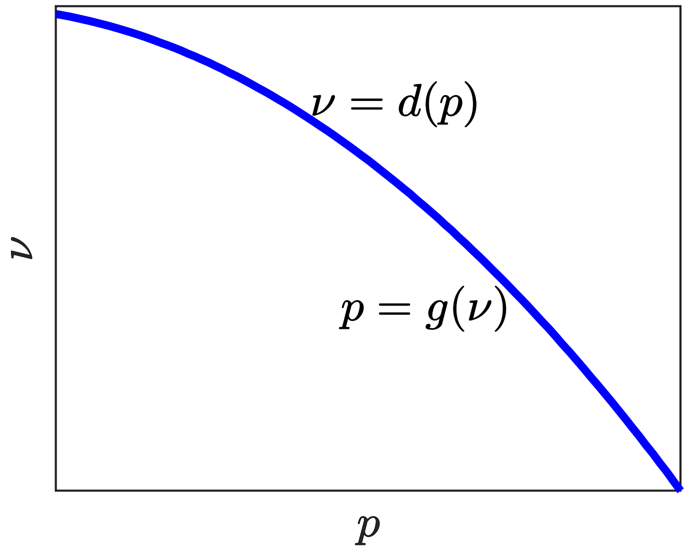


- *Demand curve d(p):* It is a decreasing curve(why?), which expresses the price the buyers are willing to pay as a function of the quantity demanded:

$$\nu = d(p)$$

- *Inverse demand curve*: It is a function that expresses the quantity that buyers are willing to pay as a function of the price:

$$p = g(\nu)$$

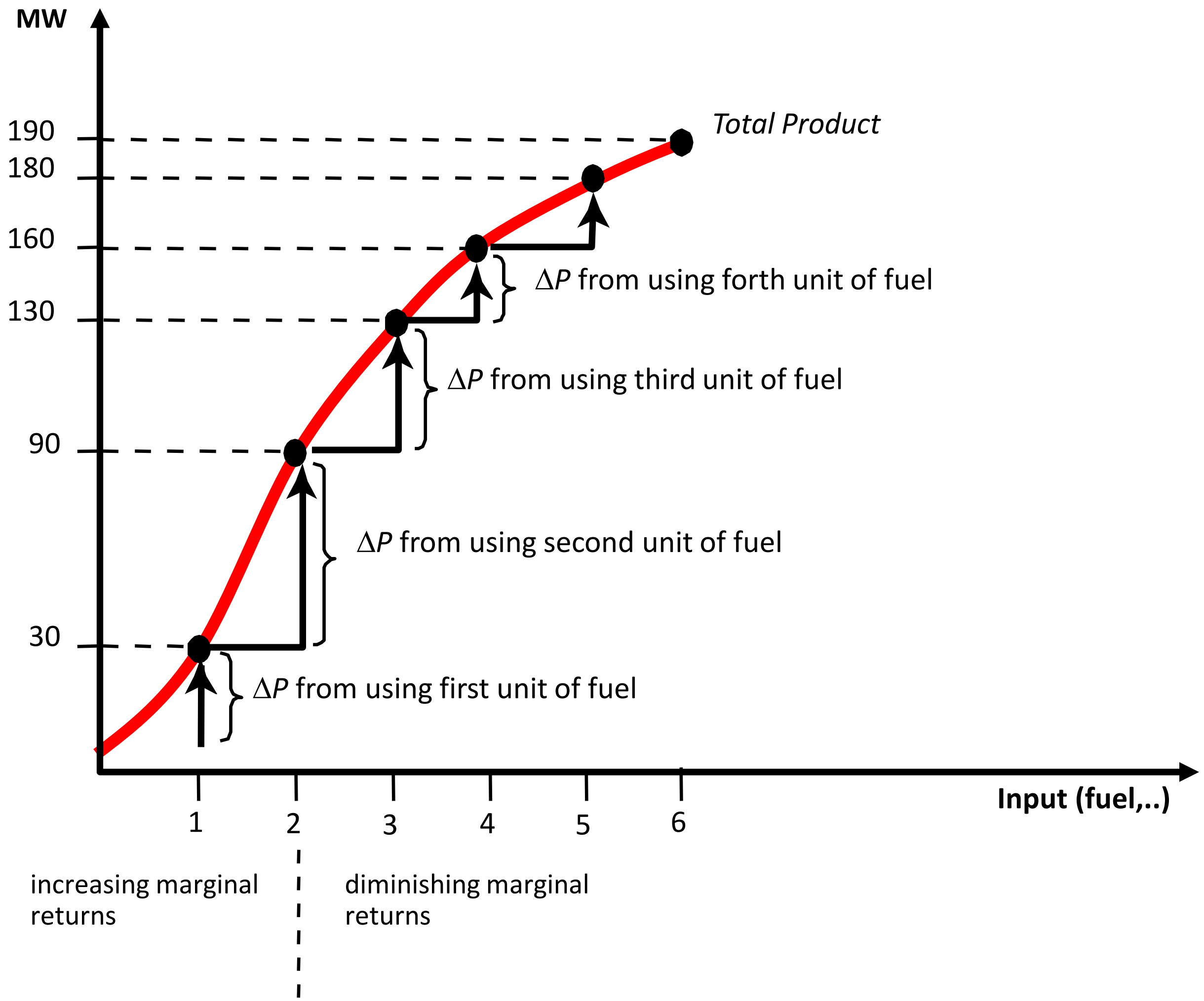


Costs

- *Fixed cost c^F*: cost that, in the short period, does not depend on the production quantity.
    - Ex. The cost of land, machines, factories, your lease, your property taxes,…
- *Variable cost $c^V(p)$*: cost depending on the production quantity.
    - Ex. Amount spent on labor, fuels, electricity, …
- *Total cost $c(p)$*: the sum of the total costs undertaken by the firm to produce the quantity p of the good. It is the sum of fixed and variable costs: $c(p) = c^F + c^V(p)$
- *Average cost: the total cost undertaken to produce a unit of product at a given level of production:* $\bar{c}(p) = \frac{c(p)}{p}$
- *Average variable cost: the variable cost undertaken to produce a unit of product at a given level of production:* $\bar{c}^v(p) = \frac{c^v(p)}{p}$
- *Marginal cost $c^m(p)$*: for a given level of production p, the derivative of the cost w.r.t the quantity p computed in p . $c^m(p) = \frac{dc(p)}{dp}$

Law of diminishing marginal returns and supply curve

- An increase in some varying inputs relative to other fixed inputs will, in a given state of technology, make total output increase but after a point the extra output resulting from the same additions of extra inputs is likely to become smaller and smaller.
- As the production quantity increases, we need to use more expensive resources for production
- As the marginal cost always increases with the increase of the product quantity, thus, the supply curve always has an upward sloping.



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Profit and maximum of profit

- Total revenue r : the money got from the selling of goods $r(p)=v(p)\cdot p$
- Profit π : it is a financial gain obtained from the difference of revenues and the total costs: $\pi=r(p)-c(p)=v(p)\cdot p-c(p)=(v(p)-\bar{c}(p))\cdot p$
- A rational firm always pursues the *maximization* of the profit.

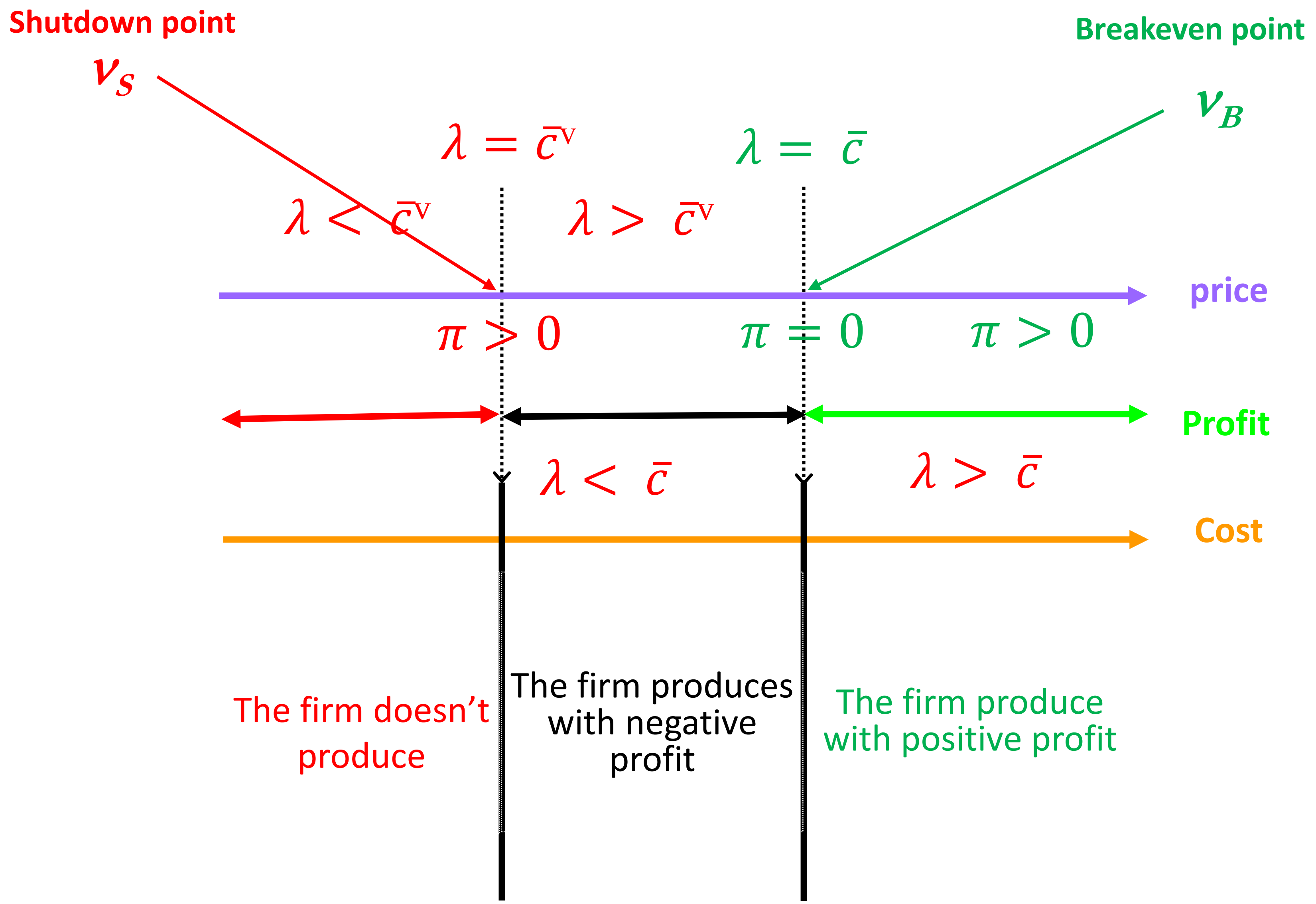
$$\max\{\pi\}=\max\{v(p)\cdot p-c(p)\}$$

$$\frac{d\pi}{dp}=r^m-c^m=\left(v(p)+\frac{dv(p)}{dp}\cdot p\right)-\frac{dc(p)}{dp}=0$$

