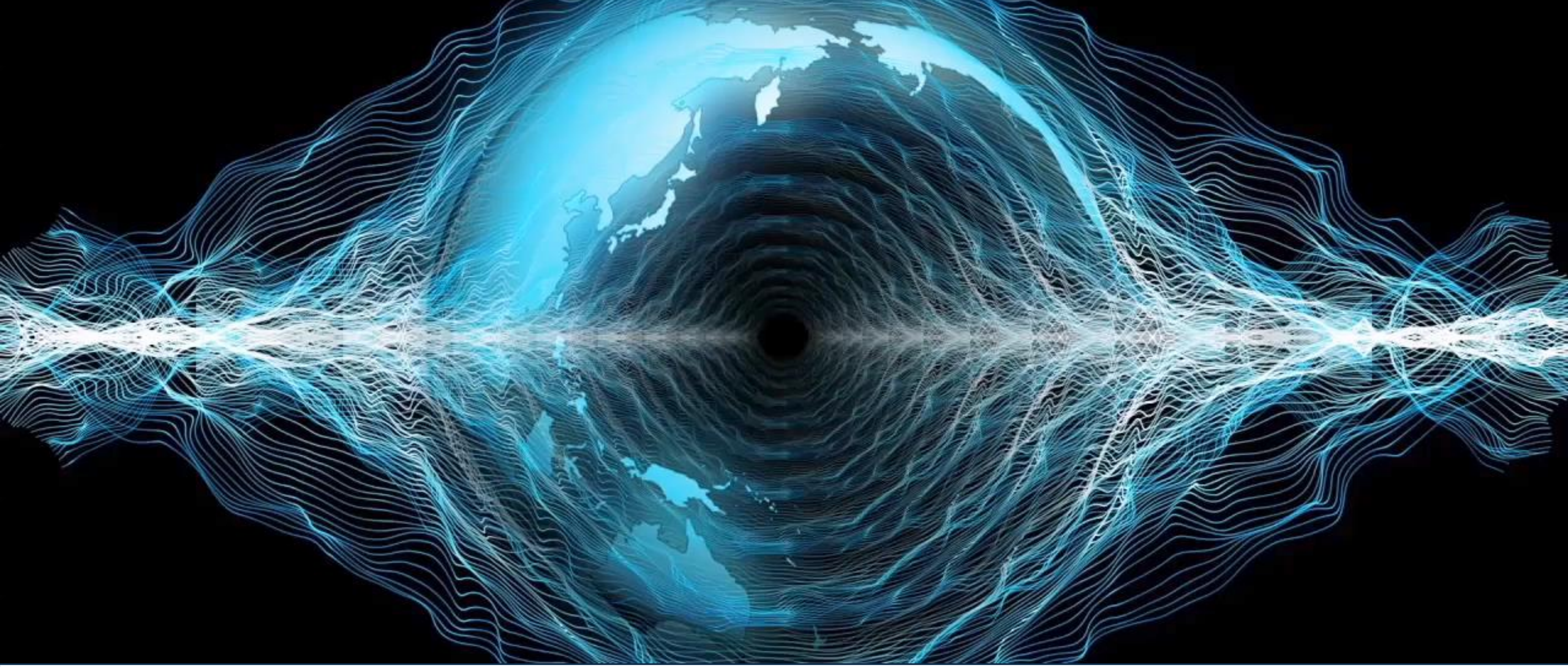
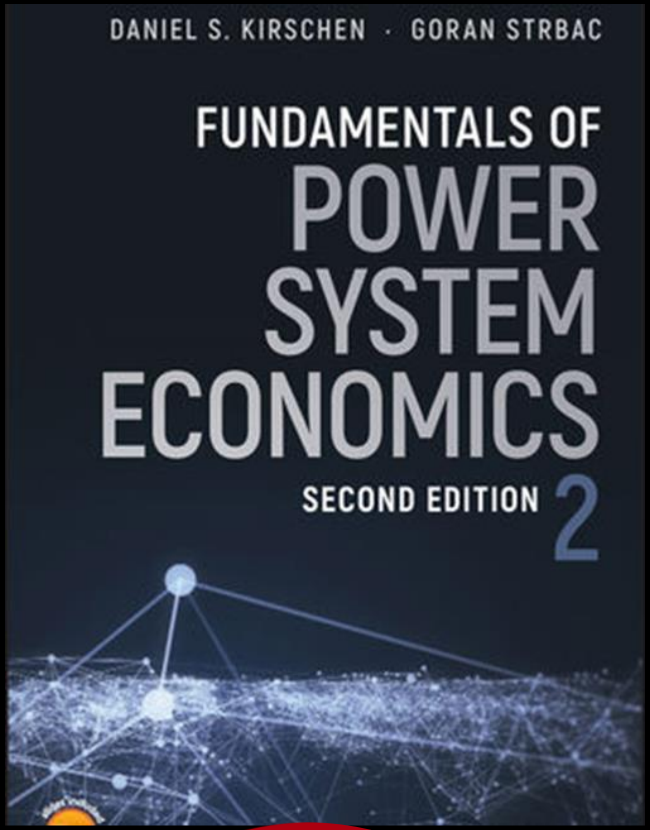


The Organization of Electricity Markets

Dr. Abeer Almaimouni

Disclaimer

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

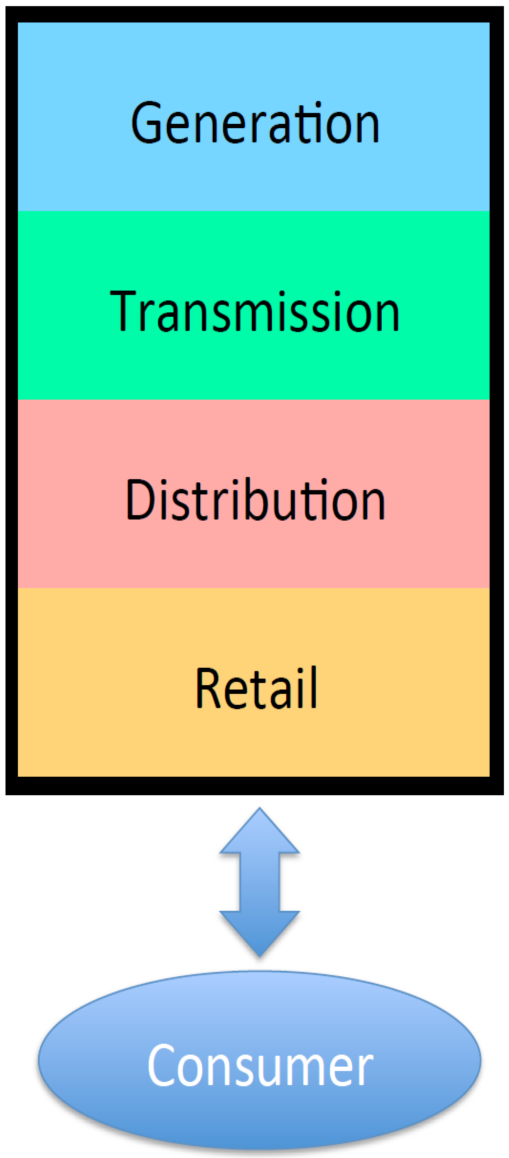


The Traditional Business Model

Traditional Utility Model

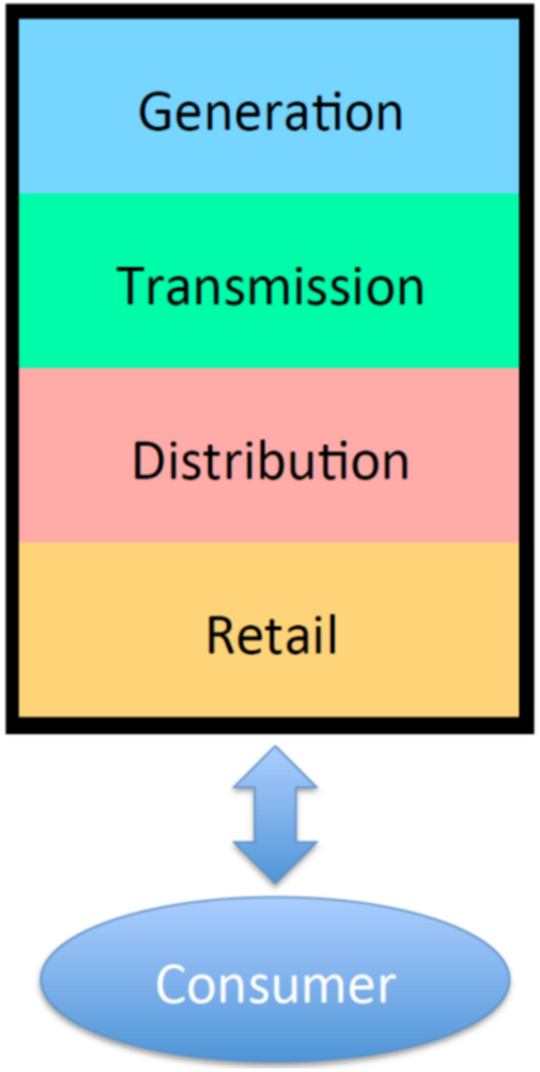
- Monopoly
  - Only supplier of electricity in a given region ("service territory")
  - Consumer does not have a choice of supplier

- Vertically integrated
  - A single organisation performs all the technical and business functions such as building generating plants, transmission lines and distribution networks, operating them in a reliable manner, and billing the consumers for the service provided.



Why vertical integration?

- Used to be considered more efficient
- Possible variants:
  - Distribution + retail
    - Many municipal utilities
    - Rural electricity cooperatives
  - Generation + transmission
    - Bonneville Power Administration
- Issues:
  - Lack of transparency
  - Poor internal communication in very large organizations



Why monopoly?

- Building a power system is expensive
- Building competing transmission and distribution networks does not make sense
- Until recently having several companies "share" a power system was too complicated
- Monopoly can be:
  - Private (investor-owned utility)
  - Public (municipal, utility district, national)
- Size of service territories varies

Problems with Public Monopolies

- A good government will run its utilities in an efficient and far-sighted manner
- This is not always the case
- Government bodies are not always efficient either
- Conflicts can arise between the objectives of the government and the objectives of the utility

Bad Things Governments Do…

- Keep rates low to please the voters
  - Utility does not have enough money for investments
- Keep rates high and use the surplus money for other programs
  - Inefficient taxation
  - Discourage consumption of electricity
- Force the utility to make unnecessary investments to create jobs

Possible solutions?

- Privatization
- Unbundling
- Competition
- Private Monopoly
- Regulation

Problems with Private Monopolies

- Monopolies are inefficient
  - No competition
  - No need to be efficient to survive
  - No incentive to be efficient:
    - Utility earns more if it invests more
    - No penalty for building "white elephants"
    - High costs passed on to consumers as high prices of electricity
    - A bankrupt utility is in nobody's interest
- Rates are "higher than they should be"

Regulation

- A private monopoly could abuse its position
  - It must be regulated by the government
- Government-owned utilities operate for the public good
  - No need for outside regulation
  - Elect new representatives if we are not satisfied

The "Regulatory Compact"

- Agreement between an Investor Owned Utility (IOU) and a government
- IOU receives the right to be the monopoly supplier over a certain territory
- IOU accepts that its rates (i.e. what it can charge consumers) will be determined by a regulator
  - Example: Washington Utilities and Transportation Commission

Rate of Return Regulation

- Regulator sets the rates so that the IOU can:
  - Recover its operating cost (fuel, personnel, etc…)
  - Recover its investments costs (plants, lines, etc…)
  - Pay a fair rate of return to its investors
- A monopoly utility is a low risk investment
  - No competition
  - A bankrupt utility is in nobody’s interest
- The rate of return can therefore be low compared to other investments

Is a regulated vertically integrated monopoly the solution?

- Regulation is difficult
  - Little basis for comparison
    - Each regulator oversees a small number of utilities
    - Each utility has a territory with different characteristics
  - Difficult to evaluate the utilities' decisions
    - Regulator does not have as much staff as the utility
    - Information imbalance

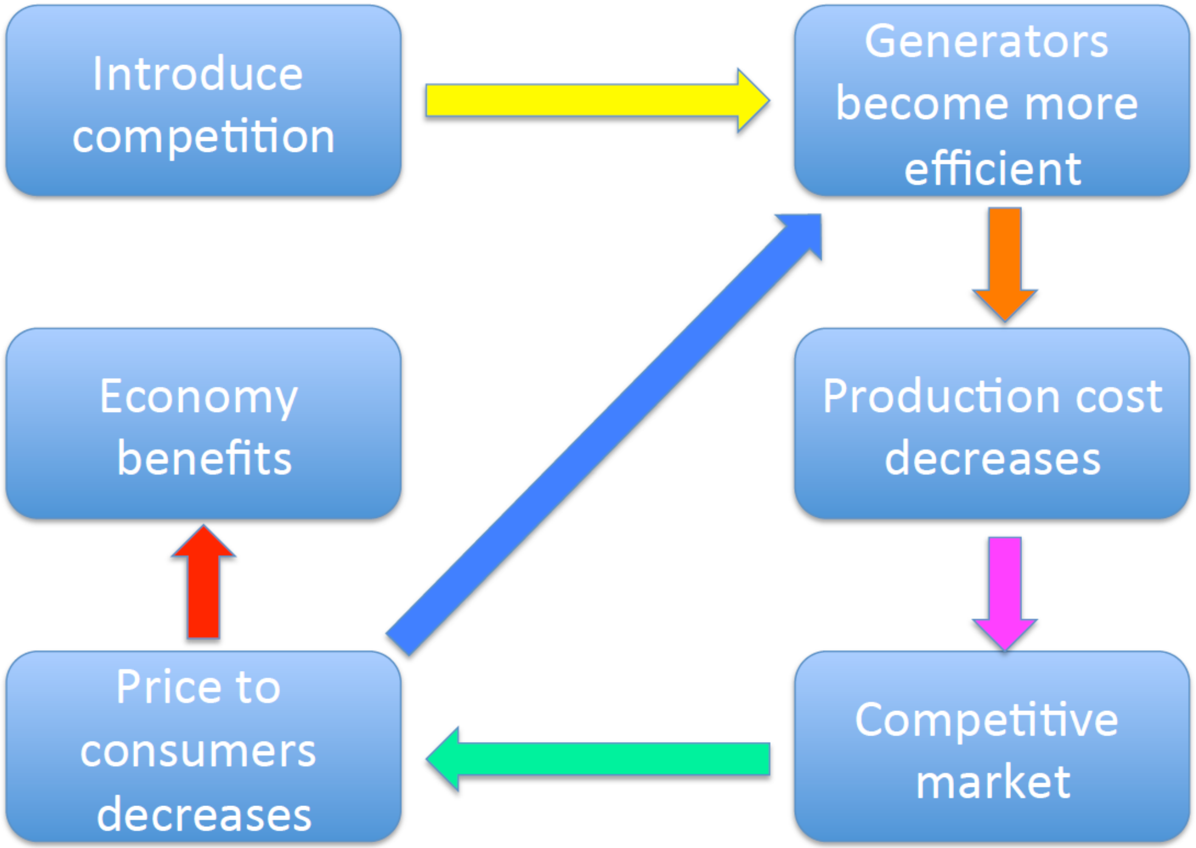
How about privatization?

- Utility can focus on its mission
- If properly regulated:
  - Utility gets the revenues it needs
  - Price of electricity reflects its true cost
  - Optimal allocation of economic resources
- Access to private sector capital
  - Important in developing countries when government is short of money for investments
- Revenue from the sale of privatized assets

How about unbundling?

- Separation between the parts where competition is possible and those where a monopoly is needed:
  - Competition between generators
  - Monopoly for transmission and distribution
- More transparency in the the system
- Essential to create a fair market
  - An independent system operator will not favor one generator over another

How about Competition?



Is deregulation the answer?

Pros of Monopoly

- All operation and investment decision are taken within a single organization and hence can be coordinated to co-optimize the reliability and the economy.
  - the maintenance of the transmission system and the maintenance of the generation units.
  - The transmission capacity and topology can match the generation capacity and location.
- Competition can jeopardize the reliability of the system.
  - A single integrated utility is replaced by a constellation of independent companies.
  - None of which has the responsibility to supply electrical energy to all the consumers.
  - Each company tries to maximize its private objectives.

Pros of Competition

- Processes more open and transparent.
- Buyers and sellers have an interest in improving to reduce costs and improve the profitability of their assets.
- System operators are forced to maintain the stability and reliability across interconnections as markets have grown geographically as larger markets provide more trading opportunities between distant generators and load.

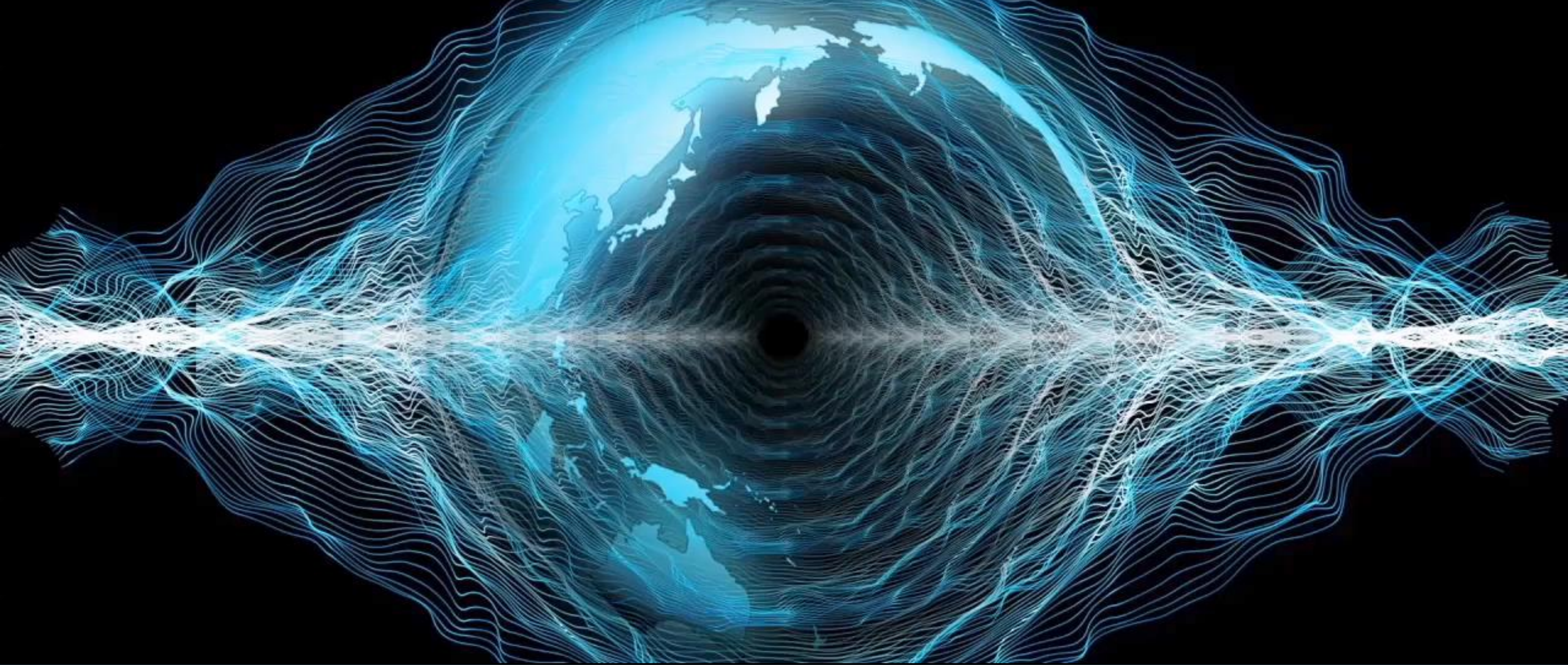
Impact on Investment

- Monopoly utilities overestimate the amount of generation capacity.
- Private companies have an incentive to match the actual evolution of the demand more closely than the recommendations of a single planning department.
- In addition, underutilized investments by a company operating in a free market represent a loss for its owners and not a liability for its customers.