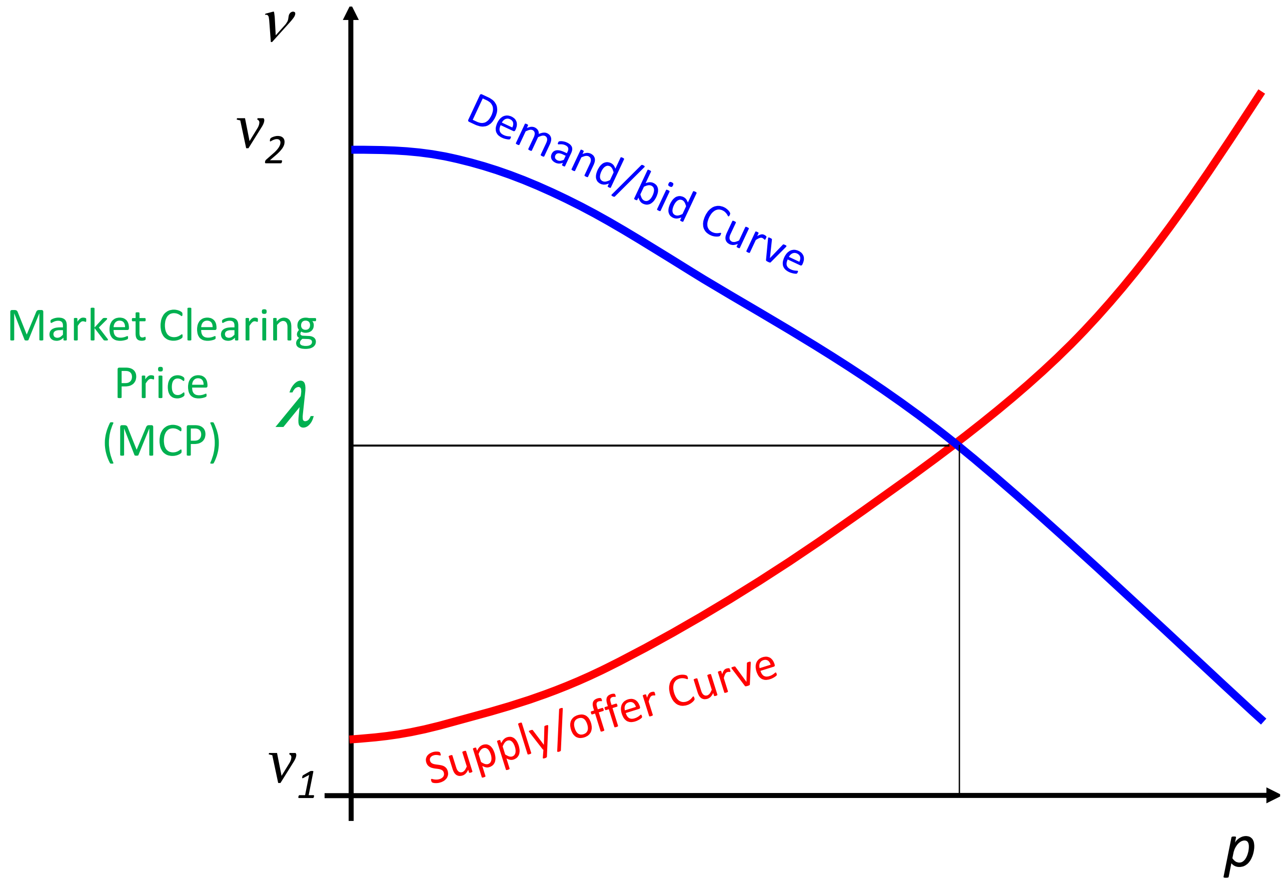
$$\Rightarrow r^m=c^m$$

- If the firm is a price taker of the market, then the profit is maximum for the quantity for which the market price is equal to the marginal costs.

Breakeven and shutdown points



Equilibrium

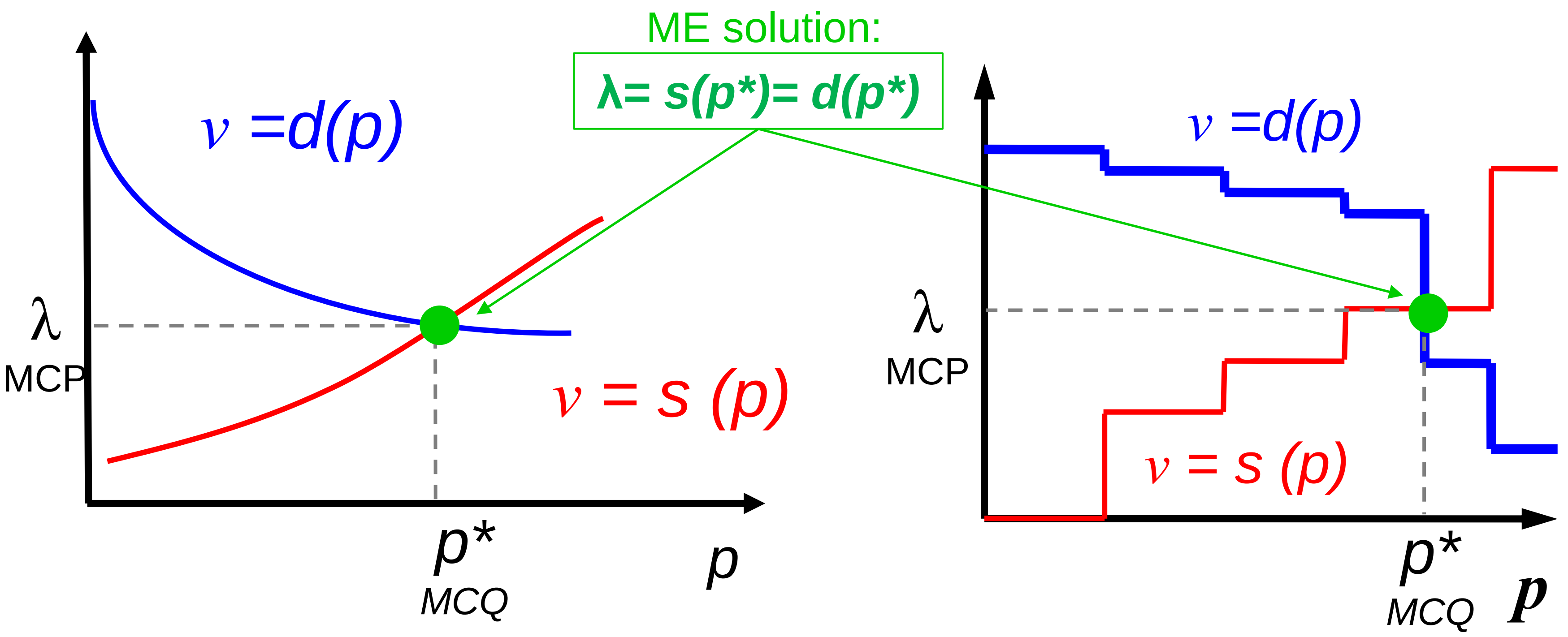


- when price is higher than λ, (v_2) more quantity is produced but less quantity is demand, then the producer will decrease the price

- when price is lower than λ, (v_1), more quantity is demanded but less quantity is produced, then demand will increase the bids, so the price will increase

Market equilibrium

- Market equilibrium condition: the quantity offered for sale by sellers at a given price (Market Clearing Price MCP) is just equal to the quantity demanded by buyers at that same price (Market Clearing Quantity MCQ).



Market efficiency indicators: surpluses

- *Consumer surplus s^D*: is the area enclosed by the bid curve and the market equilibrium price in the bid/offer curves.

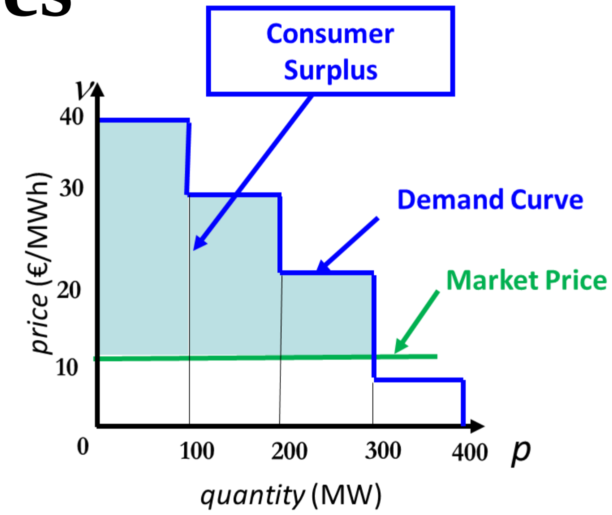
$$s^D = \int_0^{p^*} (v_d(p) - \lambda)\,dp$$

- *Producer surplus s^G*: is the area enclosed by the offer curve and the market equilibrium price in the bid/offer curves.

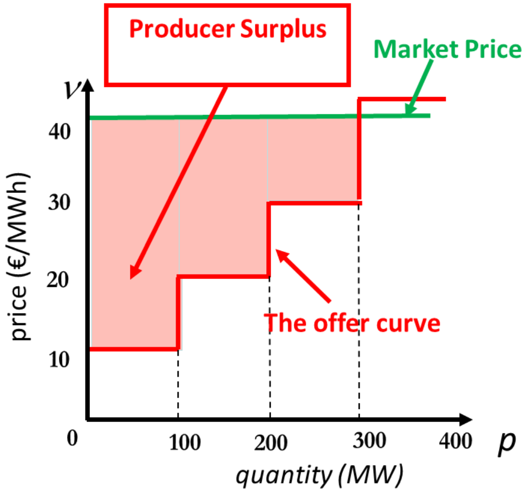
$$s^G = \int_0^{p^*} (\lambda - v_g(p))\,dp$$

- *Social surplus s^S*: the area enclosed by the offer curve and the bid curve.

$$s^S = \int_0^{p^*} (v_d(p) - v_g(p))\,dp$$

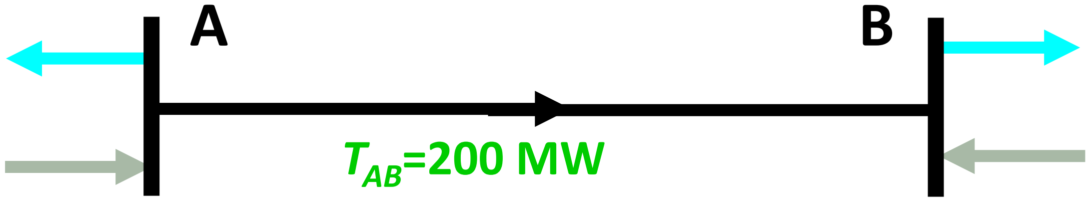


s^D=(40-10)*100+(30-10)*100+(20-10)*100=6000 ($/h)



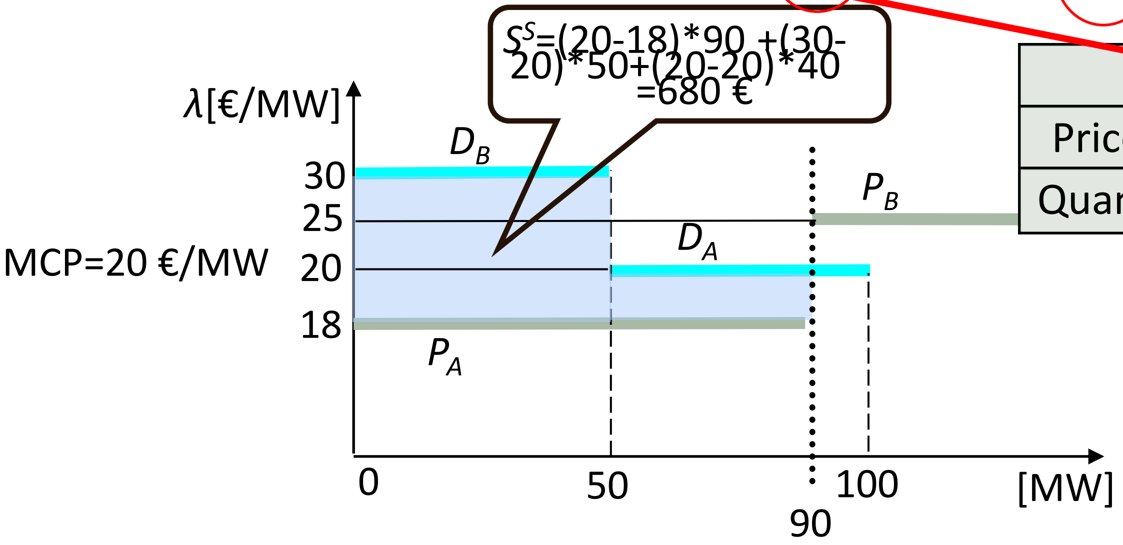
s^G=(40-10)*100+(40-20)*100+(40-30)*100=6000 ($/h)

Example: 2-bus system



OFFERS
BIDS

	P_A	D_A	P_B	D_B
Price €/MW	18	20	25	30
Quantity MW	90	50	50	50



	P_A	D_A	P_B	D_B
Price €/MW	20	20	20	20
Quantity MW	90	40	0	50

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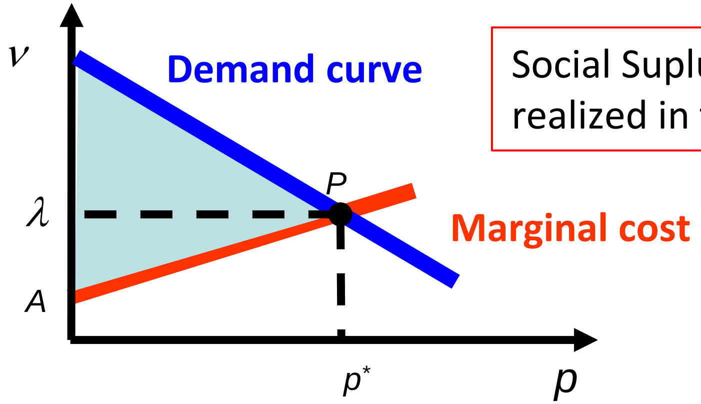
Strategic bidding behavior of the producers



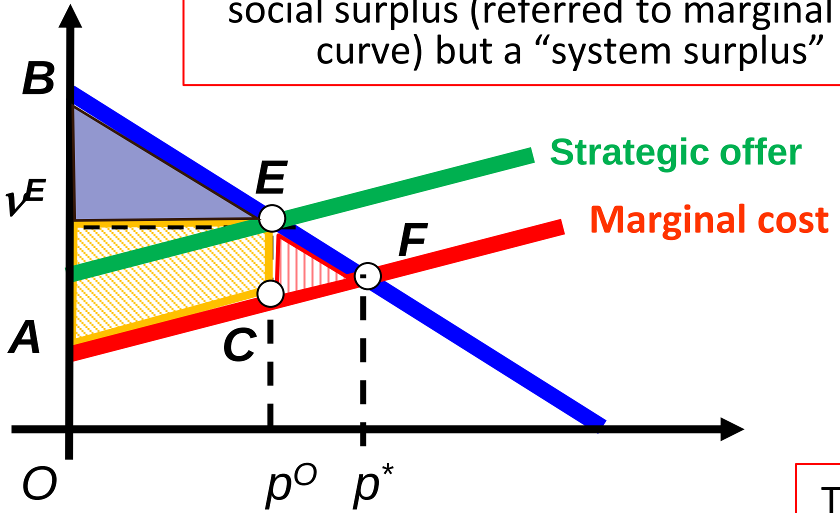
Social Suplus is maximized and realized in the market clearing

Perfect Competition Market

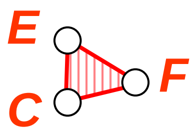
Social surplus s^S : the area between demand and marginal cost curves

System surplus s^Y : the area between demand and offer curves

Under no perfect competition the two might be different



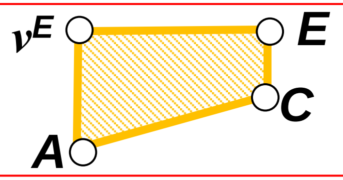
The market clearing cannot maximize the social surplus (referred to marginal cost curve) but a “system surplus”



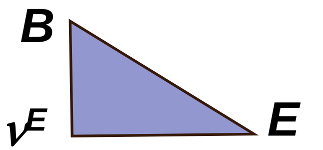
The social surplus is reduced (dead weight loss S^-)