How about the transmission and distribution networks?

- Have so far been treated as natural monopolies.
- From the economic and the reliability points of view, all lines, feeders, and other components should be connected to the same system.
- However some economist believe independent investors should have the opportunity to build new transmission facilities to satisfy specific needs that they have identified.

Let’s discuss electricity markets!

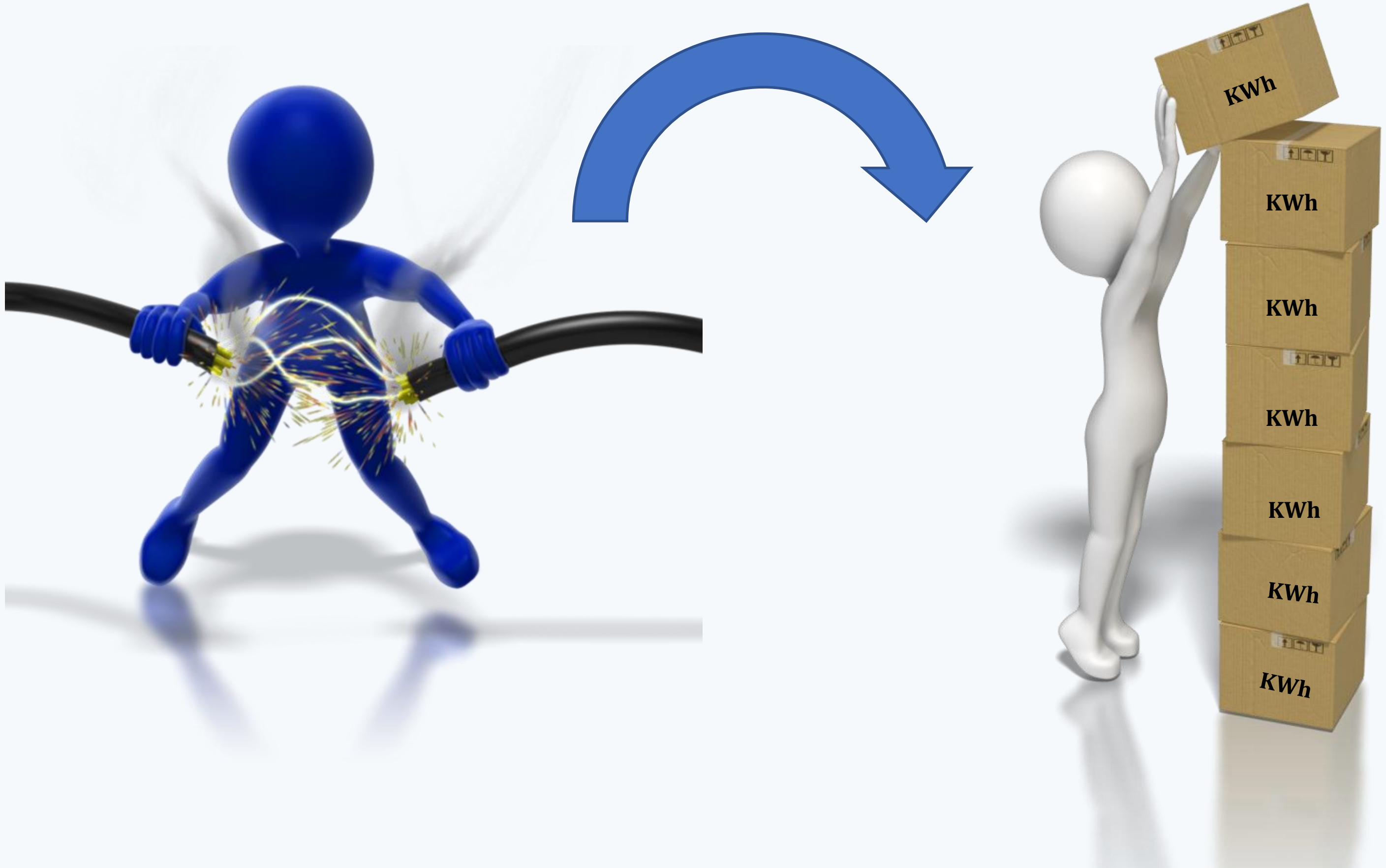


Electricity is not governed by classical economics

The building blocks of any market?

- The demand
- The supply
- A place to meet
- Transportation system
- Goods

Can the electrical energy be treated as a commodity?




WHERE?
WHO?
WHAT?
HOW?
WHY?
WHEN?

How does electricity compare to other goods?

- Linked with a physical system
  - Its delivery occurs on a continuous rather than a batch basis.
  - Generators, consumers, and the wires that connect them are mutually dependent and cannot be treated like fully independent entities.
  - Physical delivery system operates much faster than any market

How does electricity compare to other goods?

- Electricity produced by different generators is pooled
  - Generator cannot direct its production to some consumers
  - Consumer cannot choose which generator produces the energy it consumes
  - Electrical energy produced by all generators is indistinguishable
- Pooling is economically desirable
- A breakdown of the system affects everybody

How does electricity compare to other goods?

- Demand for electricity exhibits predictable daily, weekly and seasonal variations
- Electricity cannot be stored in large quantities
  - Must be consumed when it is produced
- Production facilities must be able to meet peak demand
- Very low price elasticity of the demand in the short run
  - Demand curve is almost vertical

Upholding the delicate balance

- supply and demand – generation and load – must be balanced on a second-by-second basis.
- If balance is not maintained, or if the capacity of the transmission network is exceeded, the system collapses with catastrophic consequences.

Catastrophic consequences of not maintaining the balance

- An entire region or country may be without power for many hours.
- Restoring a power system to normal is a very complex process that may take 24h or longer.
- Severe social and economic consequences.

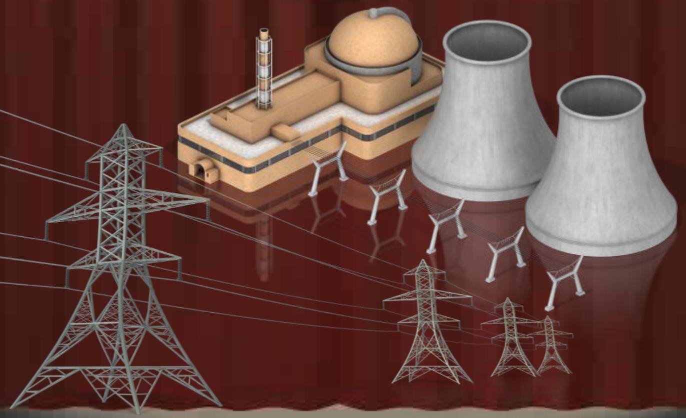
vulture.com

Can we afford to have “Free” electricity markets?

The balance must be held at practically any cost

Dramatis Personae

Who are the characters in the play?



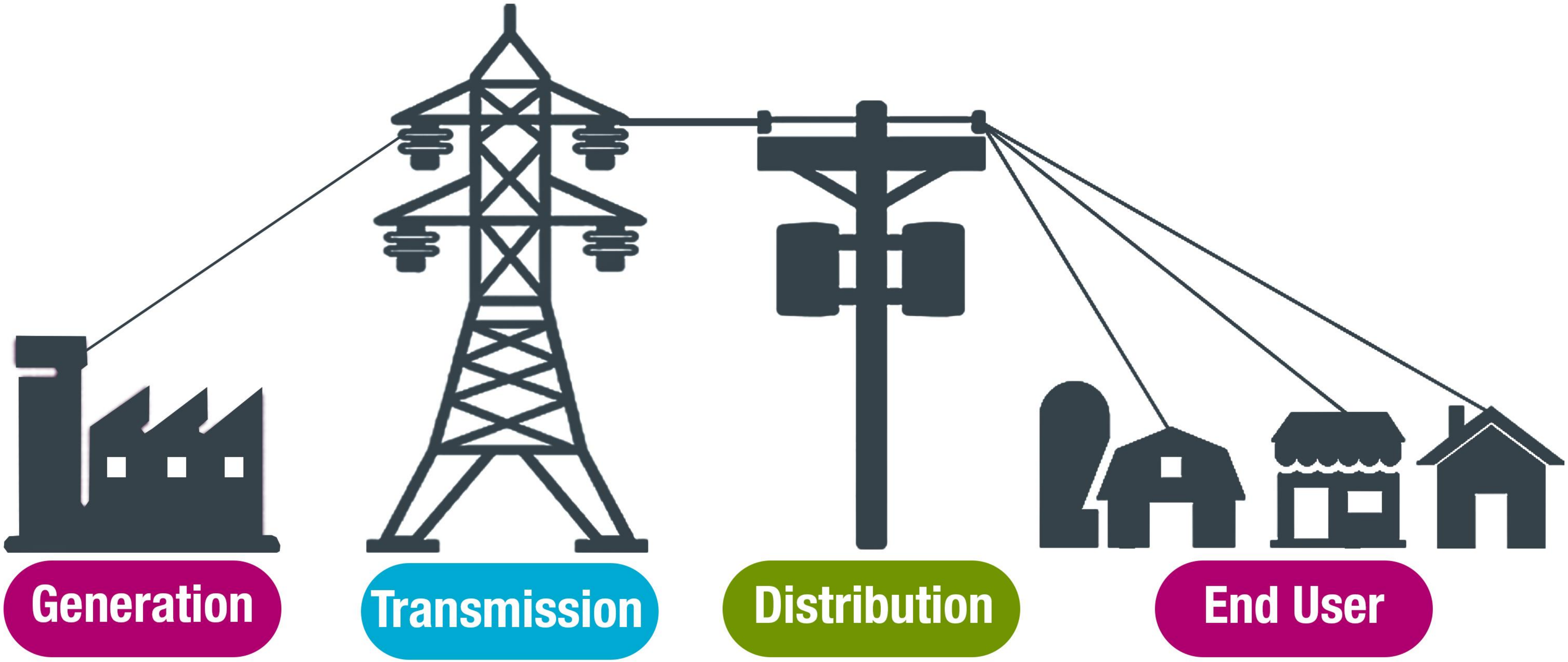
The key elements in any market?

THE DEMAND

THE SUPPLY

A PLACE TO MEET

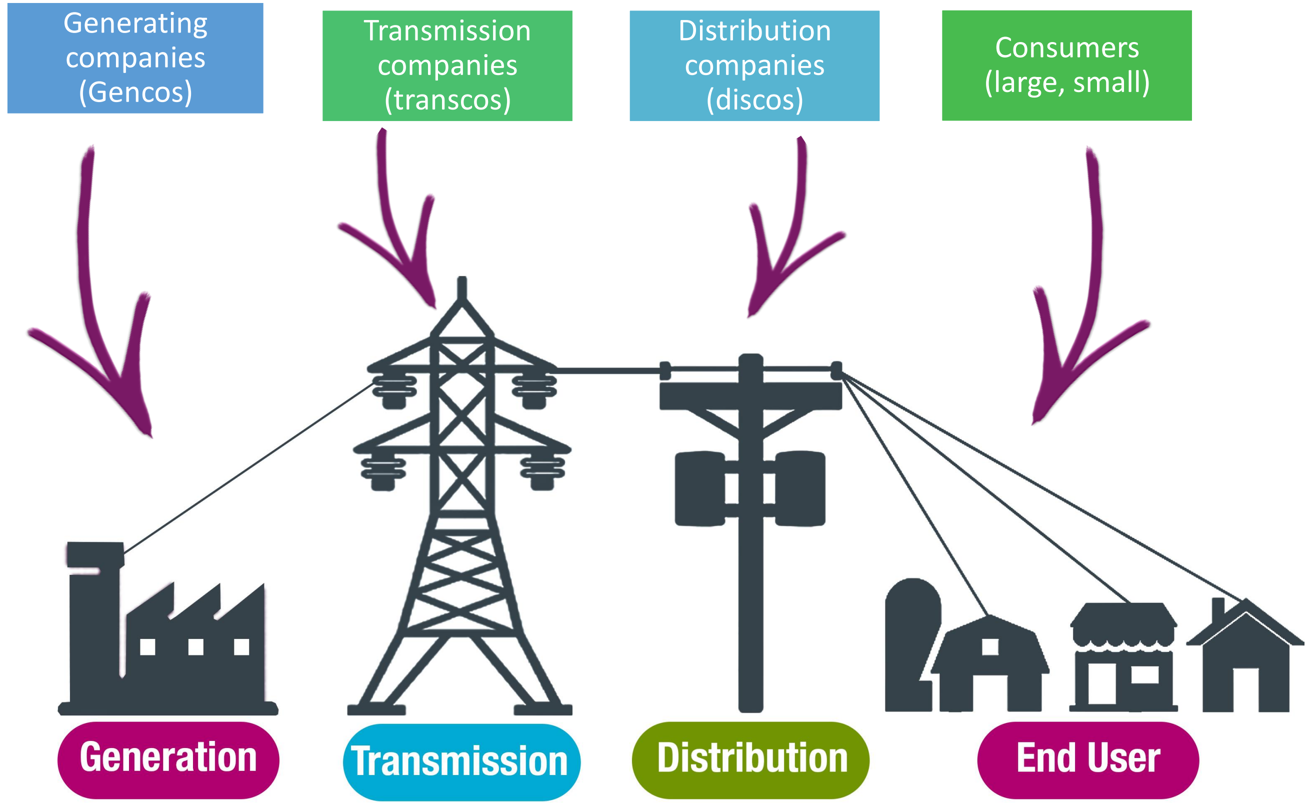
TRANSPORTATION SYSTEM



The Electric Utility Network

Source: Utilities Consumer Advocate (UCA)


Privatization
what a great idea!


Generating companies (Gencos)
Transmission companies (transcos)
Distribution companies (discos)
Consumers (large, small)
Generation
Transmission
Distribution
End User

Actors After Full Unbundling

Generating companies (Gencos)	Distribution companies (discos)
Transmission companies (transcos)	Consumers (large, small)
Independent System Operator (ISO)	Retailers
Market Operators (MO)	Regulator

- Own physical assets
- Don’t necessary own physical assets

Generating Companies

https://www.electrical4u.com/electric-power-generation/

- Own and operate power generating plants
- Compete against each other to sell energy
- Competitive advantages
  - More efficient plants
  - Cheaper fuel
  - Higher plant availability

Transmission Network Owners

https://lnibdc.com/2020/02/27/lnibdc-kingsvale-trans-line-news-release/

- Own and maintain transmission assets
  - Lines
  - Substations
  - DC lines
- Usually a regulated business
  - Revenues determined by the regulator based on the value of the assets

Distribution Network Owners

https://www.ul.com/offerings/electrical-distribution-services

- Own and operate the distribution networks
- Regulated business
  - Revenues determined by the regulator based on the value of the assets

Consumers


https://www.livescience.com/43424-who-invented-the-light-bulb.html

- Small consumers
  - Residential or commercial consumers
  - Buy electricity from a retailer
  - Buy electricity on a tariff (i.e. fixed price)
- Large consumers
  - Industrial or large commercial consumers
  - May buy directly from the electricity market
  - May buy electricity at time-varying prices
- Expected to become increasingly active

Retailers

- Buy electrical energy form generators
- Sell electrical energy to consumers
- Do not own large physical assets
- Often owned by a generator or a distribution company
- Competitive advantages
  - Negotiate good price with generators

Independent System Operator (ISO)

- Facilitate trading of electricity
  - Matches bids and offers submitted by buyers and sellers of electrical energy
  - Runs the market settlement system
    - Monitors delivery of energy
    - Forwards payments from buyers to sellers
- Requirements:
  - Fairness, independence

Regulator

- Oversees the operation of the electricity market
- Determines the allowed revenues of the monopolies (“wire companies”, i.e. transmission and distribution owners)
- Check that the wire companies maintain the quality of service

Transmission System Operator (TSO)

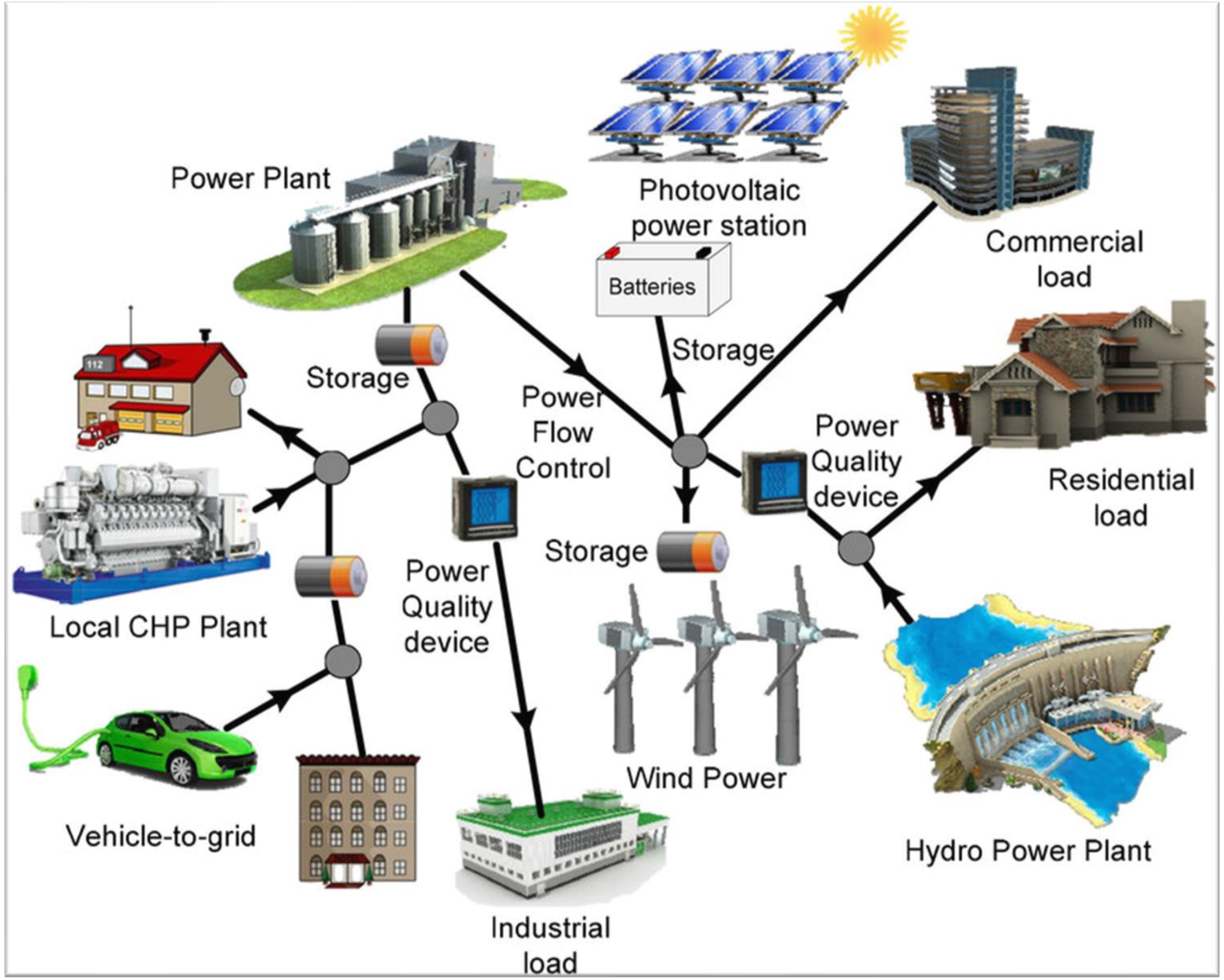
- combine the function of ISOs with the ownership of transmission assets.