Non-perfect Competition Market

Producer surplus is maximized in the market clearing

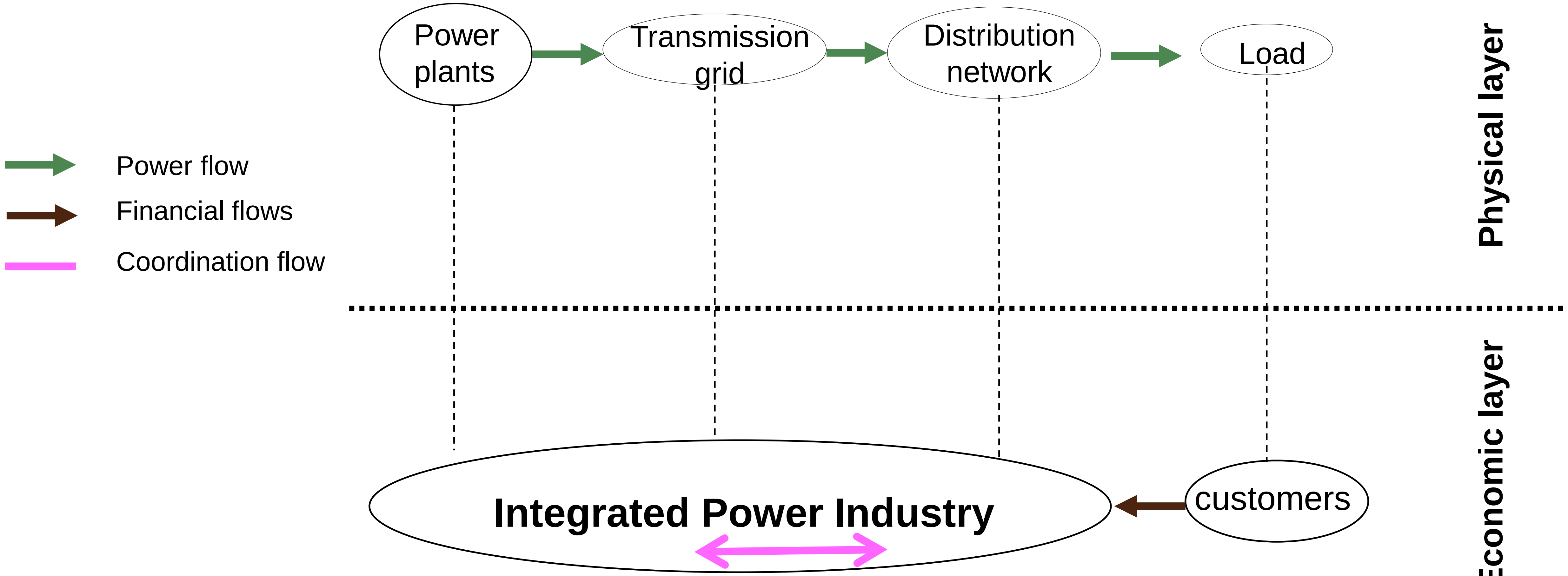


Consumer surplus is reduced in the market clearing



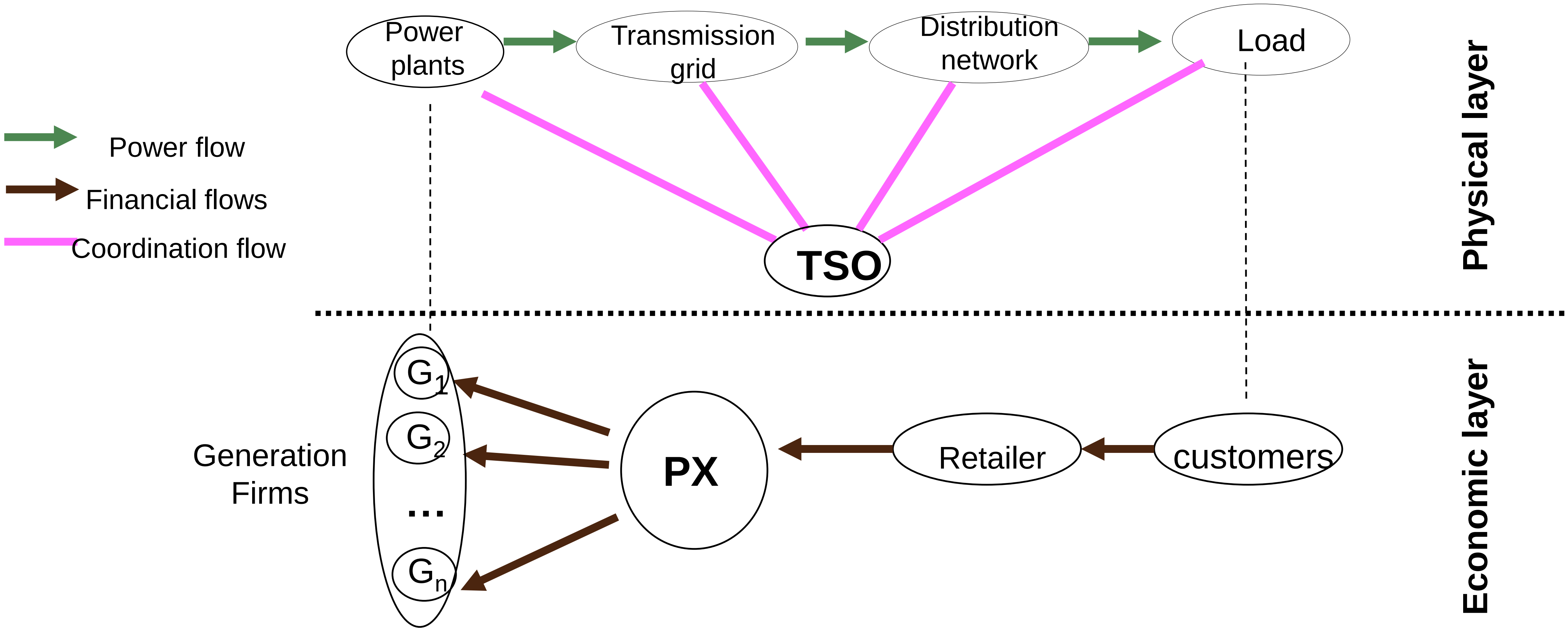
Liberalization : level0

LEVEL 0 – Monopoly (no competition): all the sectors of the electricity industry are bundled and there is only one (regulated) company



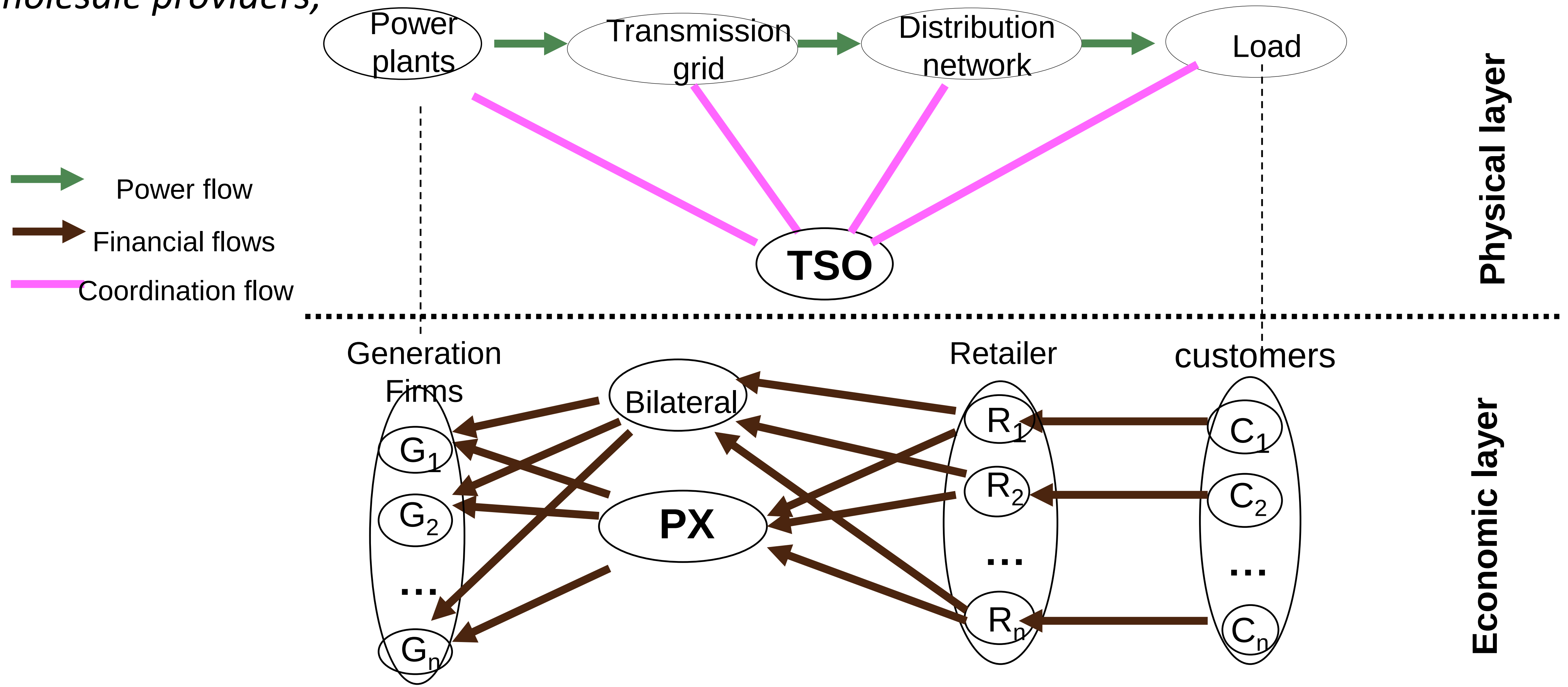
Liberalization : level1

<u>LEVEL 1 – Purchasing agency (competition in generation):</u> a single buyer buys electricity from many competing producers;



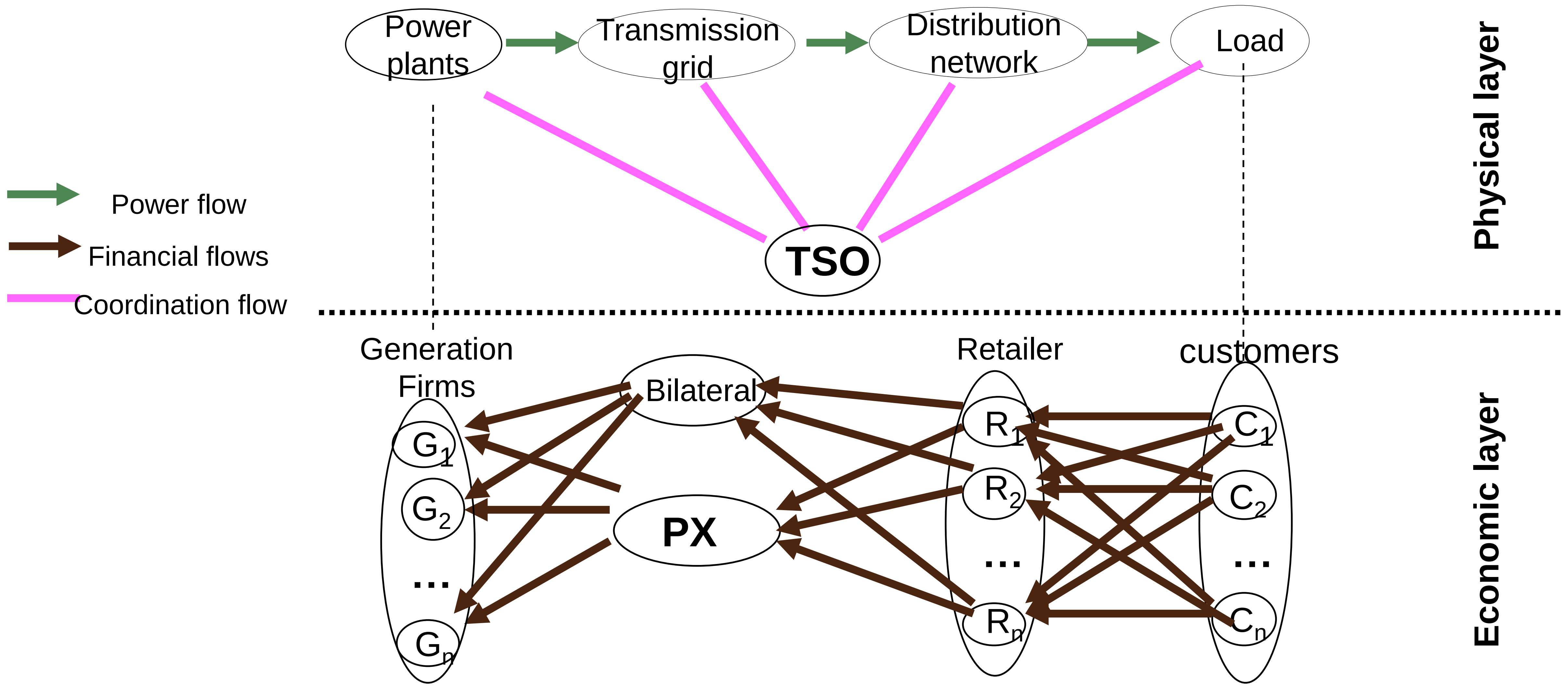
Liberalization : level2

<u>LEVEL 2 – Wholesale competition</u>: different retailers and large customers can choose different wholesale providers;



Liberalization : level3

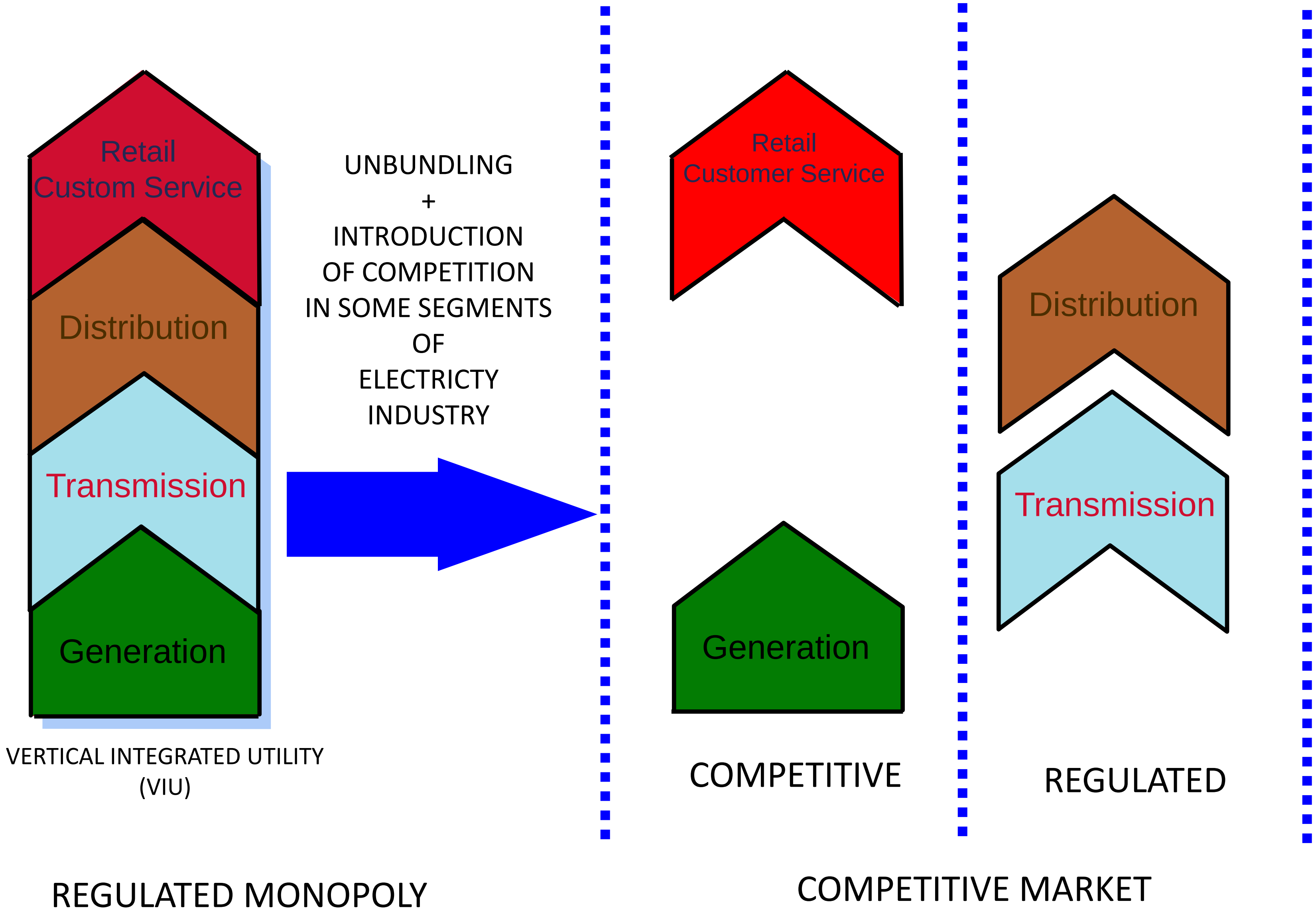
<u>LEVEL 3 – Retail competition</u>: allows all the consumers to choose their suppliers.



Levels of liberalization: from the demand side

- <u>*Monopoly (level 1)*</u>*:* Demand is forcasted by the TSO as fixed (zero elasticity demand).
- *In electricity markets (level 1,2,3)*
  - Bid submitted only above a minimum size (kWh/year)
  - The retailers can choose producers by PX (level 1,2,3) or in a bilateral way (level 2,3)
  - Consumers are fed by franchising distributors (level 0,1,2) and choose any retailer (level 3)

From regulation to liberalization



Definition of commodity and electricity as a commodity

- An economic good that is fungible (a unit of a given source commodity is interchangeable with a unit of the same commodity from other sources/suppliers).
- Different goods from different suppliers have the same quality (they cannot be distinguished on the basis of the quality)
- Examples: gold, uranium, copper, aluminum, coal, cotton, oil.
- Electricity is fungible;
- a kWh wherever and however it is generated is undistinguishable from another
  - two kWh from different suppliers are perfectly interchangeable
  - Electricity can be traded in global markets
- Electricity can be used in any quantity
- It has price difference by location
- It has price difference by time of uses
- It has price difference by time difference between contract and delivery (different time frames)

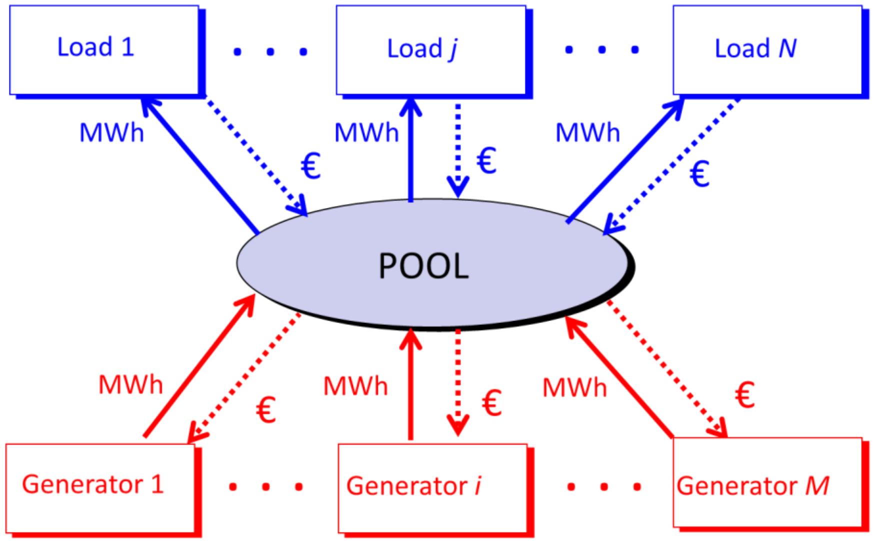
Physical and Technical Features of Electricity as a Commodity

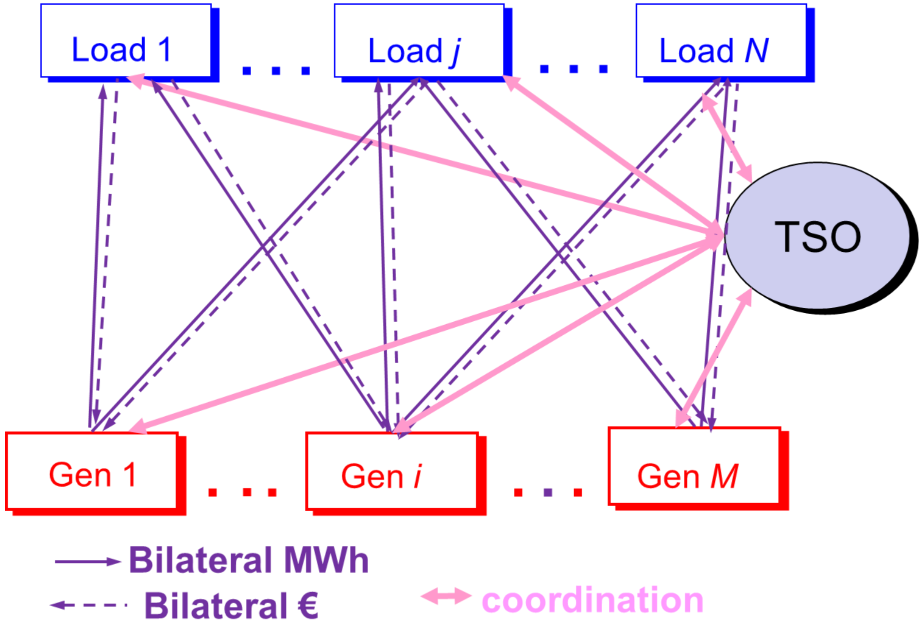
- Need for an instantaneous balance between power production and power consumption plus losses in any point in time
- Has to be delivered to the end user with proper quality specified by a set of metrics (frequency, voltage, harmonics, etc…)
- Need of reactive power for delivering real power (normal operation) although does not produce useful work
- Large scale and efficient storage of electricity is not possible with current technologies (distributed storage is a promising option for the future)
- Flows of the electricity can not be decided but are determined by the admittance matrix of the network (system physical parameters)
- Losses incurred when transferring electricity
- Operation of the power systems for generation, transmission, distribution of electricity has to respect a set of technical operational limits (line flow limit, voltage profile minimum and maximum bounds), that define the feasible region of the system, must be enforced

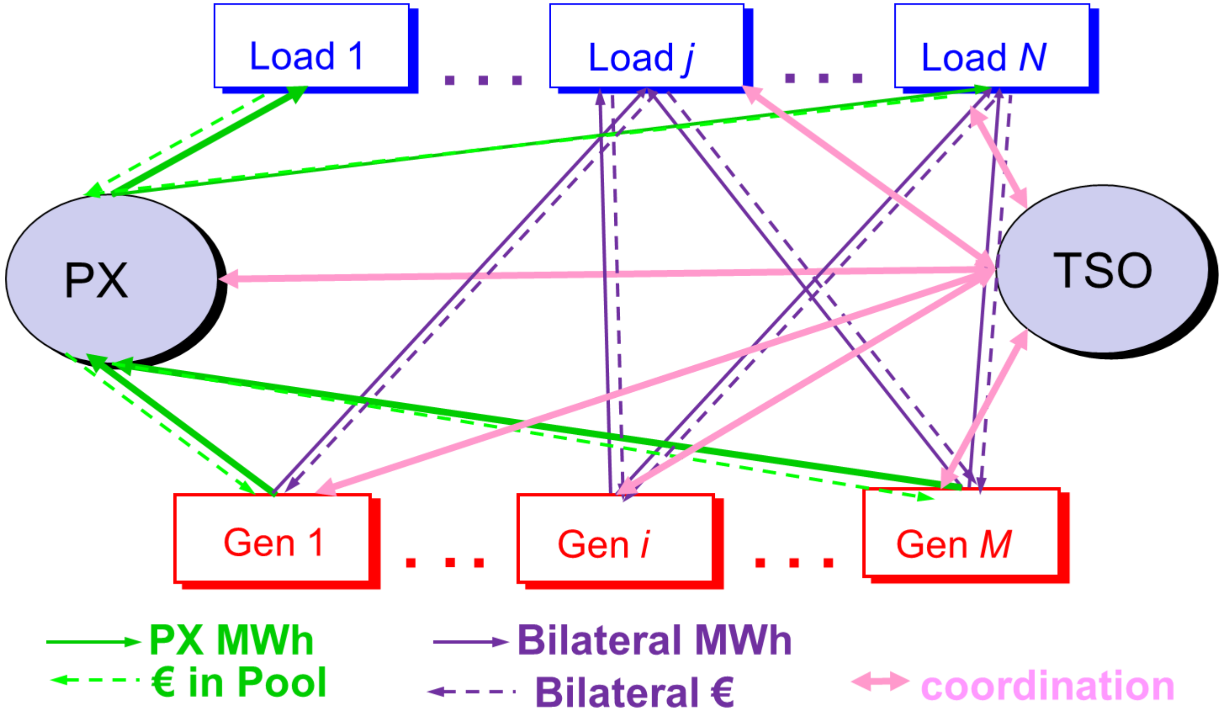
Players and entities in the electricity markets

- Generation companies
- (Independent) Transmission System Operator (TSO)
- Transmission network owners (TO)
- Brokers
- Distribution System Operators (DSO)
- Retail companies
- Wholesale customers
- Retail customers (consumers/prosumers)