New Actors After Full Unbundling

- Generating companies (Gencos)
- Transmission companies (transcos)
- Distribution companies (discos)
- Consumers (large, small)
- Independent System Operator (ISO)
- Retailers
- Market Operators (MO)
- Regulator
- Aggregators
- Storage System Operators

- Own physical assets
- Don’t necessary own physical assets
- New actors

Distributed Generation



S. Refaat, Shady & Mohamed, Amira. (2019). Smart management system for improving the reliability and availability of substations in smart grid with distributed generation. The Journal of Engineering. 10.1049/joe.2018.8215.

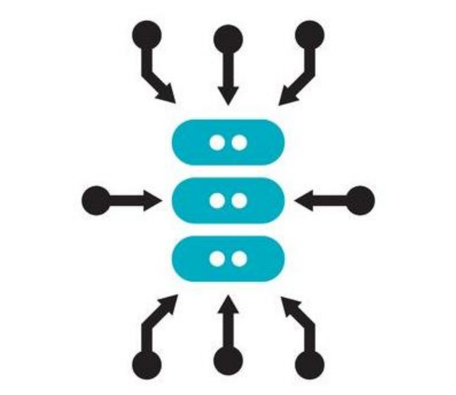
Challenges to the direct participation of the distributed energy resources and demand response in electricity markets?

The number of market participants would increase vastly making the markets unmanageable.

The rules of the wholesale markets are complex and the requirements for participation are strict.

The transaction costs prohibitively expensive for small participants.

Aggregators

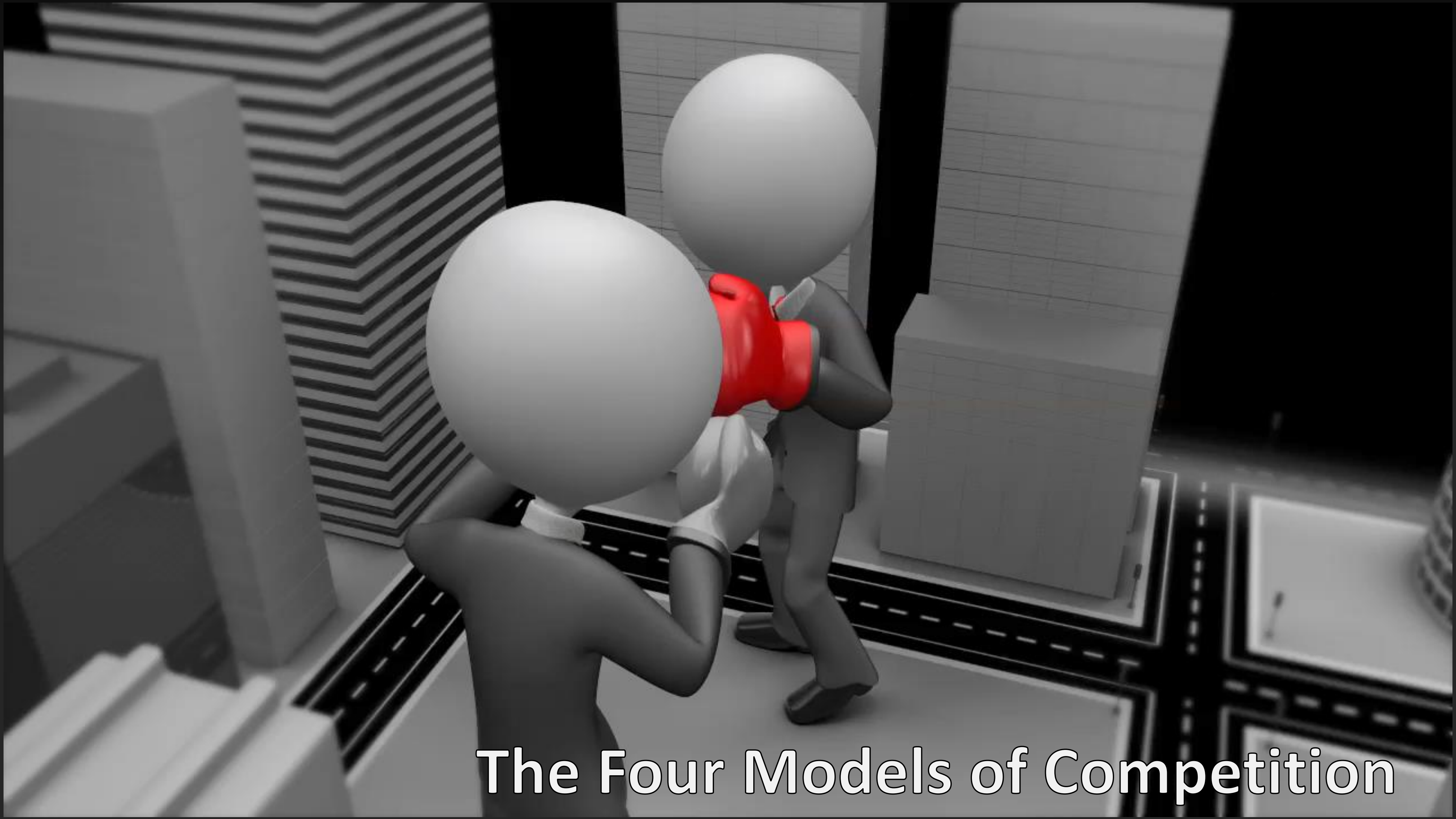


- Serve as a commercial and technical intermediary between the wholesale markets and the owners of distributed energy resources.
- Contract with a number of small consumers to reduce or shift their demand in time on request. The combined effect is then sufficiently large to be sold on the wholesale market.

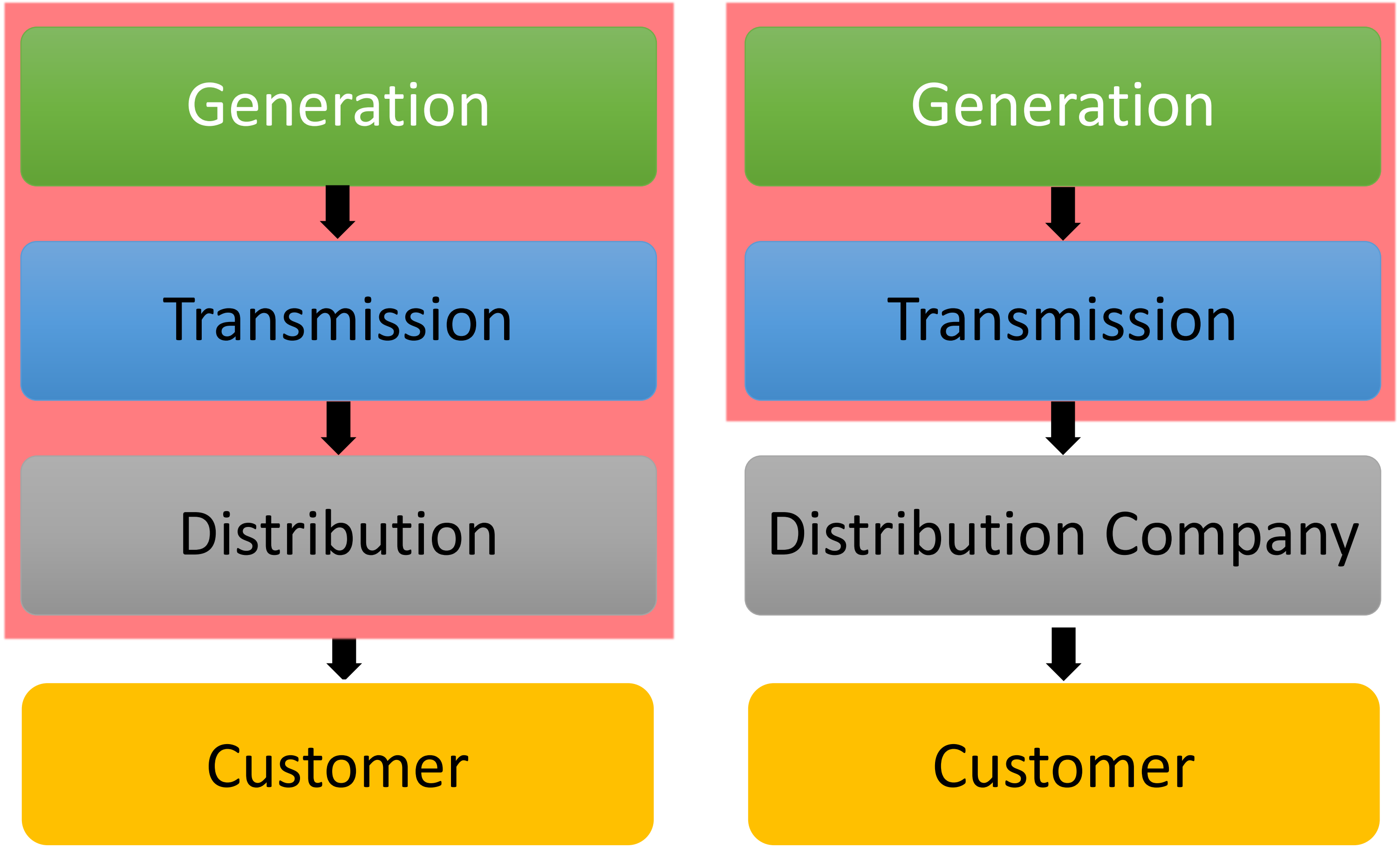
Storage System Operators

https://www.greentechmedia.com/articles/read/fluence-launches-next-generation-battery-storage-product-with-800mw-orders

- Assume batteries or other energy storage devices perform only temporal arbitrage, i.e. they buy and store energy when the price is low and release and sell this energy when the price is high.
- Take into account the fact that, because of the losses, not all of the energy bought and stored can be sold back.

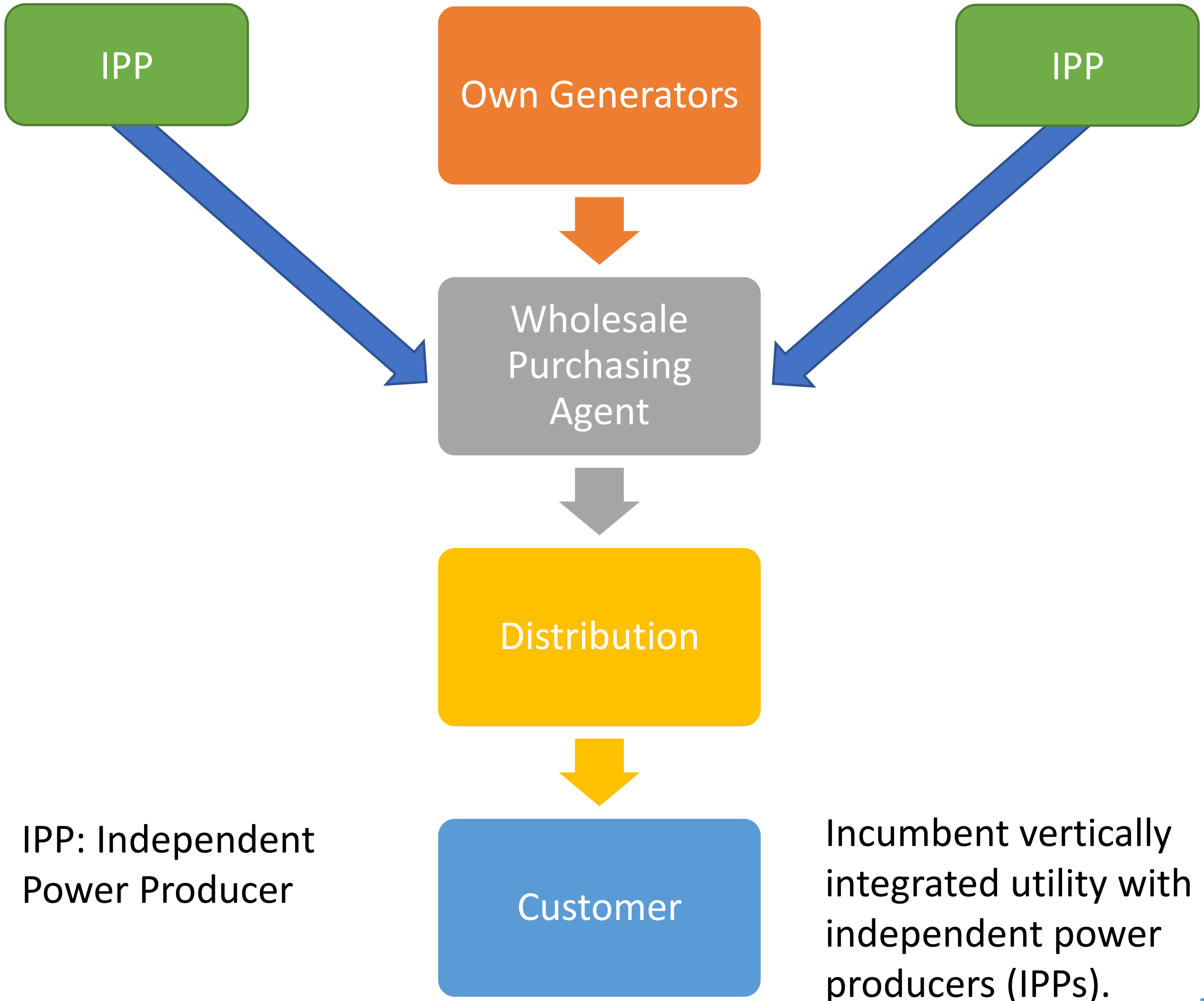

The Four Models of Competition

Four Models of Competition


Generation
Transmission
Distribution
Customer
Generation
Transmission
Distribution Company
Customer

Monopoly

Purchasing Agent

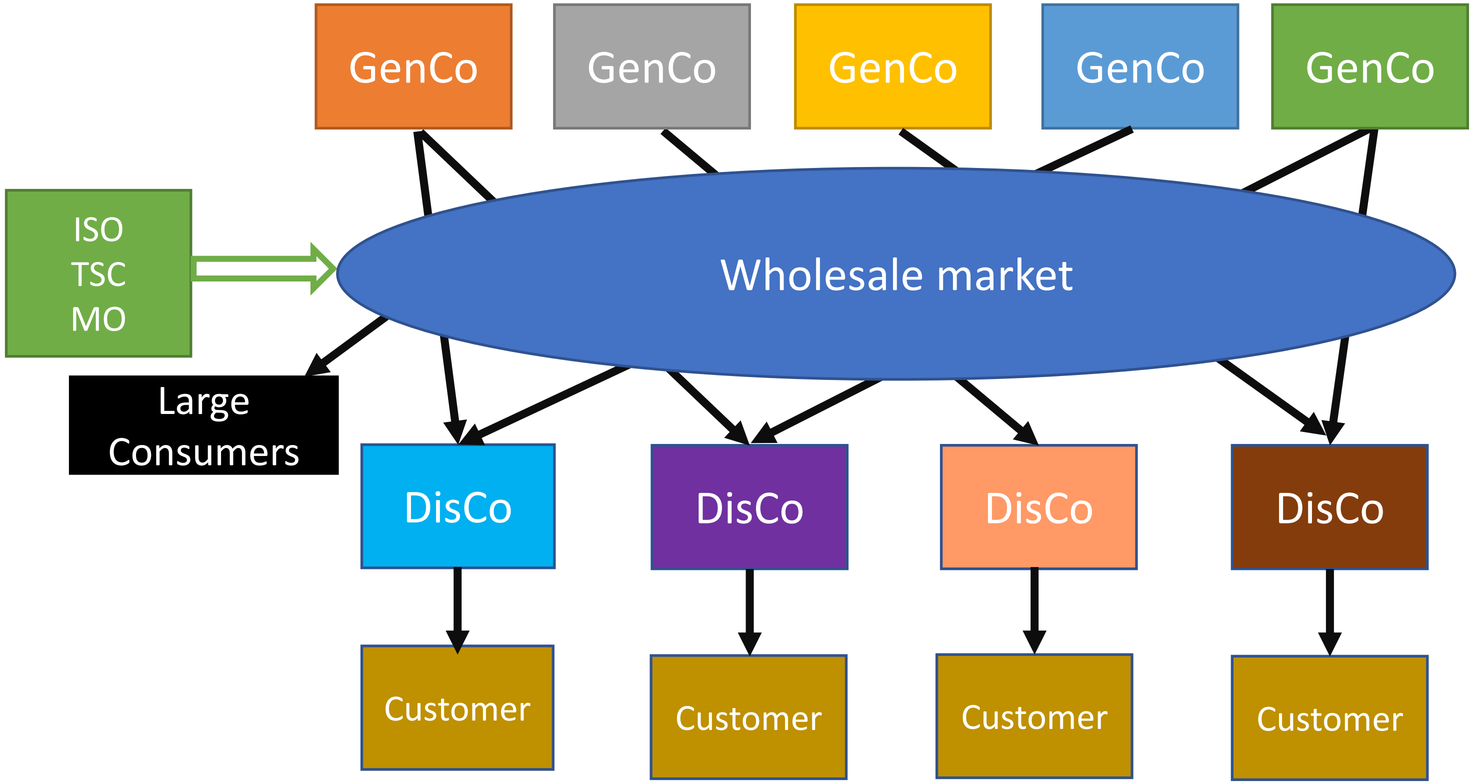


IPP: Independent Power Producer

Incumbent vertically integrated utility with independent power producers (IPPs).

Drawbacks of Purchasing Agent Model

- Introduces a degree of competition.
- Incumbent utility pays as little as possible to the IPPs.
- Incumbent company must be forced by law to buy power from IPPs.
- IPPs will try to get as high a price as they can.
- A regulator must decide an equitable price.
- No detailed information.
- The result will be economically inefficient.



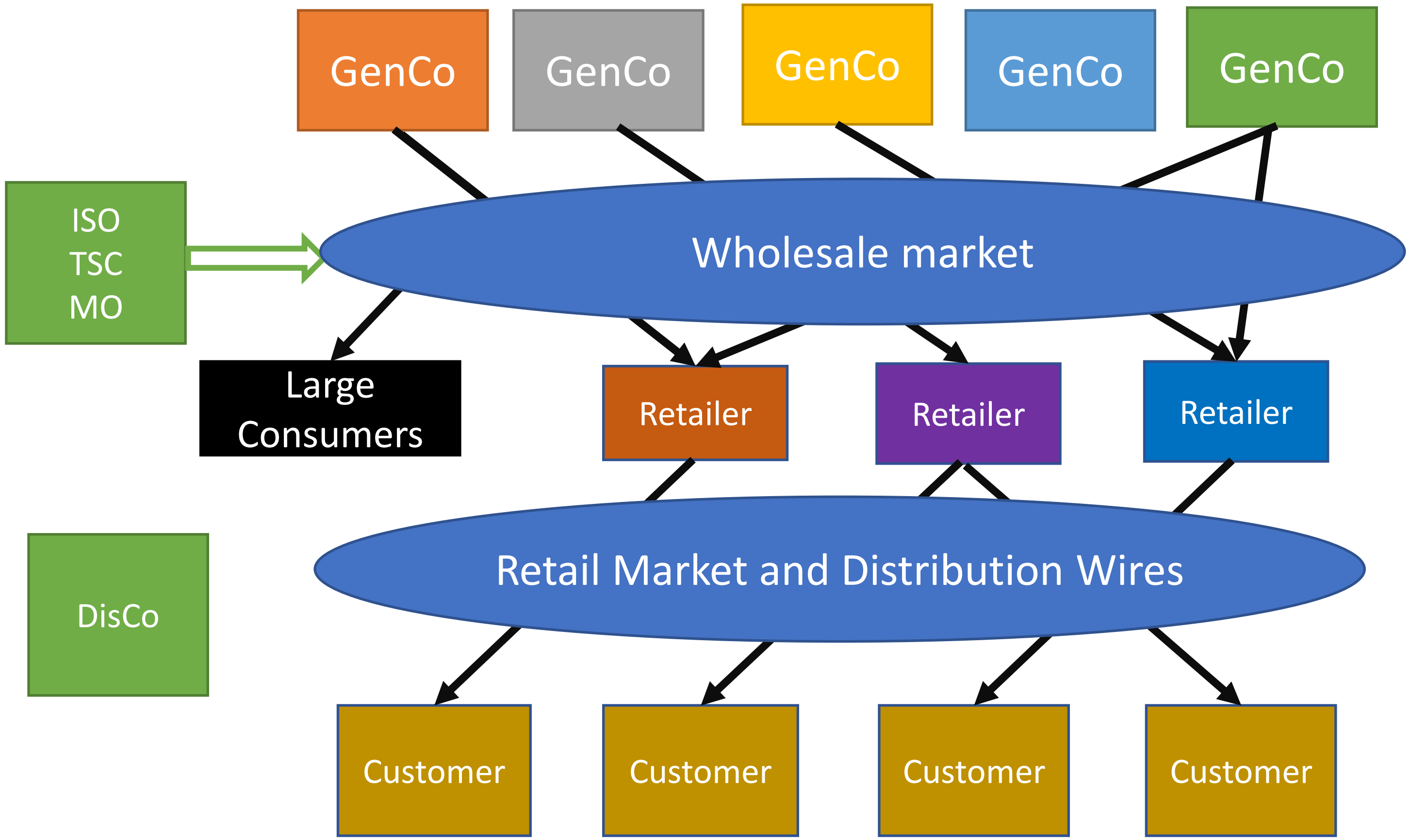
Wholesale Market

How does a wholesale market operate?

- Can operate in a centralized manner or can be based on bilateral transactions.
- The wholesale price of electricity is determined by the interplay of supply and demand.
- The retail price of electricity must remain regulated as each distribution company retains a local monopoly.

How does a wholesale market operate?

- In a centralized wholesale market:
  - Independent System Operator (ISO)
    - manage the market in an impartial and efficient manner.
    - is responsible for the reliable operation of the transmission system.
- In a bilateral wholesale market:
  - Market Operators (MOs):
    - facilitate commercial transactions between buyers and sellers of electrical energy
  - Transmission system operator (TSO),
    - Keep the system in balance and operationally reliable.
- While TSOs often own the transmission assets (lines, transformers, substations, etc.), ISOs usually do not.



Retail Competition

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How retail competition works?

- There are two markets:
  - The wholesale market as operating over the transmission network.
  - The retail market takes place over the distribution network.
- Competition can also be introduced in the retail market.
- Retailers purchase electrical energy in bulk on the wholesale market and resell it to small- and medium-size consumers.
- The “wires” activities of the distribution companies are normally separated from their retail activities because they no longer have a local monopoly for the supply of electrical energy in the area covered by their network.

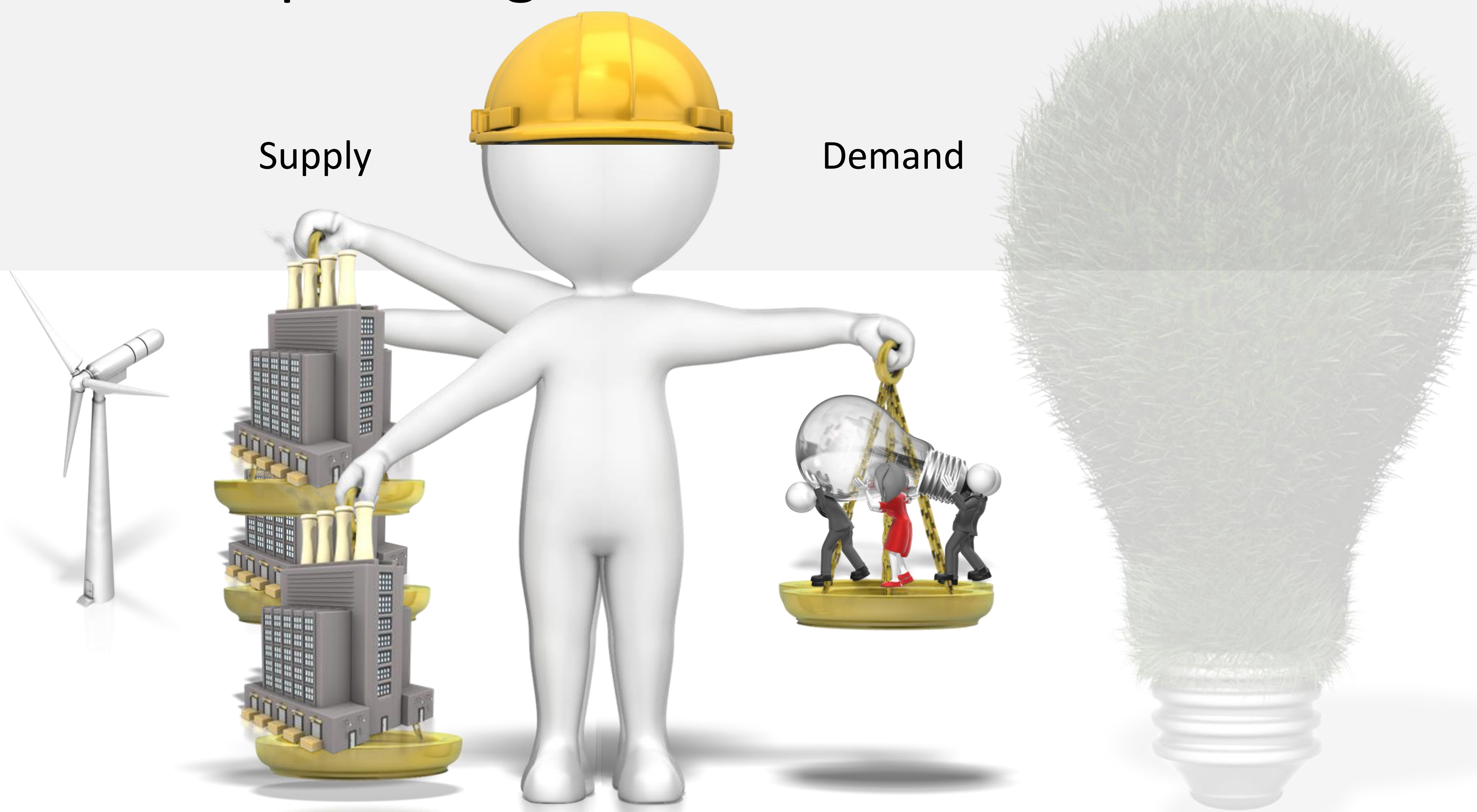
Typical re-Bundling

- Distribution + retail
- Generation + transmission network *owner*
- Generation + retail
- System operator + market operator
- Transmission owner + distribution owner

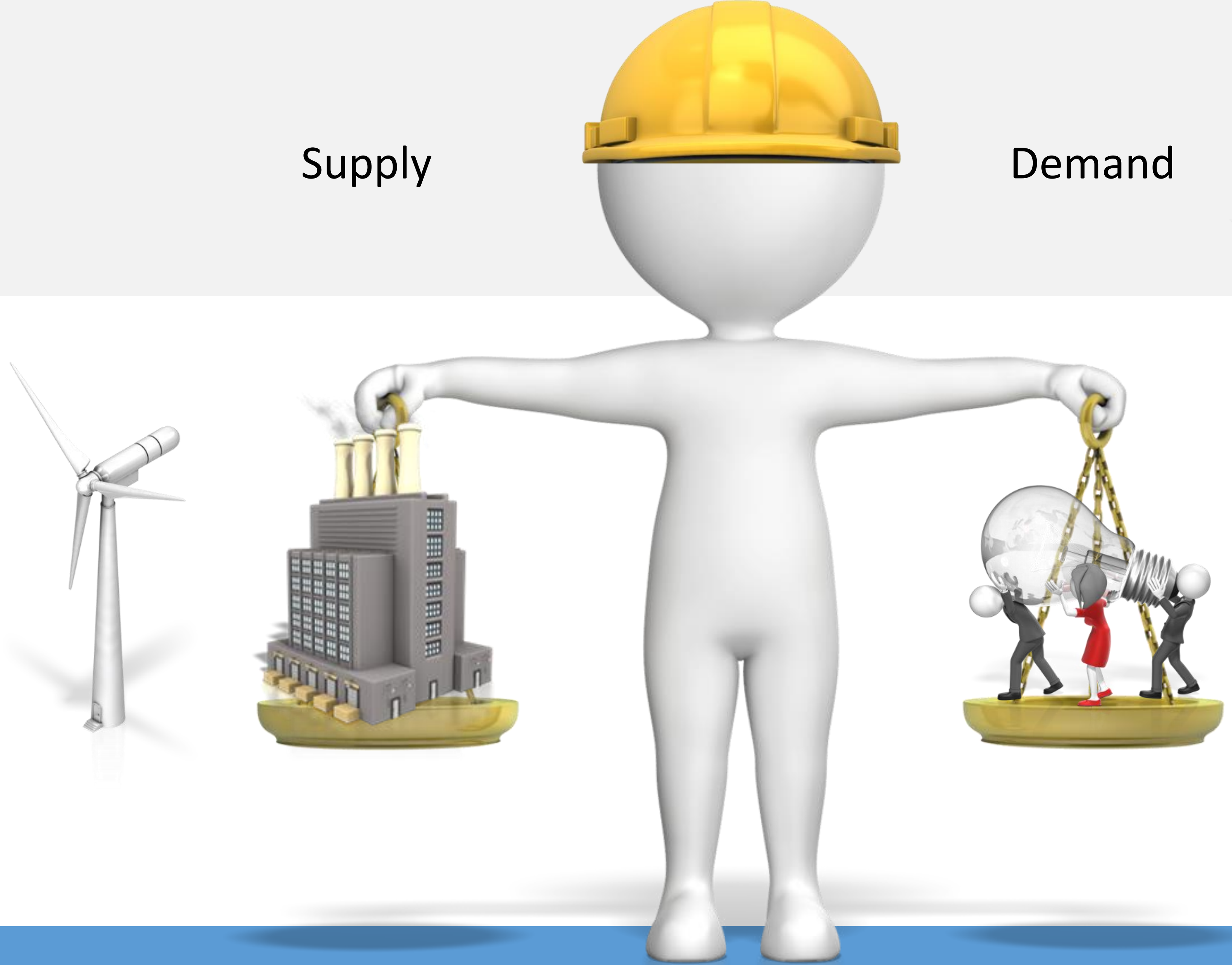
http://iea-retd.org/archives/publications/res-e-markets

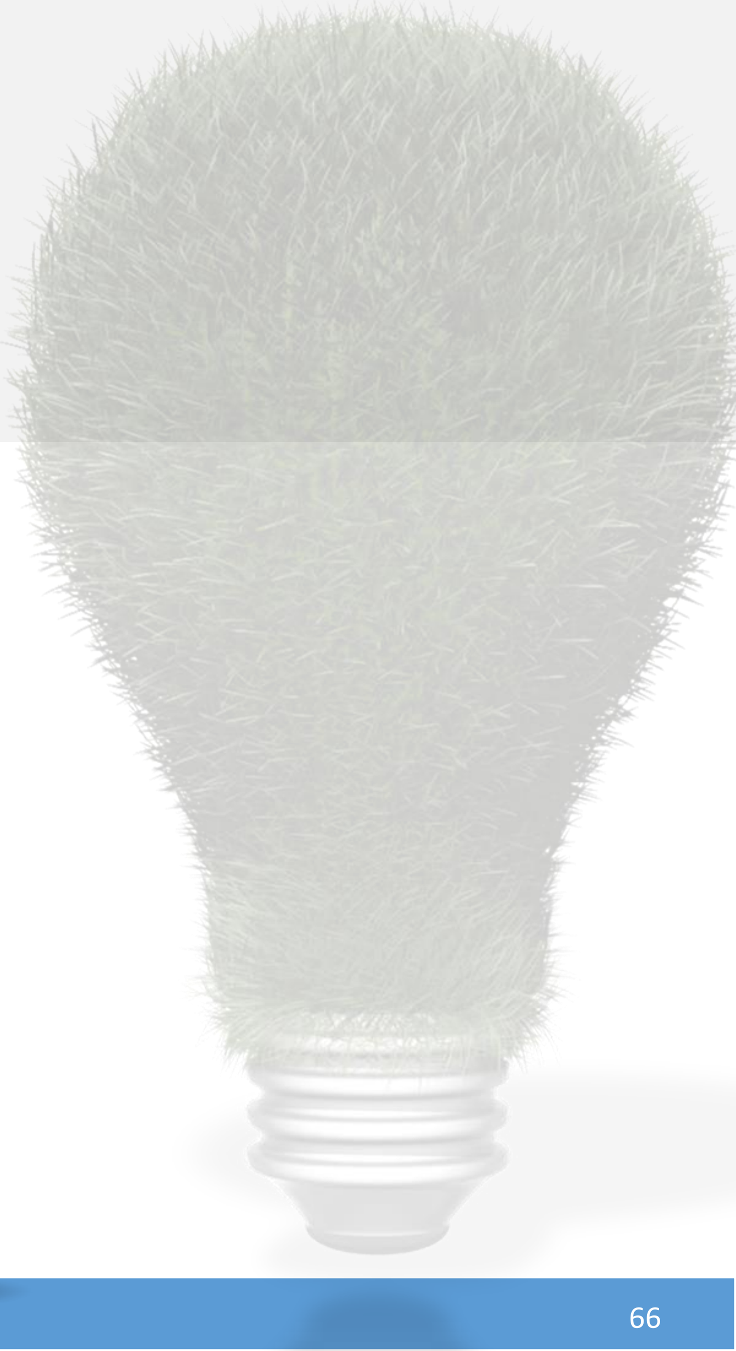
Renewable and Distributed Energy and Electricity Markets

Upholding the Delicate Balance



Upholding the Delicate Balance





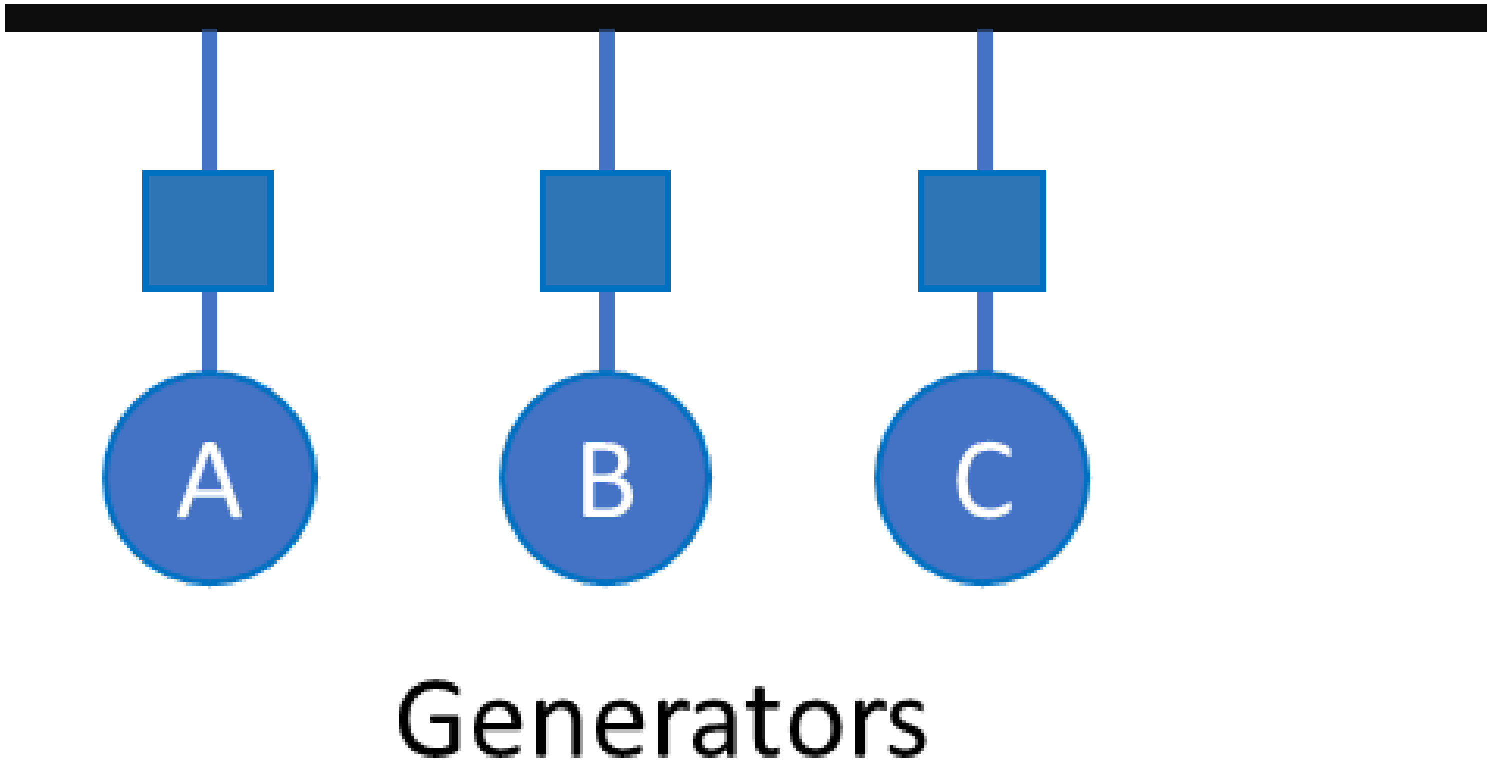
Operational Flexibility

How Electricity markets adapt?