Electricity market reference: pool model vs bilateral model

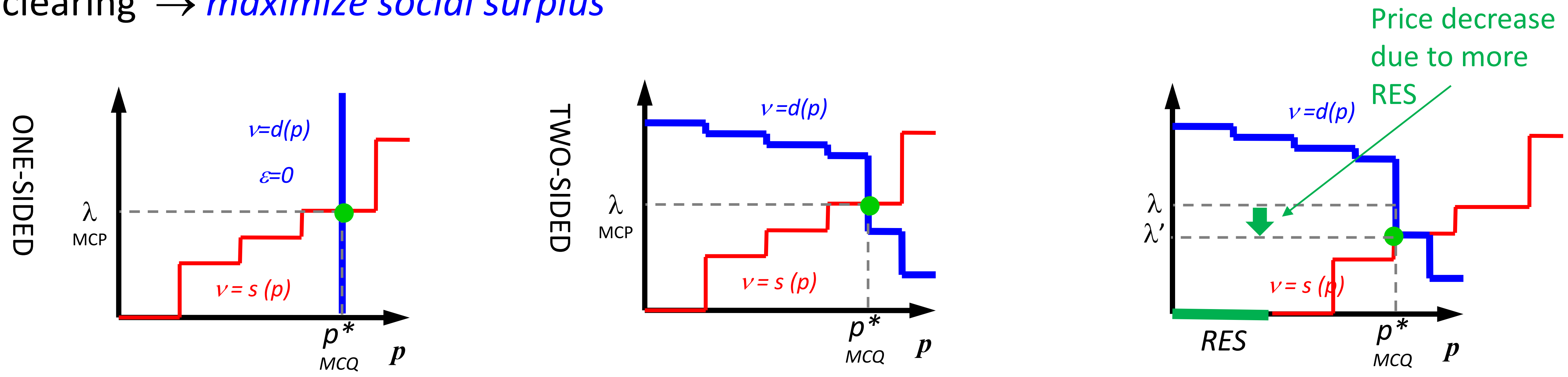






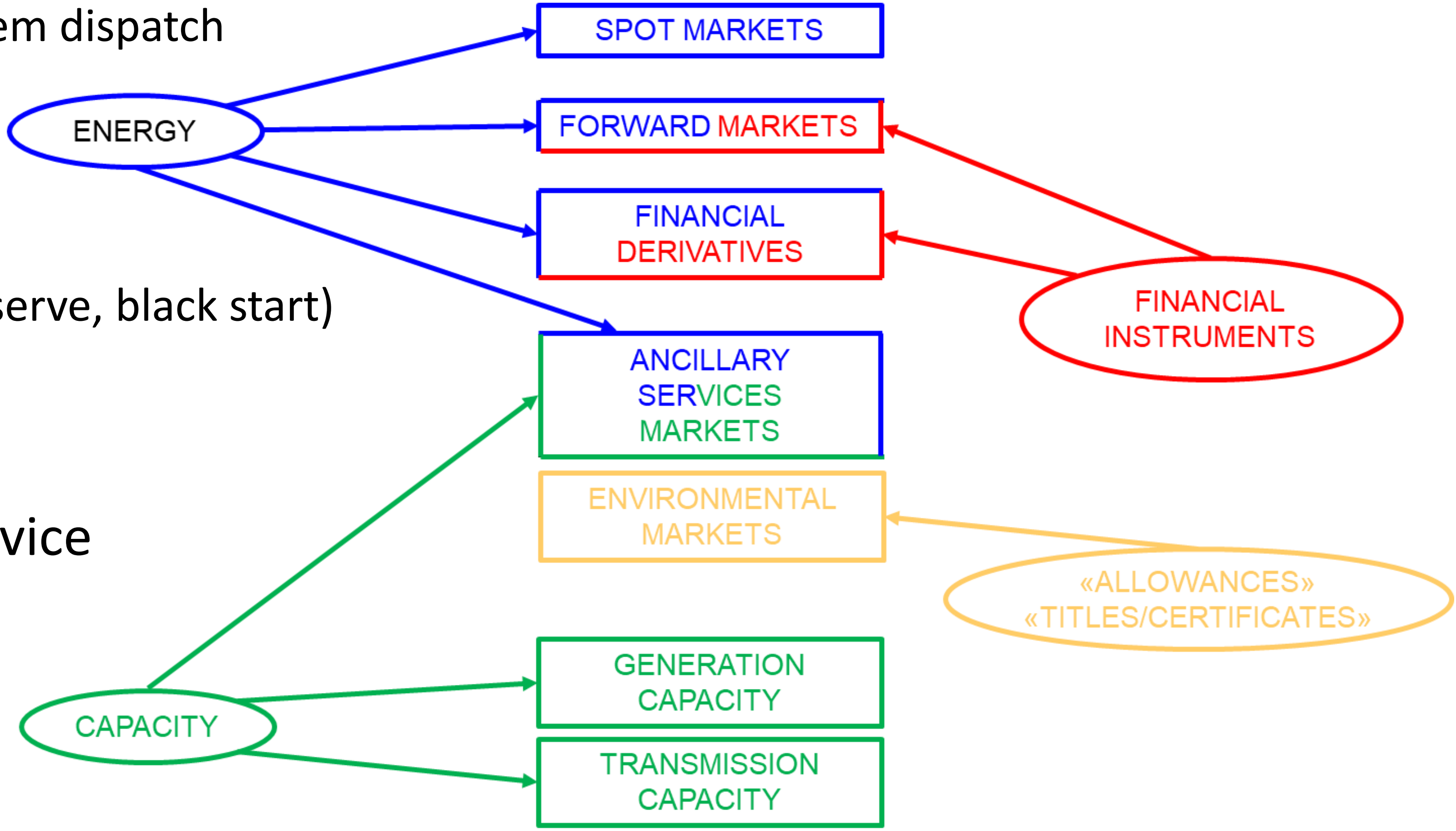
Pool model: power exchange

- Power exchange is the physical/virtual location where sellers and buyers meet to place their offers/bids
- Counterpart for each producer and each consumer
- Compulsory participation
- *One-sided*: only producers compete (to satisfy a pre-assigned demand): market clearing $\rightarrow$ *minimize production costs*
- *Two-sided*: both producers and sellers compete (to satisfy a pre-assigned demand): market clearing $\rightarrow$ *maximize social surplus*



Markets in electricity industry and traded goods

- Generation
- Transmission
    - Unit commitment and system dispatch
    - Balancing
    - Voltage regulation
    - Congestion Management
    - Security assurance (n-1, reserve, black start)
    - Network expansion
- Distribution
- Retail supply and customer service
- Financial risk hedging

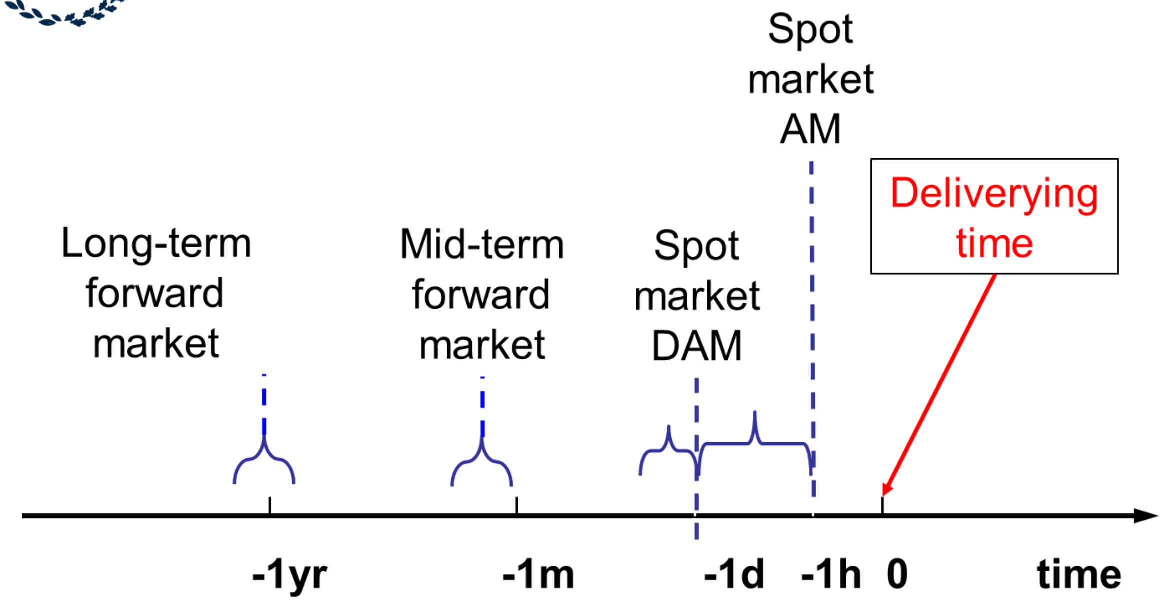


Spot markets vs forward contracts

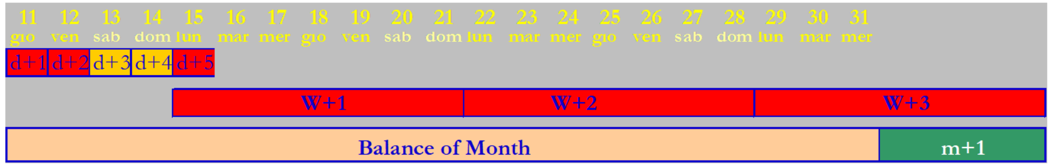
- “*Pool type*”
- The interaction seller/buyer is mediated by an institutional organization (power exchange)
- All buyers and sellers bid/offer together within a predefined time schedule
- Buyer pays “on the *spot*”
- Neither of the parties (buyers and seller) can back out of the deal
- Electricity traded for “*short time*” period (day)
- *Day Ahead Market* (DAM): trading electricity today for tomorrow. Usually offer/bids for each hour of the following day in terms of price (€)/quantities (MW)
- *Adjustment Market* (AM): trading electricity today for tomorrow or today; useful for market players to re-adjust their offers/bids to be compliant with physical constraints

- *“Bilateral type*”
- A forward contract is an agreement between two parties to buy or sell an asset at a specified point of time in the future.
- Two types: ①*physical* ②*financial*
  - Physical → electricity effectively delivered
  - Financial → risk edging tools
- The interaction seller/buyer is one-to-one
- Electricity traded for “*long time*” period (week, month, quarter, year)
- *Physical forward* markets are defined *Over The Counter* (OTC)
- Two types of OTC: ①*self-organized* ② *institutional organized* (brooker)

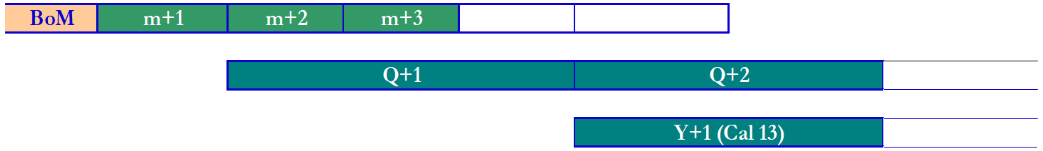
Time horizons for markets vs power profile and products