- Markets operate on a much shorter time frame than before.
- Increasing reliance on flexibility from the demand side
- New entities are emerging: Aggregators!

Markets for Electrical Energy

Assumption



- All generators and the load are connected to the same bus.

  or

- They are connected through a lossless network

What are we selling?

- Electricity is fully characterized by several physical variables:
    - Voltage
    - Current
    - Power (real and imaginary) or (average and reactive)
    - Energy

What is difference between power and energy?

- Energy is the capacity to do work (measured in watt-hour)
- Power is defined as the rate of producing or consuming energy, i.e. Power is energy per unit of time.
- Electrical power is measured in watt, which is defined as a current of one ampere, pushed by a voltage of one volt (volts x amps = watts)
- Energy is the total amount of work done, and power is how fast you can do it. In other words, power is energy per unit of time. Power is watts. Energy is watt-hours.

What should we trade in electricity markets?

- It is designed to supply energy on a continuous basis, i.e. power.
- Electricity is therefore not traded in terms of energy but rather in terms of power over a certain interval of time.
- We quantify the amount of electrical energy flowing through the grid using kilowatt-hours rather than joules.
- Power is then translated into tradable energy by integrating it over each time interval.
- The physical and market conditions are assumed constant over each trading period, the price of energy is also deemed uniform over each trading period.

How to choose the right time interval for trading?

A short time interval (say 5 min):

- Trading reflects more accurately the instantaneous conditions in the physical system.
    - important in systems with a significant amount of wind or solar generation because of the rapid and unpredictable changes they cause.
- Not always practical as generating companies need to know that they will be synchronized for a long period of time before they bring a large thermal unit online.
    - technical constraints and the need to recover the start-up cost.

Can we have both?

Electricity trading is organized as a sequence of forward markets with progressively shorter trading periods and a spot market

Forward markets

Handle trading in large amounts of energy over long periods of time.

They operate slowly and close far in advance of the beginning of the delivery period (also known as “real time”).

The market of last resort.

It operates closest to real time. It typically handles only a small fraction of the overall energy needs.

Operates in real time.

This arrangement not only helps market participants manage their risks but also gives the system operator time to identify conditions that might affect the operational reliability of the system.

Forward markets

Two approaches:

CENTRALIZED TRADING (ALSO KNOWN AS "POOL TRADING")

BILATERAL TRADING (ALSO KNOWN AS DECENTRALIZED TRADING)

https://idbinvest.org/en/blog/energy/how-calculate-cost-generating-electricity

Bilateral Trading

Bilateral Trading

- Pool trading is an unusual form of market
- Bilateral trading is the classical form of trading
- Involves only two parties:
  - Seller
  - Buyer
- Trading is a private arrangement between these parties
- Price and quantity negotiated directly between these parties
- Nobody else is involved in the decision
- Occasionally facilitated by brokers or electronic market operators
- Takes different forms depending on the time scale

Bilateral Trading- Customized long-term contracts

- Customized long-term contracts
  - Flexible terms
  - Negotiated between the parties
  - Duration of several months to several years
  - Advantage:
    - Guarantees a fixed price over a long period
  - Disadvantages:
    - Cost of negotiations is high
  - Worthwhile only for large amounts of energy

Bilateral Trading- Trading “over the counter” (OTC)

- Smaller amounts of energy
- Delivery according to standardized profiles, i.e. a standardized definition of how much energy should be delivered over different periods of the day and week
- Advantage:
  - Much lower transaction cost
- Used to refine position as delivery time approaches

Bilateral Trading- Electronic Trading

- Electronic trading
  - Buyers and sellers enter bids directly into computerized marketplace
  - All participants can observe the prices and quantities offered
  - Automatic matching of bids and offers
  - Participants remain anonymous
  - Market organizer handles the settlement
  - Advantages:
    - Very fast
    - Very cheap
    - Good source of information about the market

Bilateral Trading

- The market equilibrium will be reached by the repeated interaction between the supply and the demand.
- The price of each transaction is set independently by the parties involved.
- There is thus no “official” price and trading can be described as “decentralized.”
- Independent reporting services gather anonymized data about over-the-counter (OTC) trading and publish summary information about prices and quantities in a form that does not reveal the identity of the parties involved.
- This type of reporting enhances the efficiency of electricity trading by indicating direction of the market.

Example Bilateral Trading

- Borduria Power trades on the Bordurian electricity market that operates on a bilateral basis.
- Assume that the marginal cost of these units is constant over their range of operation.
- Because of their large startup costs, Borduria Power tries to keep unit A synchronized to the system at all times and to produce as much as possible with unit B during the daytime. The startup cost of unit C is negligible.

Unit	Type	Pmin (MW)	Pmax (MW)	MC ($/MWh)
A	Large Coal	100	500	10.0
B	Medium Coal	50	200	13.0
C	Gas Turbine	0	50	17.0

Example Bilateral Trading

Contractual position of Borduria Power for the 2: 00–3: 00 p.m on June 11.

Type	Contract date	Buyer	Seller	Amount (MWh)	Price ($/MWh)
Long term	January 10	Cheapo Energy	Borduria Power	200	12.5
Long term	February 7	Borduria Steel	Borduria Power	250	12.8
OTC	April 7	Quality Electrons	Borduria Power	100	14.0
OTC	May 31	Borduria Power	Perfect Power	30	13.5
OTC	June 8	Cheapo Energy	Borduria Power	50	13.8

Net position: Sold 570 MW
Production capacity: 750 MW

Unit A: 500 MW
Unit B: 70 MW
130 MW of spare capacity on unit B

Kirschen, Daniel S.; Strbac, Goran. Fundamentals of Power System Economics (Kindle Locations 1764-1767). Wiley. Kindle Edition.

Example Bilateral Trading

Pending offers and bids on Borduria Power Exchange (BPeX) at midmorning on 11 June for the period from 2:00 till 3:00 pm:

Net position: Sold 570 MW
Production capacity: 750 MW

Unit A: 500 MW
Unit B: 70 MW
130 MW of spare capacity on unit B

11 June 14:00-15:00	Identifier	Amount[MW]	Price ($/MWh)
Bids to sell energy	B5	20	17.50
	B4	25	16.30
	B3	20	14.40
	B2	10	13.90
	B1	25	13.70
Offers to buy energy	O1	20	13.50
	O2	30	13.30
	O3	10	13.25
	O4	30	12.80
	O5	50	12.55

Kirschen, Daniel S.; Strbac, Goran. Fundamentals of Power System Economics (Kindle Locations 1764-1767). Wiley. Kindle Edition.

Example Bilateral Trading

Pending offers and bids on Borduria Power Exchange (BPeX) at midmorning on 11 June for the period from 2:00 till 3:00 pm:

Net position: Sold 630 MW
Self schedule: Unit A: 500 MW
Unit B: 130 MW
Unit C: 0 MW

11 June 14:00-15:00	Identifier	Amount[MW]	Price ($/MWh)
Bids to sell energy	B5	20	17.50
	B4	25	16.30
	B3	20	14.40
	B2	10	13.90
	B1	25	13.70
Offers to buy energy	**O1**	**20**	**13.50**
	O2	**30**	**13.30**
	O3	**10**	**13.25**
	O4	30	12.80
	O5	50	12.55

Kirschen, Daniel S.; Strbac, Goran. Fundamentals of Power System Economics (Kindle Locations 1764-1767). Wiley. Kindle Edition.

Example Bilateral Trading

Pending offers and bids on Borduria Power Exchange at midmorning on 11 June for the period from 2:00 till 3:00 pm:

Unexpected problem: unit B can only generate 80 MW

Options: - Do nothing and pay the spot price for the missing energy
- Make up the deficit with unit C
- Trade on the power exchange

Buying is cheaper than producing with C

New net position: Sold 580 MW

New schedule: A: 500 MW, B: 80 MW, C: 0 MW

11 June 14:00-15:00	Identifier	Amount[MW]	Price ($/MWh)
Bids to sell energy	B5	20	17.50
	B4	25	16.30
	B3	20	14.40
	B2	10	13.90
	B1	25	13.70
Offers to buy energy	O1	20	13.50
	O2	30	13.30
	O3	10	13.25
	O4	30	12.80
	O5	50	12.55

Centralized Trading

The key elements in any market?

THE DEMAND

THE SUPPLY

A PLACE TO MEET

TRANSPORTATION SYSTEM

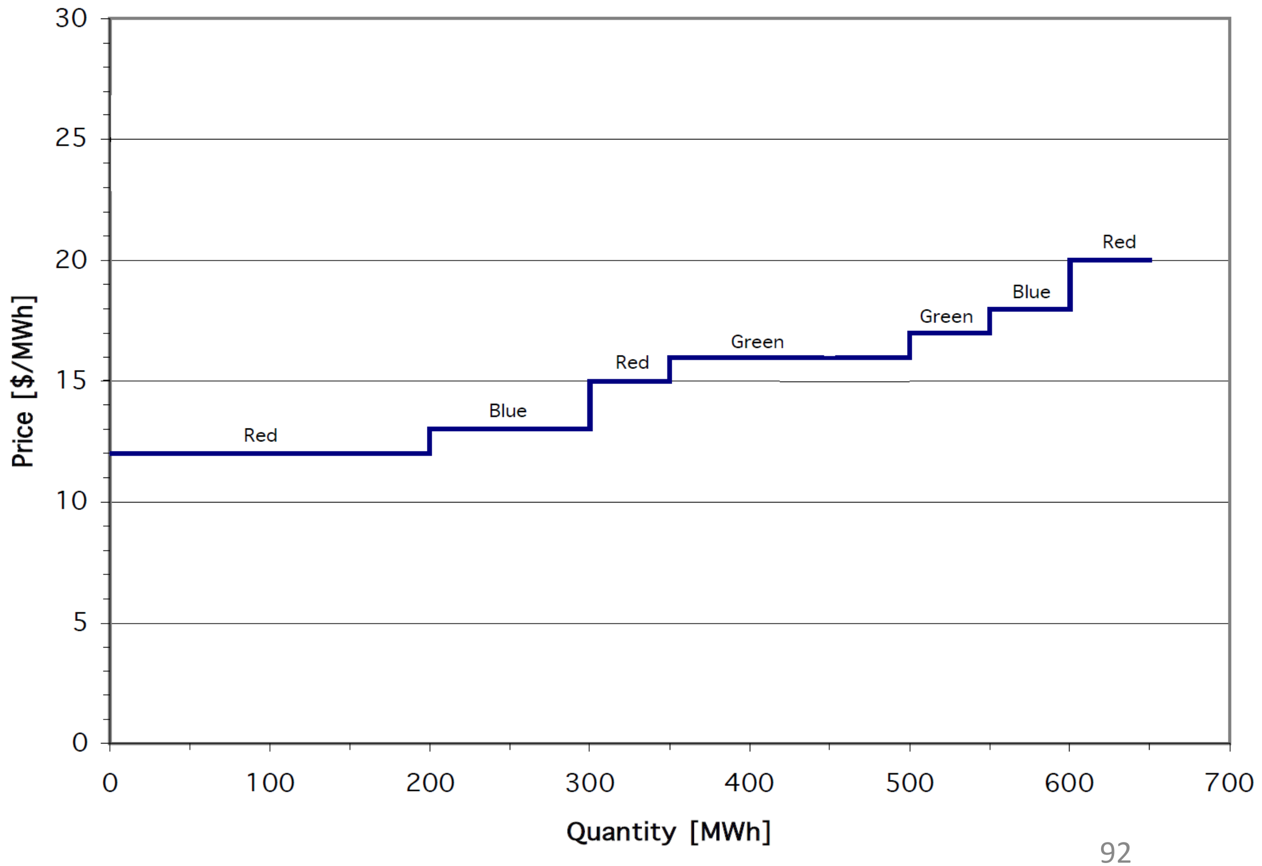
Constructing the supply curve

- Market provides a mechanism for determining this equilibrium in a systematic way.
- Generating companies submit offers to supply a certain amount of electrical power at a certain price for the period under consideration.
- These offers are ranked in order of increasing price. From this ranking, a curve showing the offer price as a function of the cumulative quantity offered can be built. This curve is deemed to be the supply curve of the market.

Constructing the supply curve

The centralized forward market of Syldavia has received the offers shown below for the 9: 00– 10: 00 a.m. trading period on June 11.

	Company	Quantity (MWh)	Price ($/MWh)
Offers	Red	200	12.00
	Red	50	15.00
	Red	50	20.00
	Green	150	16.00
	Green	50	17.00
	Blue	100	13.00
	Blue	50	18.00



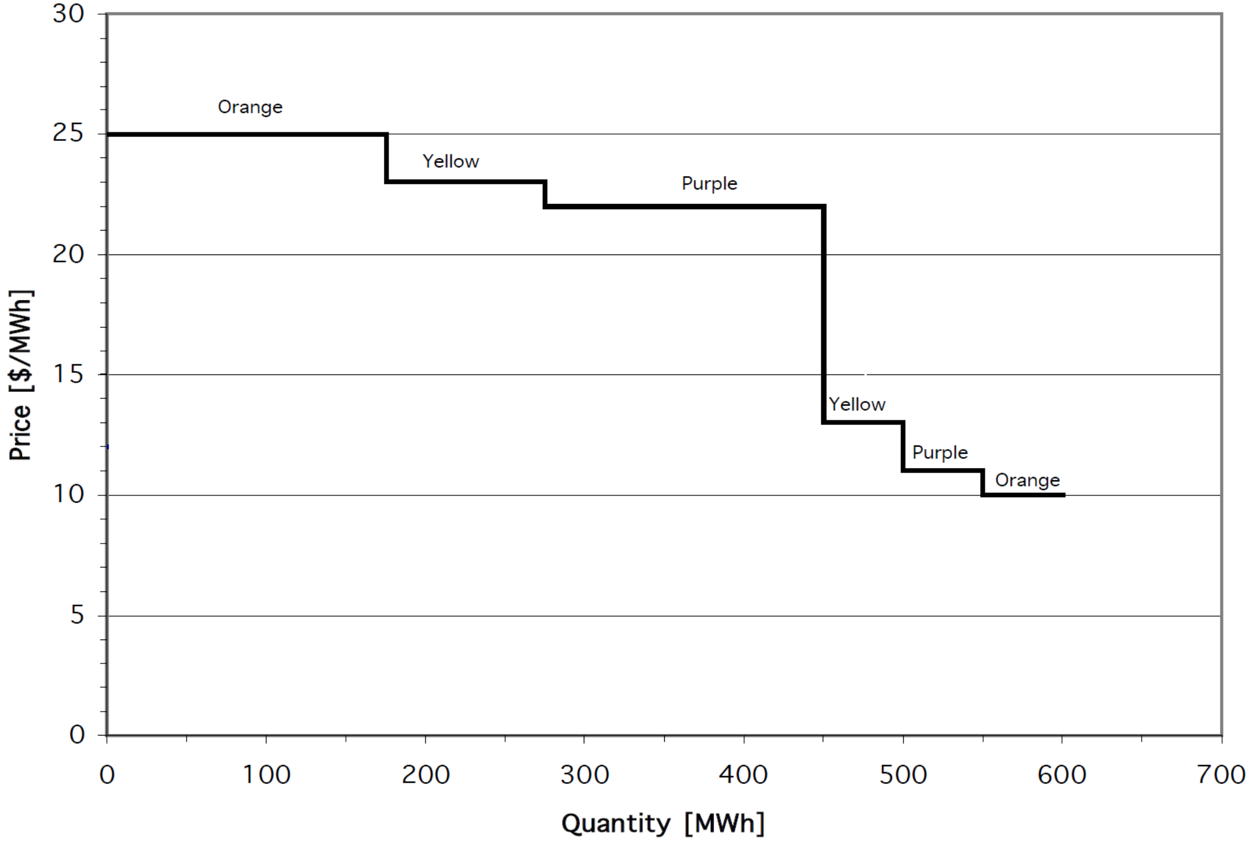
Constructing the demand curve

- Consumers to submit bids to the system operator specifying the quantity they need and the price that they would be willing to pay.
- These offers are then ranked in decreasing order of price to create a demand curve.

Constructing the demand curve

Offers in the Electricity Pool of Syldavia for the period from 9:00 till 10:00 on 11 June:

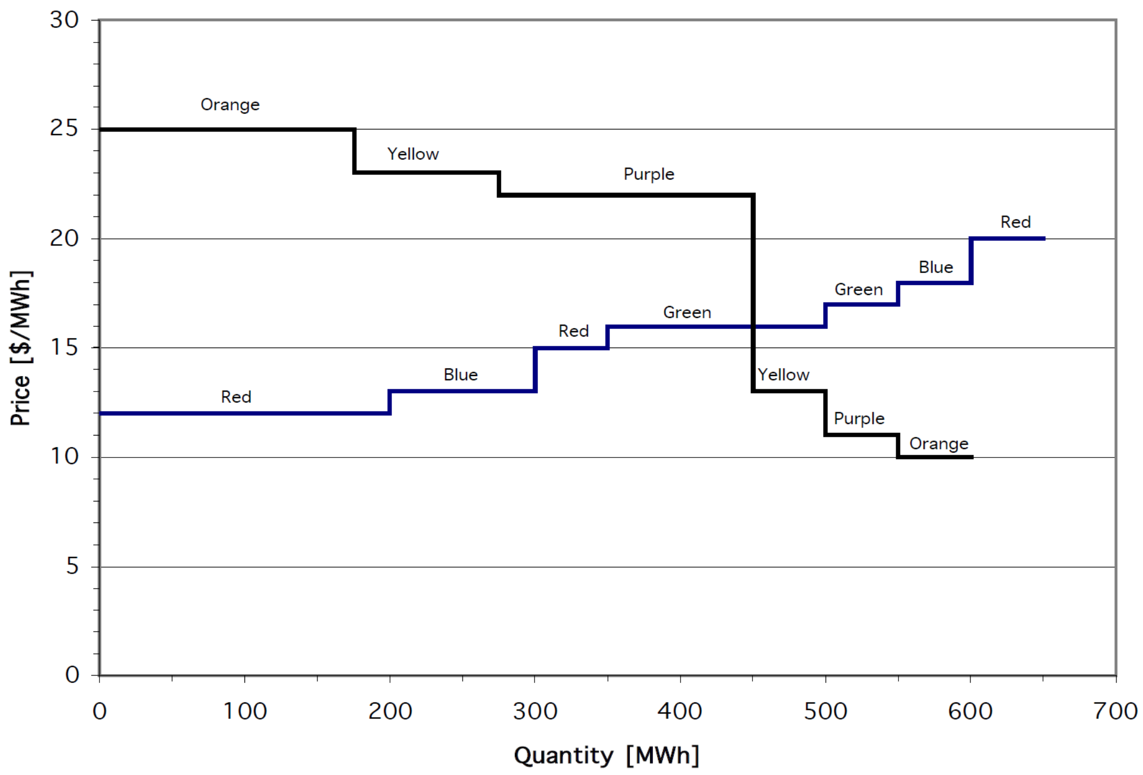
	Company	Quantity (MWh)	Price ($/MWh)
Bids	Yellow	50	13.00
	Yellow	100	23.00
	Purple	50	11.00
	Purple	150	22.00
	Orange	50	10.00
	Orange	200	25.00



The market equilibrium

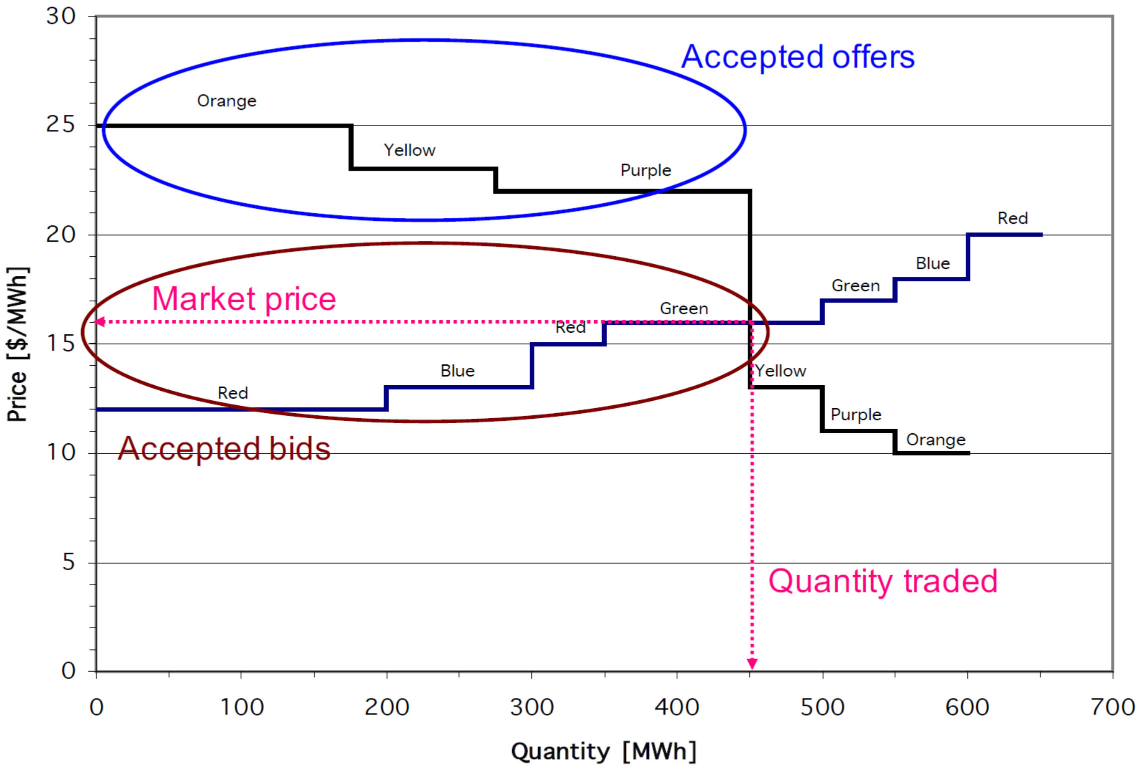
- The intersection of these constructed supply and demand curves determines the market equilibrium.
- All the offers submitted at a price lower than or equal to the market clearing price are accepted.
- Market clearing price represents the price of one additional megawatt-hour of energy and is therefore called the System Marginal Price or SMP.

SMP is 16.00 $/ MWh and that 450 MWh will be traded.



Generators are paid this SMP

- Generators are paid this SMP irrespective of the offers and bids that they submitted.
- The process of finding the intersection between these constructed supply and demand curves emulates the operation of a market and thus maximizes the global welfare.



Clearing the market for 1 hr

- Market price: 16.00 $/MWh
- Volume traded: 450 MWh

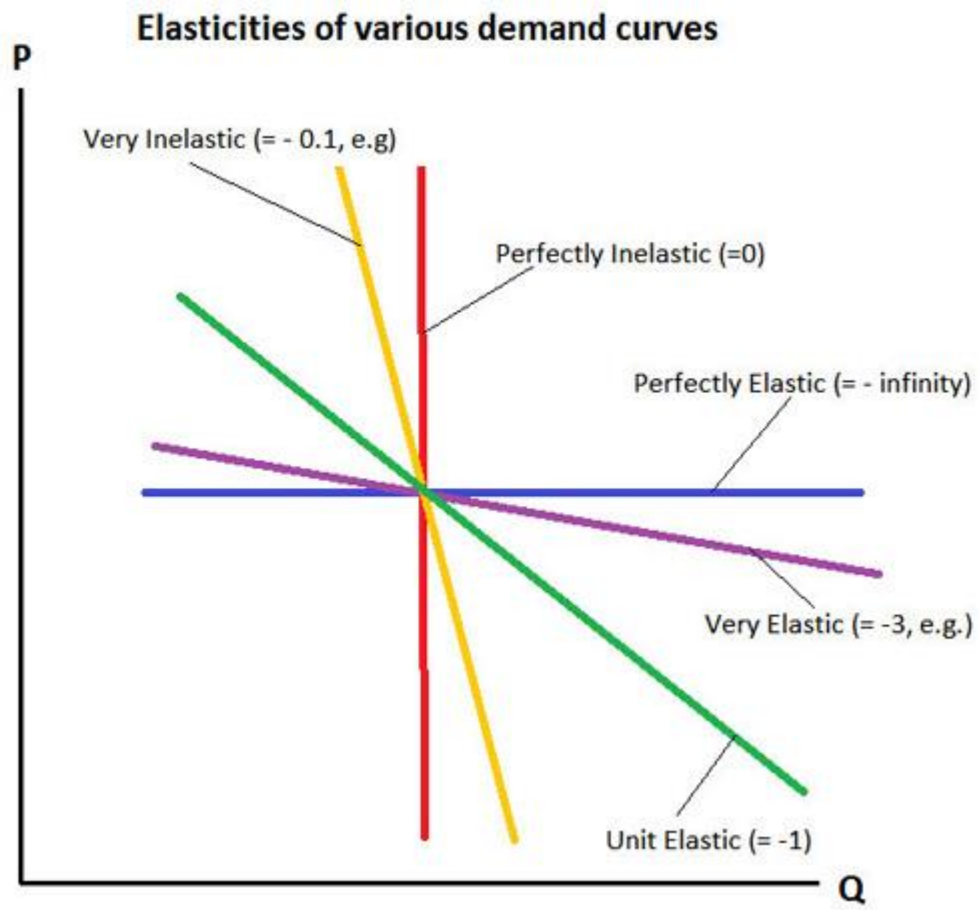
Company	Production [MWh]	Consumption [MWh]	Revenue [$]	Expense [$]
Red	250		4,000.	
Blue	100		1,600	
Green	100		1,600	
Orange		200		3,200
Yellow		100		1,600
Purple		150		2,400
Total	450	450	7,200	7,200

Wouldn't paying every generator its asking price reduce the average price of electricity?

- a pay-as-bid scheme is not adopted.
- It discourage generators from submitting offers that reflect their marginal cost of production.
- All generators would try to guess the SMP and would offer at that level to maximize their revenues.
- At best, the SMP would remain unchanged. Most likely, The SMP would be somewhat higher.
- some low-cost generators would then be left out of the schedule and be replaced by generators with a higher marginal cost of production.
- economically inefficient because optimal use is not made of the available resources.
- generators are likely to increase their prices slightly to compensate themselves for the additional risk of losing revenue caused by the uncertainty associated with trying to guess what the SMP might be.
- An attempt to reduce the price of electricity would therefore result in a price increase!

Note about the demand curve

- Since the demand for electricity is highly inelastic, this step is often omitted and the demand is set at a value determined using a forecast of the load.
- In other words, the demand curve is assumed to be a vertical line at the value of the load forecast.



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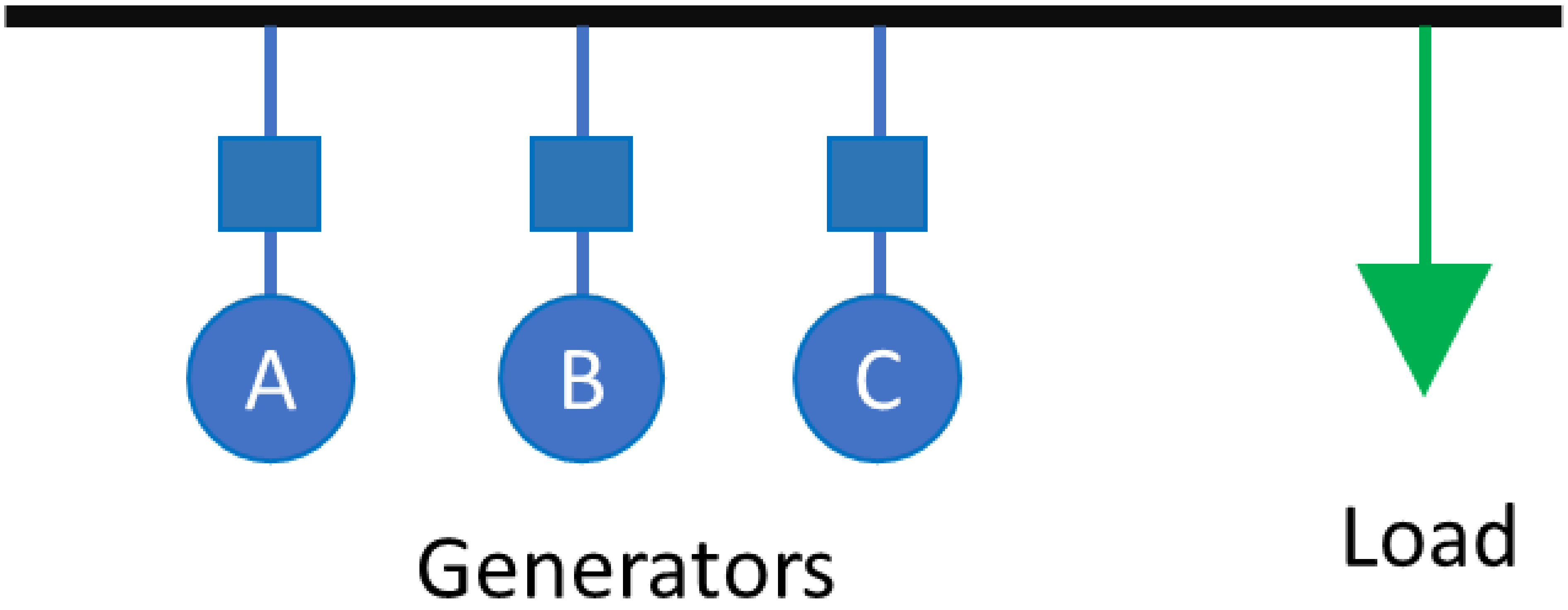


Economic Dispatch

Given load, set of units on-line, taking into the account the limits of each generator, how much should each unit generate to meet this load at minimum cost

If the demand is assumed constant and the offers reflect the marginal cost of production, a centralized market performs an economic dispatch, i.e. it determines how much each generator should produce to supply the load at minimum cost.

Is an hour-by-hour market clearing practical?

Minimum up/down time:

- Once synchronized, such a unit must often continue producing power for a certain number of hours to avoid mechanical damage caused by excessive temperature gradients. Similarly, once it has been shut down, it must typically remain idle for a certain number of hours before it can be restarted.

Ramp up and ramp down constraints:

- The rate at which the output of a unit can increase or decrease is also limited.

Minimum generation:

- The output of large generating units usually cannot be reduced to zero. Instead, it must remain above its “minimum stable generation,” which can be a significant fraction of its rated output.

Start-up:

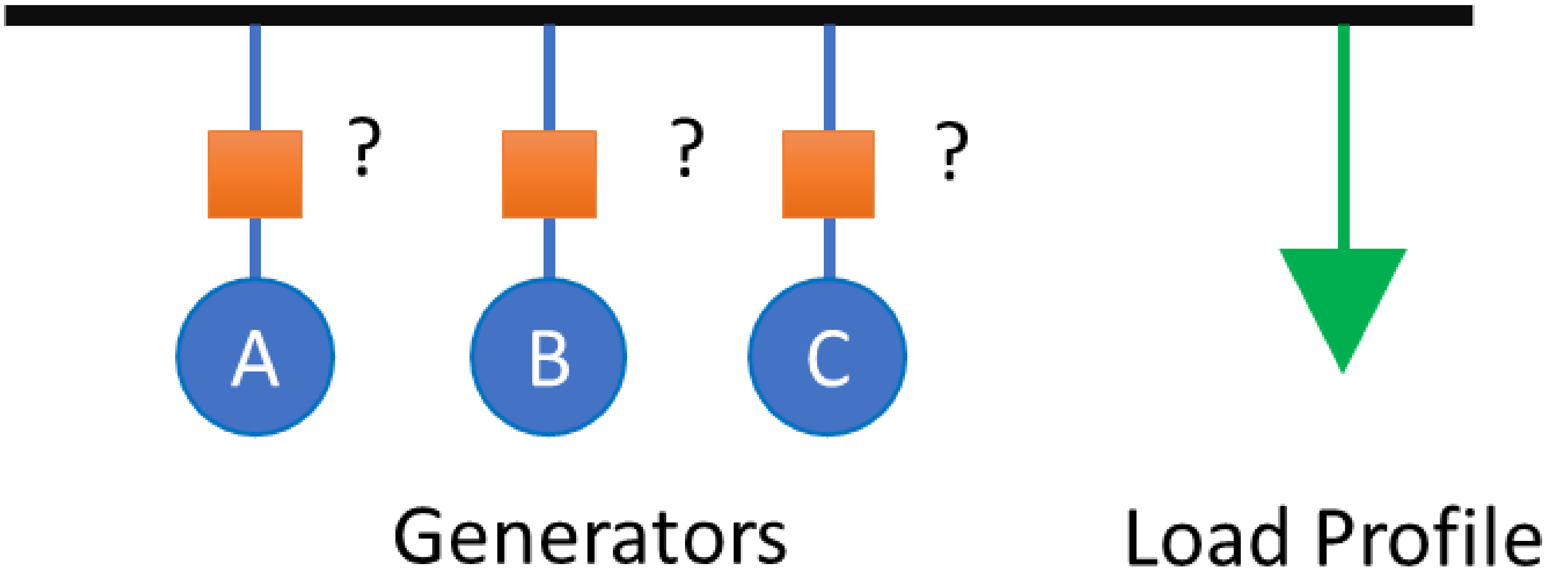
- Synchronizing a large thermal generating unit to the system can take several hours.

start-up and no-load cost:

- a large, efficient thermal generating unit usually burns a significant amount of fuel before it can begin injecting electrical energy into the grid. The cost of this fuel represents a fixed “startup cost” that must be amortized over the sale of enough electrical energy to justify starting this unit.