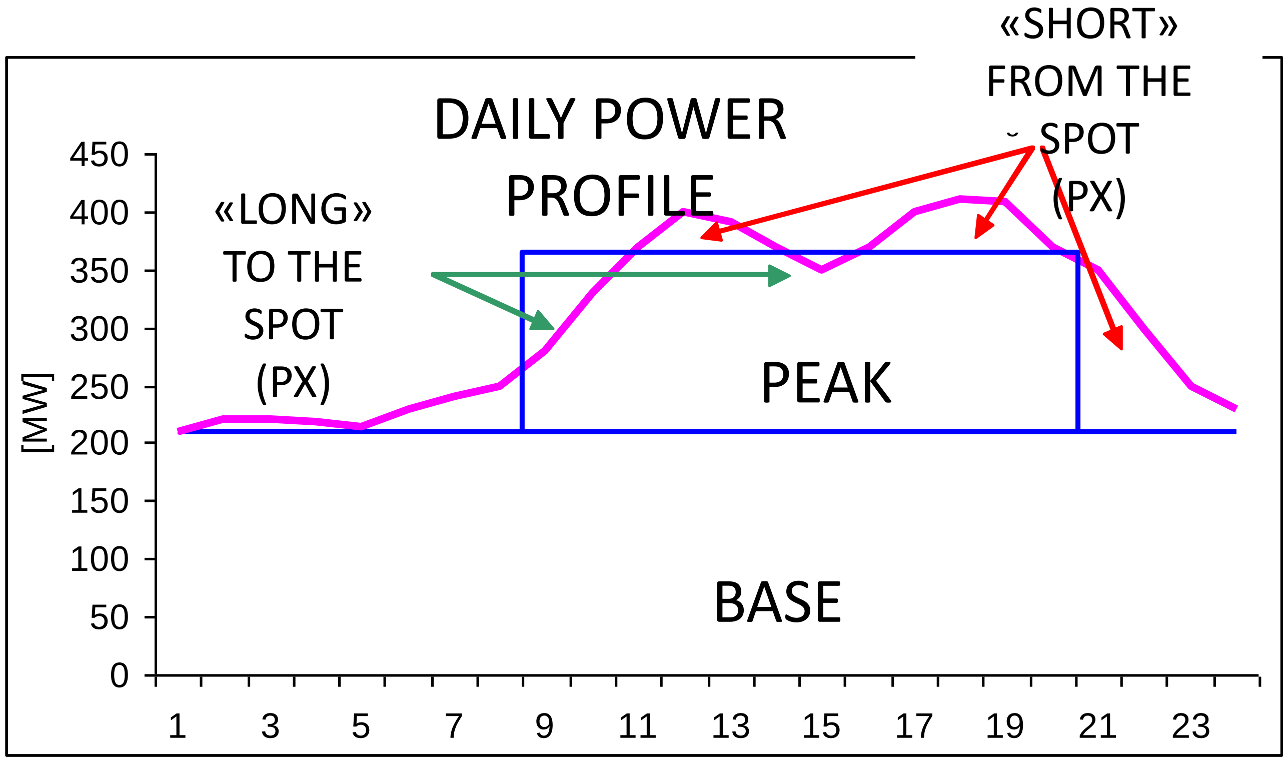


- Days: d+1, d+2, ….
- Weeks w+1, w+2, …



- Months: m + 1, m + 2, m + 3 …
- Quarters: Q +1, Q + 2, Q + 3 …
- Years: Y + 1, Y+2





Network impacts on electricity markets

- Possibly constraining physically the market transactions
- Need to manage the scarcity of transmission capacity
- Affecting market performance: efficiency, surpluses, prices
- Providing market power opportunities to generation companies
- Causes network related costs (investment, congestion, losses,…)
- Requirement for a dedicated market for managing network issues (ancillary service)

Operative needs of the network

SHORT-TERM

- Unit commitment and power dispatch (maintenance requirements, technical constraints)
- Keeping the system “feasible” (power balance, voltage control, line overload and angular instability avoidance)
- Keeping the system secure in normal state (assure overcoming of a set of contingency, n-1 security)
- Allowing for recovering from emergency state (black start)

LONG-TERM

- Expected load increase following
- Capacity deployment
- Storage deployment
- Infrastructure re-enforcement (transmission/distribution)
- Enhancement of regulation and (ancillary service) market design

Adequacy margin

Market clearing and congestion

- Electricity markets are run *over a network* where the commodity is injected, flows and is withdrawn under network constraints (physical and operational constraints)
- The market clearing provides a system dispatch (power injected and withdrawn at each bus of the network) that must comply with the physical/operational requirements for a feasible and secure operation of power systems
- Congestion is:
  - a situation in which the scarcity of transmission capacity emerges
  - a *misalignment between* electricity *marke*t outcomes and *network constraints* (physical and operational)
  - an *activation* of some *network constraints* (max line flows, min/max voltages, n-1 security)

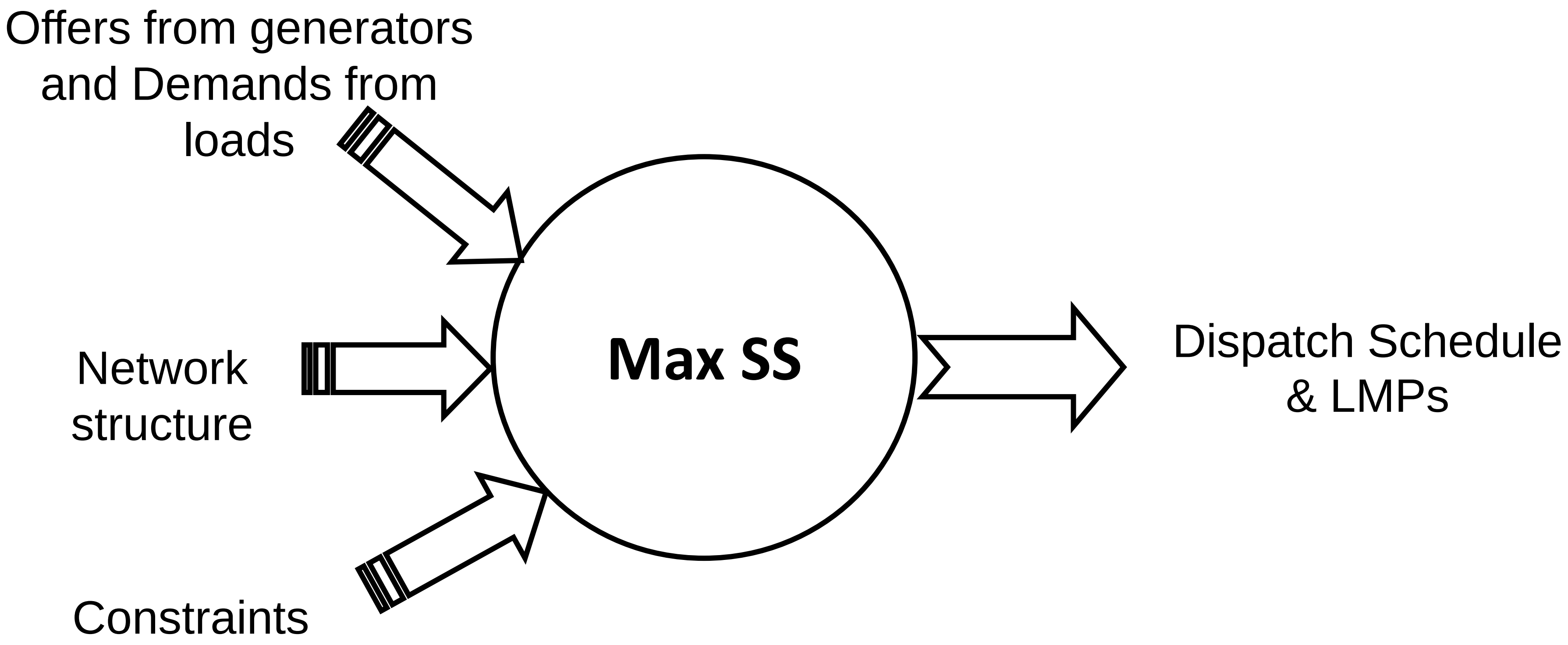
Market clearing and network dispatch

- Two processes:
  - *Market clearing* (pure) is based on the *maximization of the social surplus* with constraints only on the total quantity produced equal to the total quantity withdrawn and on the maximum quantity of each offer/bid
  - *Network dispatch* is based on the *analysis of line flow limits, voltage profile and n-1 security*, provided a set of power injection (withdrawal) from generators (loads) feasible
- The two processes aim, all in all, to maximize the social surplus (*economic goal*) while keeping the system in feasible and secure operation (*technical goal*)
- *Congestion* may arise from the *misalignment* of the *market clearing* results with the *network constraints* of the network dispatch

Main conceptual approaches for net consideration in market

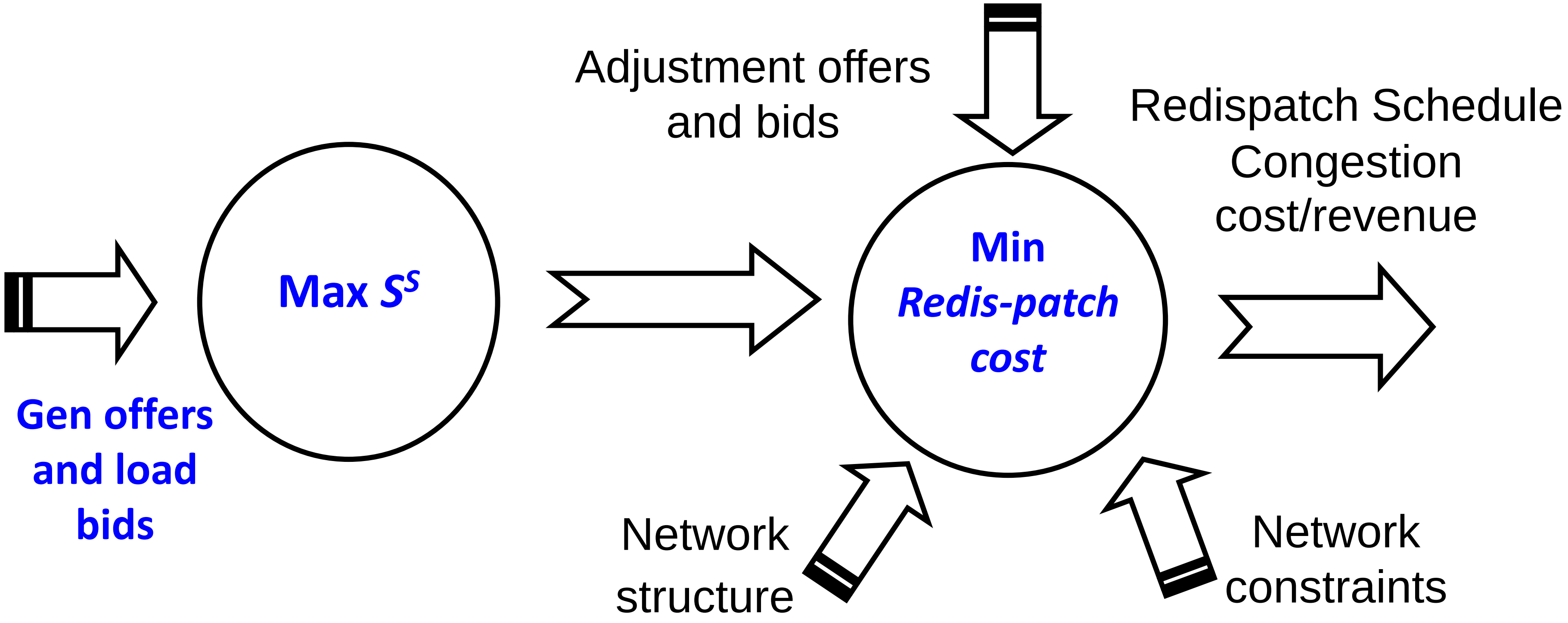
- Market clearing and network dispatch must be aligned to assure, at most, a managed congestion in terms of having network limits binding
- Two possible approaches are conceptually possible:
- ① *Allocation* (of transmission capacity): introduce *additional constraints in the market clearing* (network constrained market clearing) to consider explicitly "in one shot" the network constraints (or the main of them) along with the market ones
- ② *Alleviation* (of arising congestion): implement a *network dispatch after the market clearing* if its results (power injection/withdrawal) do not satisfy the network constraints of the network dispatch (a network re-dispatch with reference to the results of the market clearing – "two shots procedure")