Risk:

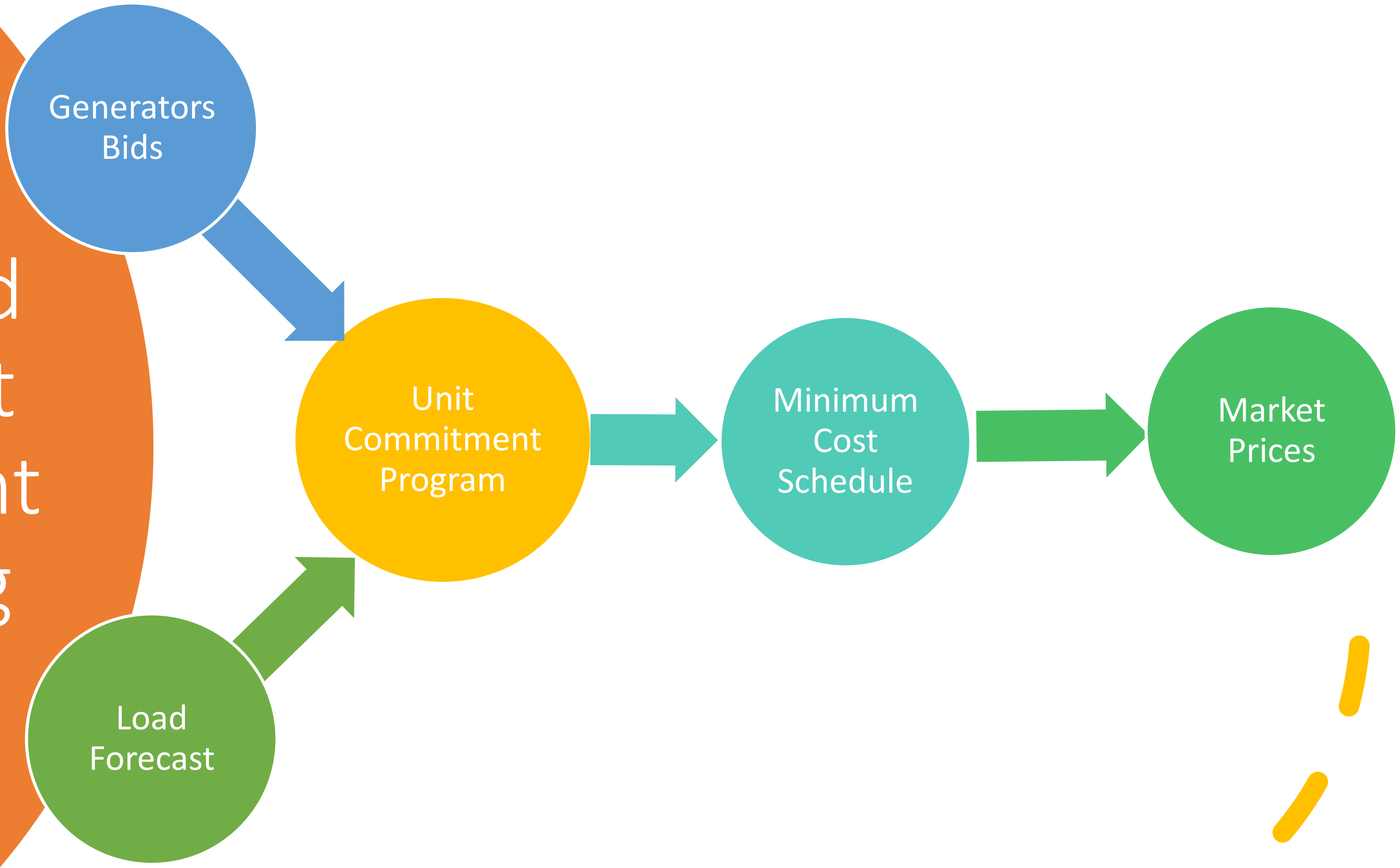
- Uncertainty on generation schedule leads to higher prices



Unit Commitment

- Given load profile (e.g. values of the load for each hour of a day) and the set of units on-line, considering the limits of the generating units, when should each unit be started, stopped and how much should it generate to meet the load at minimum cost?

A day-ahead market: unit commitment pool trading

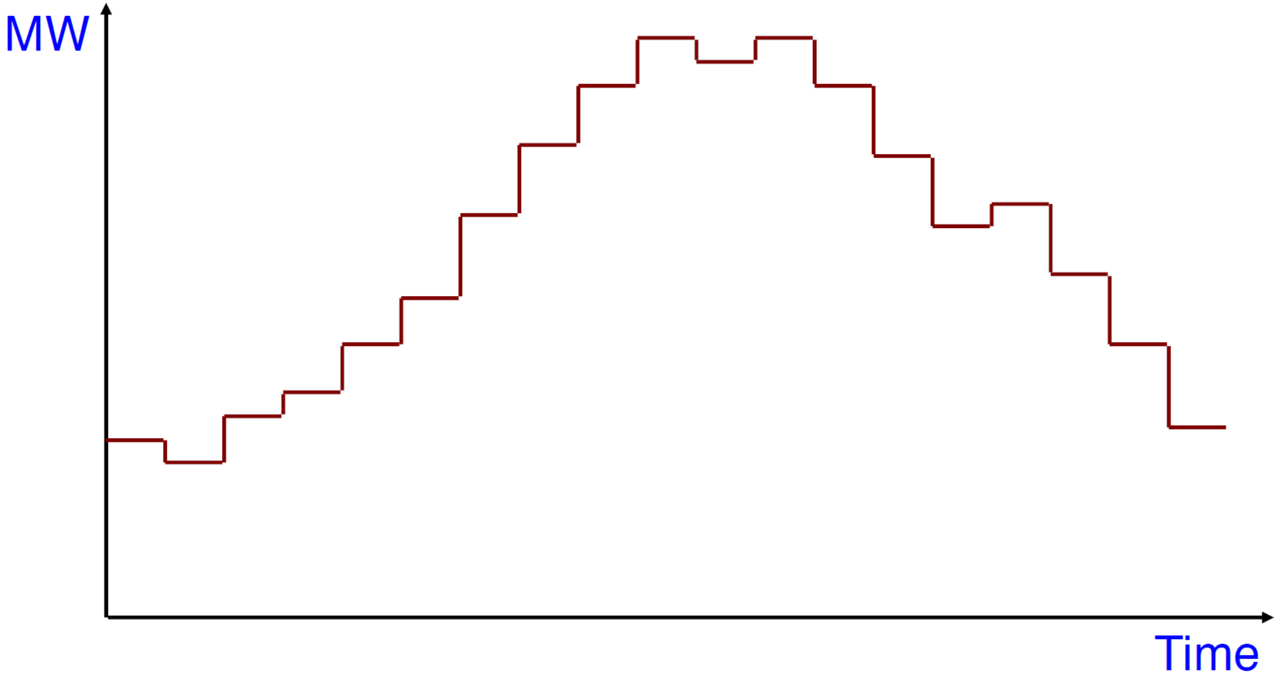


Generators Bids

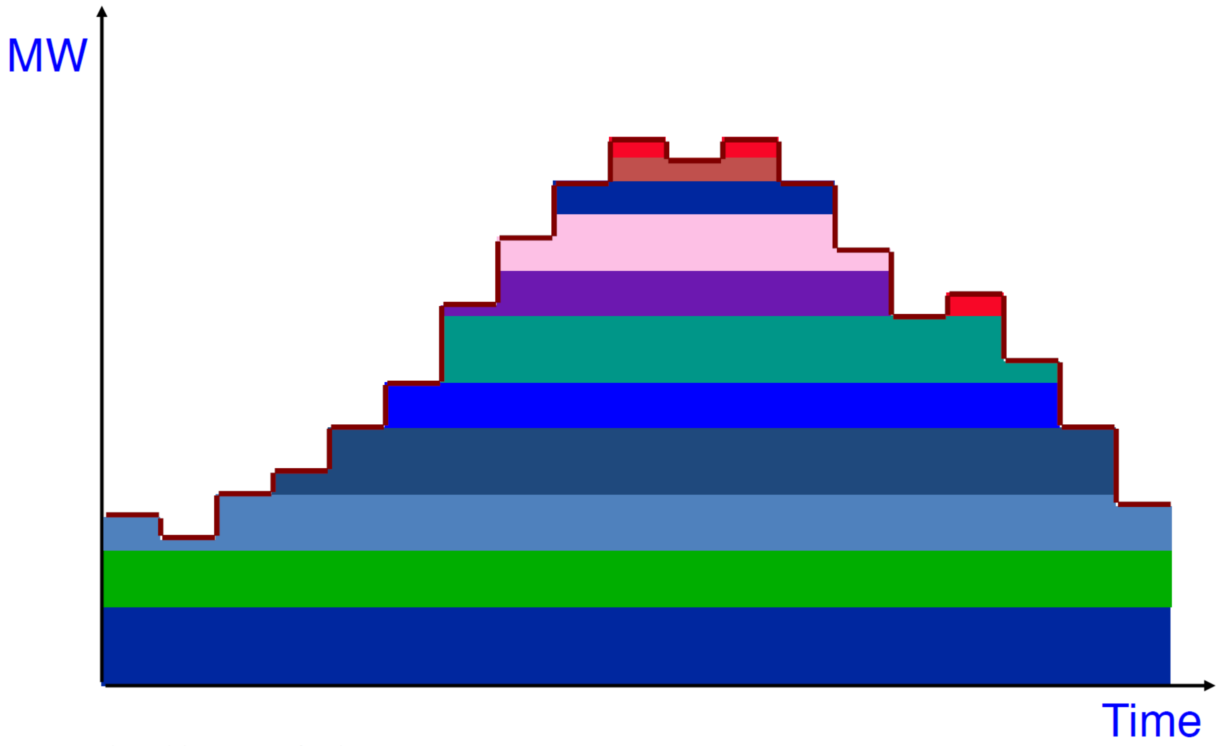
- All units are bid separately
- Components:
  - piecewise linear marginal price curve
  - start-up price
  - parameters (min MW, max MW, min up, min down,...)
- Bids do not have to reflect costs
- Bidding very low to “get in the schedule” is allowed

Load Forecast

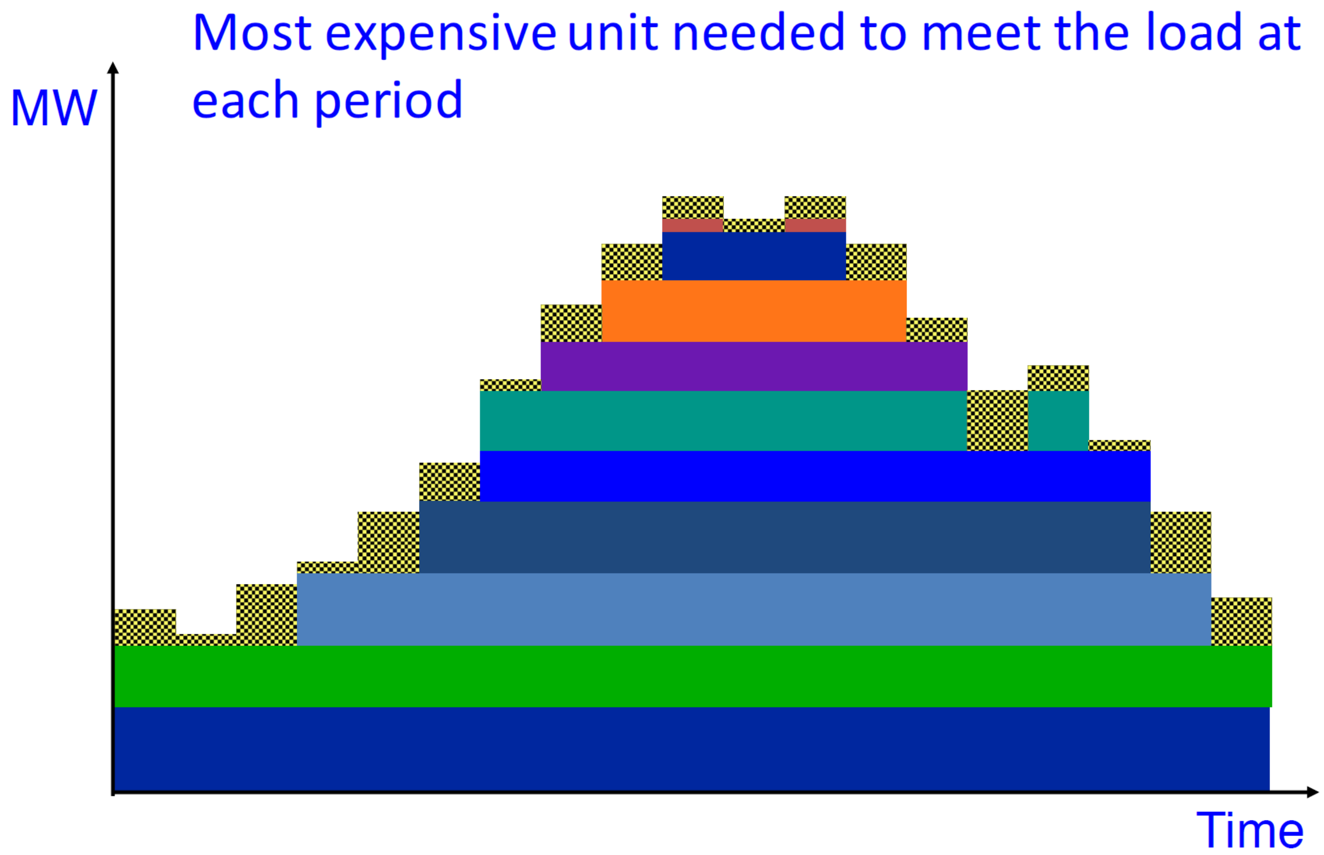
- Load is usually treated as a passive market participant
- Assume that there is no demand response to prices



Generation Schedule

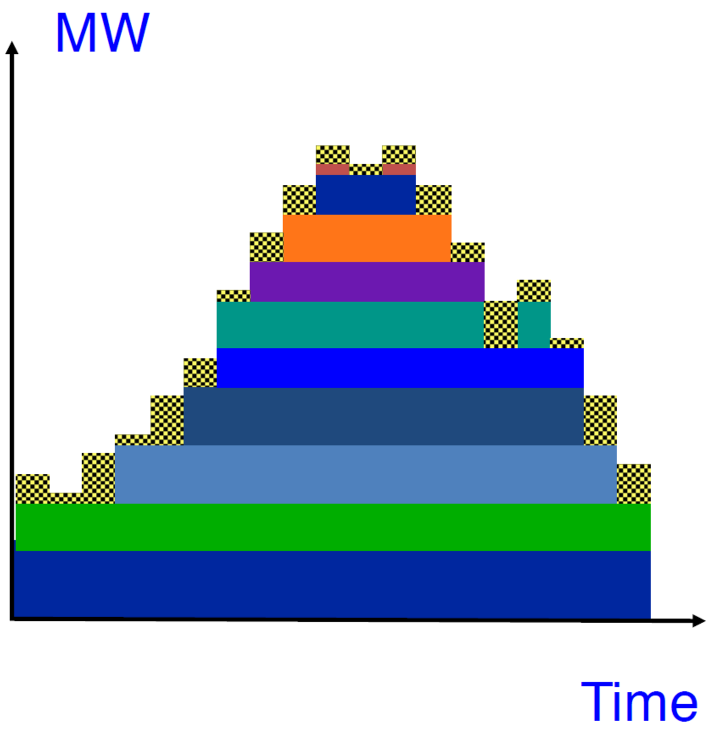


Marginal Units



Market Price

- Bid from marginal unit sets the market clearing price at each period
- System Marginal Price (SMP)
- All energy traded through the pool during that period is bought and sold at that price



A day-ahead market-Example

- Let's consider a market with 3 generators, a scheduling horizon of 3 hours, and a trading period of 1 hour.
- For simplicity, we ignore the startup costs, the ramp rate limits as well as the minimum up- and down-time constraints. We also assume that the cost functions of the generators involve only a fixed cost α_i and a constant marginal cost β_i:

Generating unit i	Minimum generation (MW)	Maximum generation (MW)	Marginal cost β_i (\$/MWh)	Fixed cost α_i (\$/h)
1	0	500	10	500
2	100	350	30	250
3	0	200	35	100

A day-ahead market-Example

- Demand data

Time period t	1	2	3
L(t) (MW)	550	750	1050

A day-ahead market-Example

- Period 1: The 550 MW demand can be met with three combinations of units: 1& 2, 1& 3, 2& 3.

Possible combination	P_1(MW)	P_2(MW)	P_3(MW)	Total Cost($)
1& 2	450	100		$500 + 10 \times 450 + 250 + 30 \times 100 =$ \$ 8250
1& 3	500	50		$500 + 10 \times 500 + 100 + 35 \times 50 =$ \$ 7350
2& 3		350	200	$250 + 30 \times 350 + 100 + 35 \times 200 =$ \$ 17850

- Unit 1 has a large fixed cost but by far the lowest variable cost. It should therefore be dispatched as much as possible.
- Unit 2 has a lower marginal cost than that of unit 3, but a higher fixed cost and a larger minimum stable generation. Dispatching unit 2 during period 1 would force us to reduce the output of unit 1 to 450 MW, resulting in a larger total cost.
- The optimal dispatch for period 1 is thus P1 = 500 MW, P3 = 50 MW.
- Unit 3 is the marginal unit, and the market price for this period is therefore set at its marginal cost,35 \$/MWh.

A day-ahead market-Example

- Period 2: The 750 MW

Possible combination	P_1(MW)	P_2(MW)	P_3(MW)	Total Cost($)
1& 2	500	250		$500 + 10 \times 500 + 250 + 30 \times 250 = \$\,13250$
1& 3	Not feasible			
2& 3	Excludes the cheap unit			

- Since unit 2 is the marginal unit, the price for period 2 is set at its marginal cost of 30 $/ MWh. Note that this price is lower than the price for period 1, even though the demand is higher.