Allocation “one shot”



Allocation “two shots”

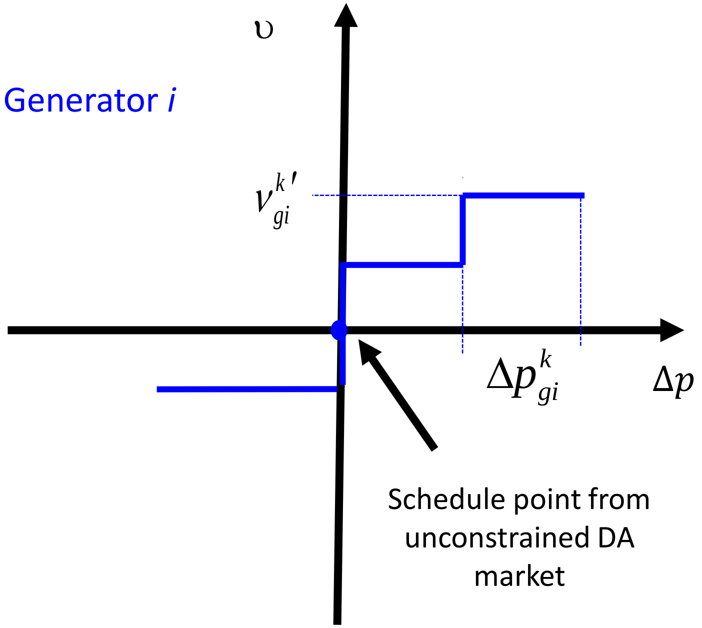
- ① Dispatch without considering network constraints; if the dispatch leads to line overloads → ②
- ② Minimum cost re-dispatch with consideration of transmission constraints considering additional offers and bids (pay-as-bid) from generators and loads

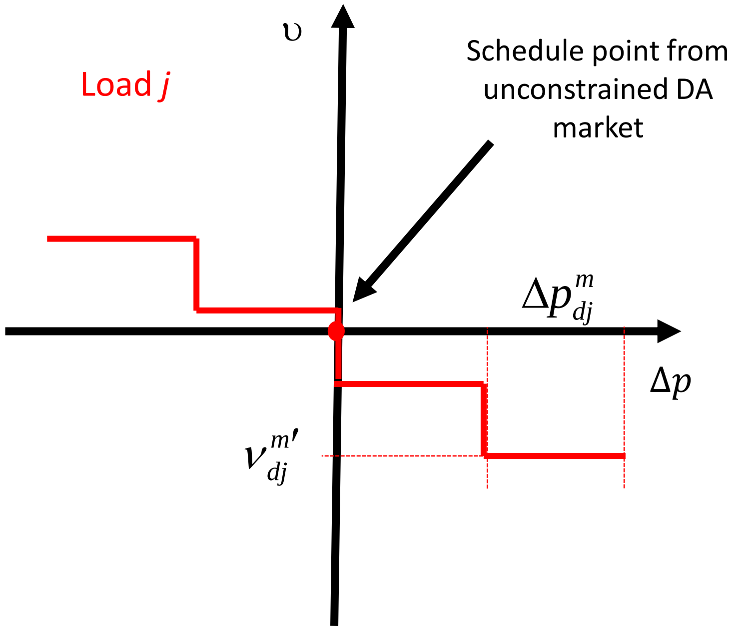


Adjustment bids

υ < cash flow into TSO

υ > cash flow out TSO





Adjustment offers from generators

Adjustment bids from loads

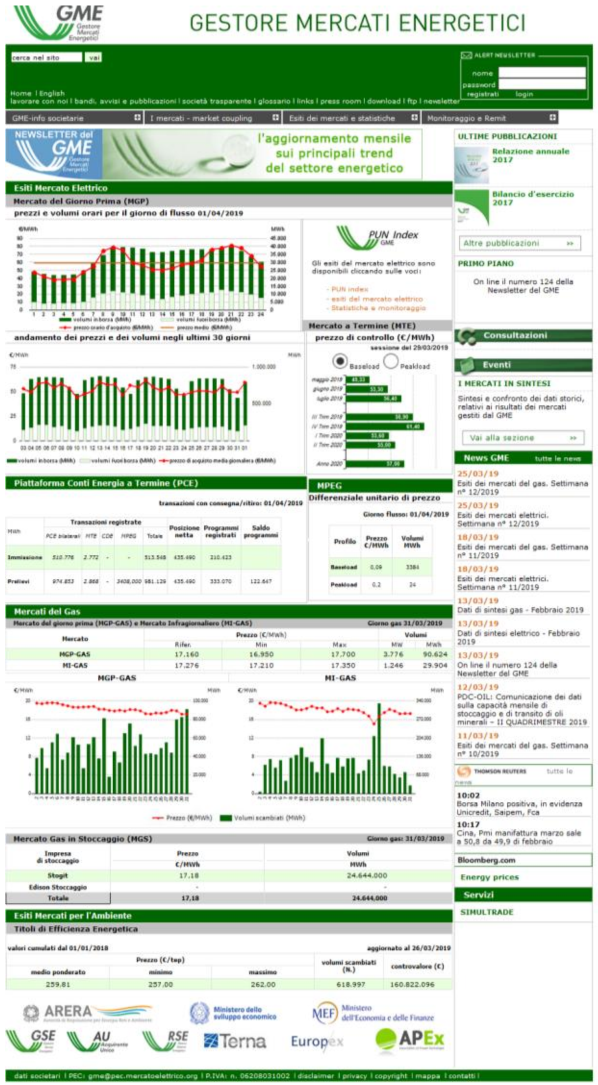
$$\left|\Delta p_{gi}^{k}\right| \cdot v_{gi}^{k\,\prime} > 0 \quad \text{paid to generator by TSO}$$

$$\left|\Delta p_{gi}^{k}\right| \cdot v_{gi}^{k\,\prime} < 0 \quad \text{paid to TSO by generator}$$

$$\left|\Delta p_{dj}^{m}\right| \cdot v_{dj}^{m\prime} < 0 \quad \text{paid to TSO by load}$$

$$\left|\Delta p_{dj}^{m}\right| \cdot v_{dj}^{m\prime} > 0 \quad \text{paid to load by TSO}$$

GME: Italian power exchange



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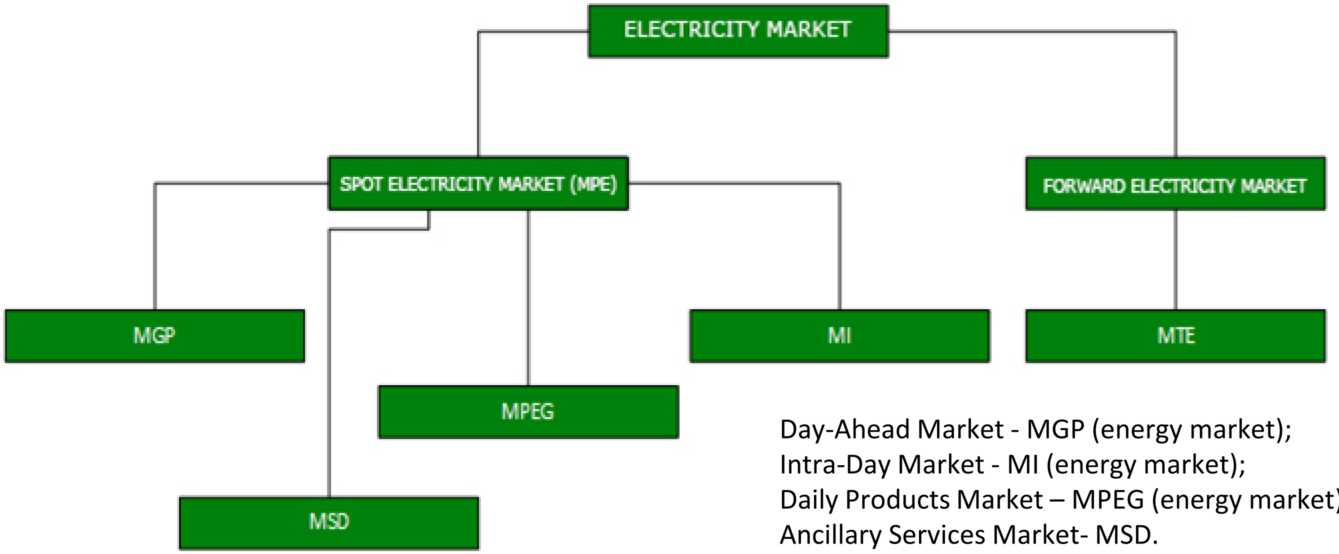

Day-Ahead Market - MGP (energy market);
Intra-Day Market - MI (energy market);
Daily Products Market – MPEG (energy market);
Ancillary Services Market- MSD.

- Spot market → «mercato a pronti», managed by Gestore Mercati Energetici (GME)
- Forward Market → «mercato a termine», managed by:
  - Mercato a Termine Elettrico (MTE) (physical): operated by GME
  - IDEX (financial), operated by Borsa Italiana (Italian Stock Exchange)
  - Various international brokers