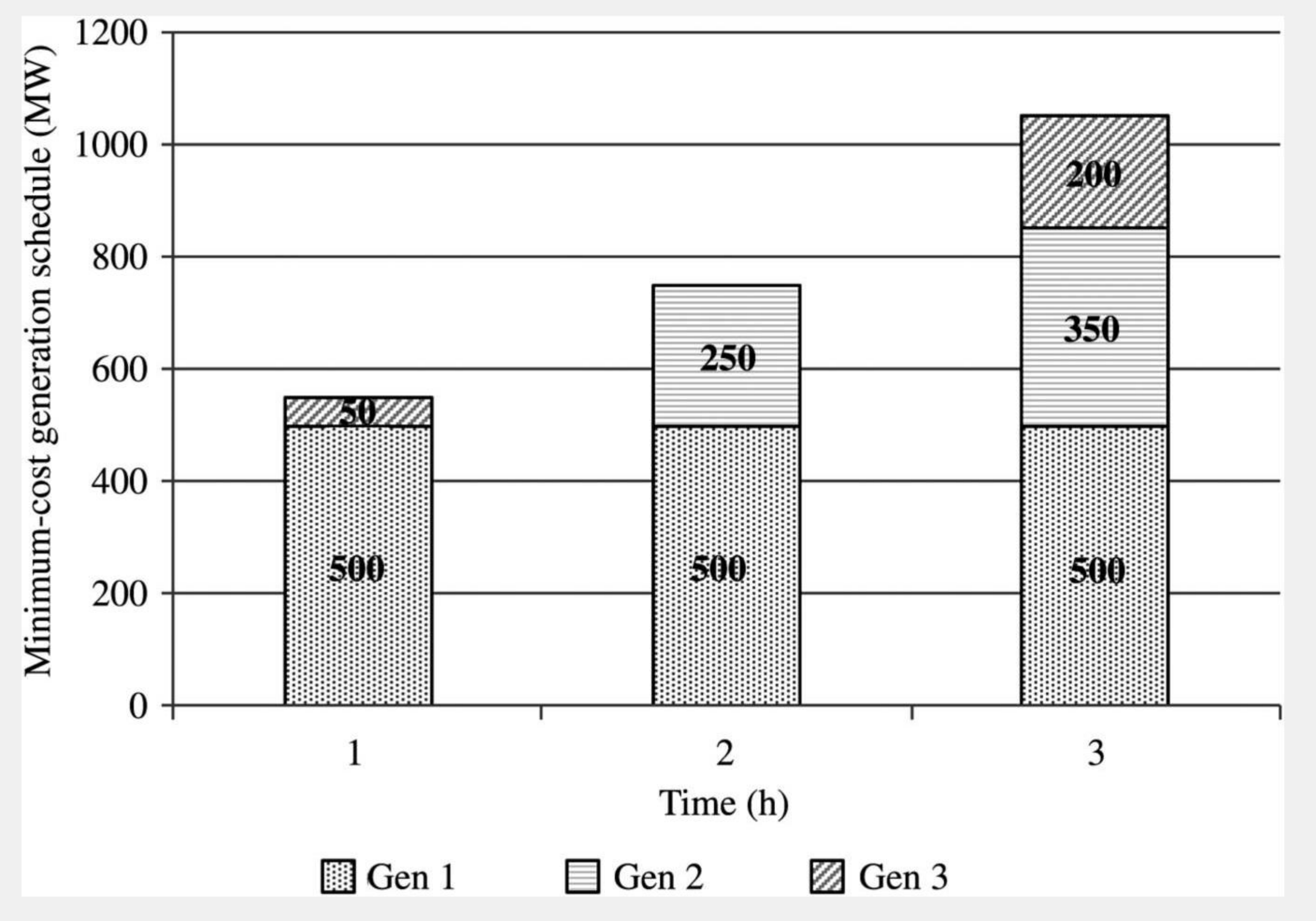
A day-ahead market-Example

- Period 3: The 1050 MW

Possible combination	P_1(MW)	P_2(MW)	P_3(MW)	Total Cost($)
1& 2&3	500	350	200	500 + 10 × 500 + 250 + 30 × 350 + 100 + 35 × 200 = $ 23 350.

- All three units are needed to meet the load during this period and the optimal dispatch.
- Units 1 and 2 being loaded at their maximum output, unit 3 is the marginal unit and the price for this period is 35$/MWh.

A day-ahead market-Example



- Minimum cost generation schedule for this unit commitment problem
- Because of the simplifications that we have made, we can consider each period separately.

The centralized markets

- Day-ahead centralized electricity markets are run by the system operator.
  - facilitates the integration of forward markets with the needs to maintain the balance of the system and to ensure operational reliability.
  - important in systems where network constraints have a significant impact on the market.
  - avoids the multiplication of organizations.
  - It blurs the lines between the various functions that need to be performed in an electricity market.

The centralized markets

- Some economists view centralized as an administered approximation of a market rather than a true market.
    - Small and medium electricity consumers have very little incentive to take an active part in an electricity market.
    - Even when they are aggregated, the retailer that represents them has only a limited ability to adjust consumption in responses to changes in prices.
    - The demand is deemed to be passive and is represented by a load forecast in many centralized markets to lower transaction cost.
    - Direct negotiations between consumers and producers are essential if efficient prices are to be reached.

The centralized markets

- Provides a mechanism for reducing the scheduling risk faced by generators.
    - The unit commitment calculation avoids unnecessary unit shutdowns and the market rules typically ensure that generators recover their start-up and no-load costs.
    - Generators run the risk that for some periods it may not have sold enough energy to keep the plant on-line when they sell energy for market period separately.
    - They either sell energy at a loss to keep the unit running or to shut it down and face the expense of another start-up at a later time.
    - This reduction in risk requires the implementation of more complex market rules.
    - Such rules reduce the transparency of the price setting process and increase opportunities for price manipulations.

The centralized markets

- Generators and retailers who participate in a day-ahead centralized market are typically obliged to sell their entire production or buy their total consumption through this market. However, they usually retain the right to enter into bilateral financial contracts .
    - Some centralized day-ahead markets also allow bilateral trading.
    - The quantities traded bilaterally are taken into account in the clearing process, but these transactions do not set the market price.

Are the generators making profit?

Are the generators making profit?

- While unit 1 is profitable during each period, units 2 and 3 are unprofitable during the periods where they are the marginal unit, because they set the price at their marginal cost and therefore do not recover their fixed costs.

Period	Price ($/MWh)		Unit 1	Unit 2	Unit 3
1	35	Output(MWh)	500	0	50
		Revenue($)	17500	0	1750
		Cost($)	5500	0	1850
		Profit($)	12000	0	**-100**
2	30	Output(MWh)	500	250	0
		Revenue($)	1500	7500	0
		Cost($)	5500	7750	0
		Profit($)	9500	**-250**	0
3	35	Output(MWh)	500	350	200
		Revenue($)	17500	12250	7000
		Cost($)	5500	10750	100
		Profit($)	12000	1500	**-100**

Recovering the Fixed Costs

- The price for each period is determined by the marginal cost of the marginal unit and does not factor in fixed costs.
- There is no guarantee that generating units will be able to recover their fixed costs (i.e. their no-load and startup costs).

Proposed or implemented approaches to ensure generators recover their cost

Approach 1: Uplift Payments Compensating the Unrecovered Costs

Approach 2: Uplift Payments Compensating for Profit Suboptimality

Approach 3: Convex Hull Pricing

Approach 1: Uplift Payments Compensating the Unrecovered Costs

- The market operator calculates the unrecovered cost Γi(t) incurred by each generator at each period based on its complex bid and the marginal price.
- To be able to reimburse these costs to the generators, the market operator must charge the consumers an uplift payment.
- This uplift is usually allocated on the basis of each consumer's demand during each period.
- The total payment by the consumers for time period t consists of an energy payment at a price and an uplift payment.

$$\mathrm{K}(t) = \pi_t^* \mathrm{L(t)} + \sum_{i=1}^{N} \Gamma_i(t) \times \frac{\mathrm{L(t)}}{\sum_{t=1}^{T} \mathrm{L(t)}} \quad \forall t \epsilon T$$

where:

$\Gamma_i(\mathrm{t})$: uncovered cost incurred by generator i at each period t

π_t^*: marginal price

Approach 1: Uplift Payments Compensating the Unrecovered Costs

time period	1	2	3
Energy payments at π_t^* ($)	19250	22500	36750
Uplift payment ($)	105.3	143.6	201.1

- Based on the results of previous example, generators 2 and 3 should receive uplift payments of $ 250 and $ 200, respectively.
- The table shows how much money the consumers will pay at each hour for energy and as uplift payments calculated.

Approach 2 : Uplift Payments Compensating for Profit Suboptimality

- Treat each unit as a profit-seeking entity whose ability to maximize its profits is constrained by centralized scheduling.
- Uplift payments should compensate generators for the difference between the profits that they collect under the minimum cost schedule and the profits that they would achieve if they were allowed to self-schedule given the market prices determined by the centralized schedule.
- Since the self-schedule always results in a larger profit than does the centralized schedule, the difference between these two values is called profit suboptimality.
- Under this approach, every generator that suffers from profit suboptimality is entitled to an uplift payment equal to this loss of profit. These payments are allocated to the demand side.
- For each generating unit, this hypothetical self-schedule is given by the solution of the following optimization problem:

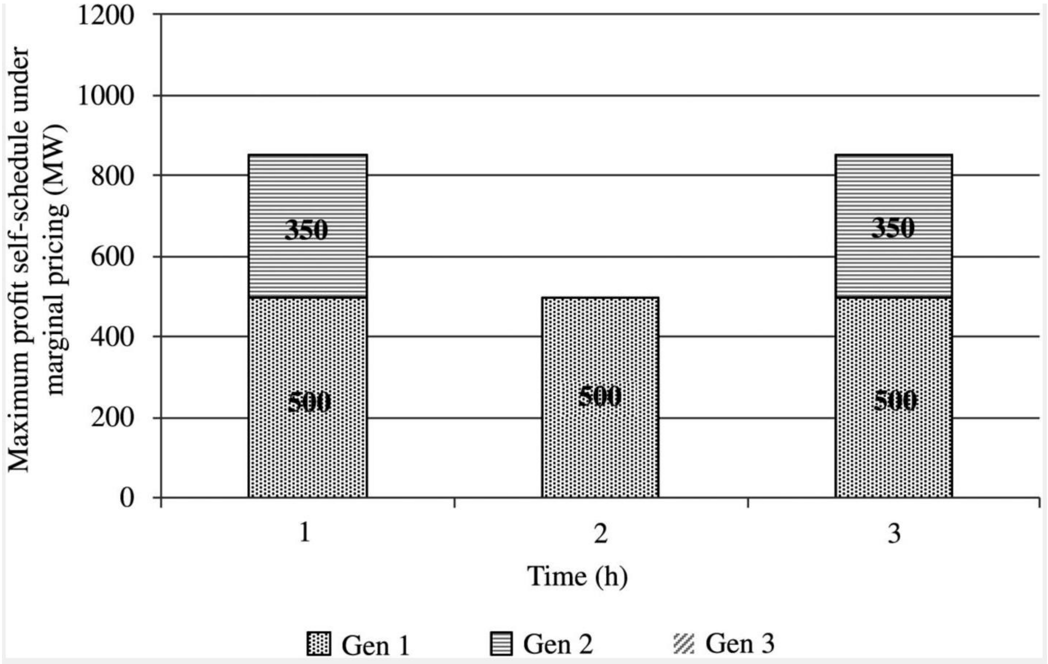
$$max_{P_i(t)u_i(t)} \sum_{t=1}^{T}[\,\pi_t^* \, P_i(t) - C_i(P_i(t))u_i(\mathrm{t}))]$$

where

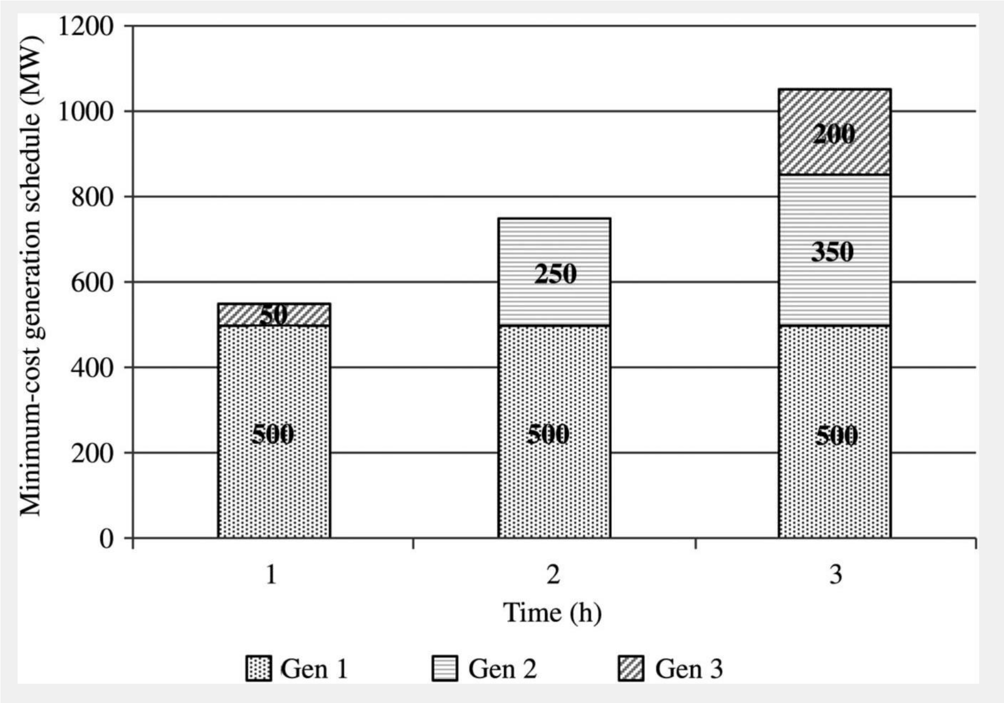
- π_t^*: marginal price
- $Pi(\,t)$ is the power produced by unit i during period t.
- $Ci(\,Pi(\,t))\ \ is\ the\ cost\ of\ producing\ a\ constant\ Pi(\,t)\ with\ unit\ i\ during\ period\ t.$
- ui (t) is the status of unit i during period t (ui(t) = 1 if unit i is on, 0 otherwise).

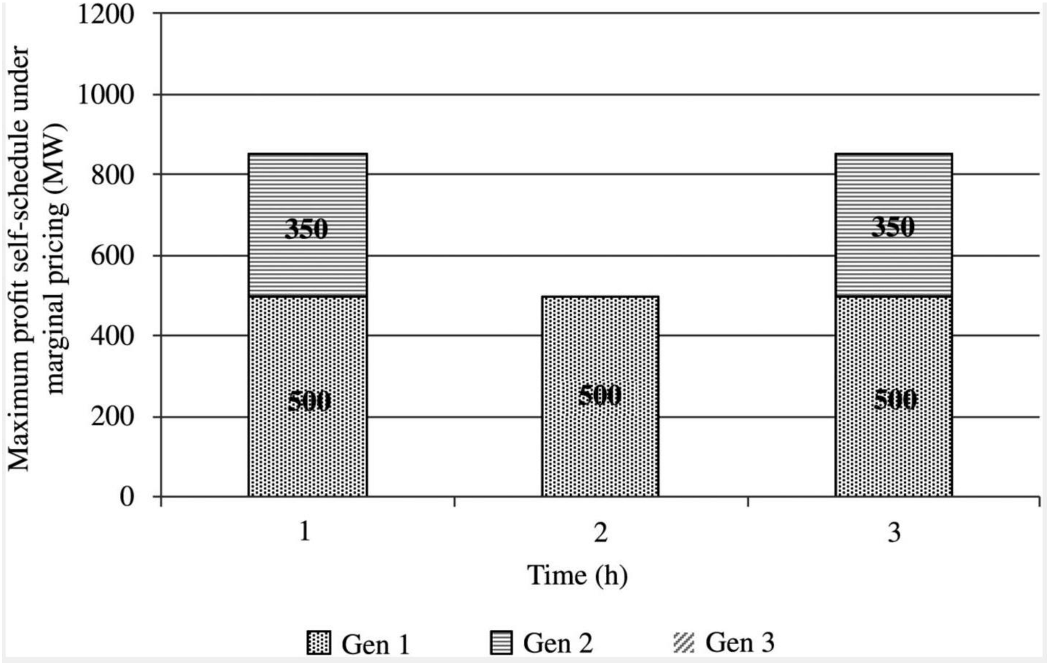
Approach 2 : Uplift Payments Compensating for Profit Suboptimality

- It is clearly not a feasible schedule because it does not respect the load/ generation balance constraint.
- Self-scheduling would make no difference for unit 1 because it produces its maximum output and does not set the marginal price.
- unit 2, which was not scheduled to produce during period 1 under the centralized schedule, would find it profitable to produce its maximum output at the marginal price set by unit 3 because this price is high enough to allow it to recover its fixed costs.
- given the opportunity to self-schedule, unit 2 would not produce during period 2, and unit 3 would not produce during periods 1 and 3 because they set the marginal prices during those periods and do not recover their fixed costs.



Approach 2 : Uplift Payments Compensating for Profit Suboptimality





Approach 2 : Uplift Payments Compensating for Profit Suboptimality

Generator	1	2	3
Minimum-cost schedule profit ($)	33500	1250	– 200
Self-schedule profit at π_t^* ($)	33500	3000	0
Profit suboptimality at π_t^* ($)	0	1750	200

- For example
  - Generator 1:
  - Total revenue=(35+30+35)x500=$50,000
  - Total cost=10x3x500+3x500=$16,500
  - Minimum-cost schedule profit ($)= 50,000-16,500=$3350

Approach 3: Convex Hull Pricing

- Uplift payments are controversial because they represent an out-of-market intervention.
- convex hull pricing aims to minimize total uplift payments by adjusting the market prices.
- Under this scheme, electric energy prices are set to minimize the profit suboptimality (i.e. the difference between the profits from self-scheduling and centralized scheduling) across all generation units and time periods.

Pool vs. Bilateral Trading

- Pool
  - Economically unusual because administered centrally
  - Price not transparent
  - Facilitates security function
  - Makes possible central optimization
  - Historical origins in electricity industry
  - Mostly US
  - Except Pacific Northwest
- Bilateral
  - Economically purer
  - Price set by the parties
  - Hard bargaining possible
  - Generator assume scheduling risk
  - Must be coordinated with security function
  - Mostly Europe

Spot Markets

https://www.thejournal.ie/electricity-ireland-2132930-May2015/

Why we need spot markets?

The **spot market** or **cash market** is a public financial **market** in which financial instruments or commodities are traded for immediate delivery.

investopedia.com/

- Demand side:
  - Errors in load forecast
- Supply side:
  - Unpredicted generator outages
- Gaps between load and generation must be filled quickly
- Depending on the jurisdiction, the spot market is called “real-time market,” “balancing market,” “intraday market,” or “balancing mechanism” .
- The trading period ranges from 1 h to 5 min.

“Managed” spot market?

- Balance load and generation
- Run by the system operator
- Maintains the security of the system
- Must operate on a sound economic basis
  - Use competitive bids for generation adjustments
  - Determine a cost-reflective spot price
- Not a true market because price is not set through interactions of buyers and sellers
- Indispensable for treating electricity as a commodity

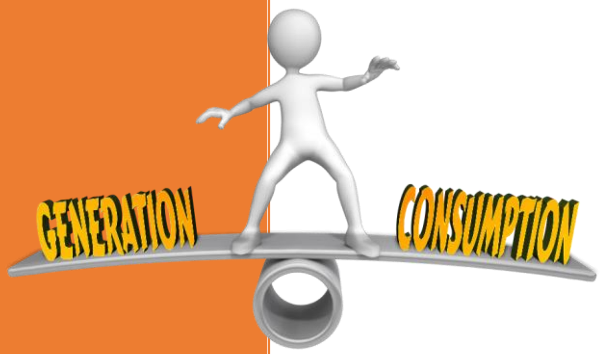
The functionality of a generic spot market

Obtaining Balancing Resources

- There are always small imbalances .
- Imbalances:
  - forecasting errors by the participants:
    - relatively small
    - evolve gradually.
    - have a known probability distribution.
    - Many generating units can adjust their output at a rate that is sufficient to cope with the first type of imbalances.
  - generator failures:
    - often large, unpredictable, and sudden.
    - requires resources that can increase their output rapidly and sustain this increased output for a sufficiently long time.
- The system operator must obtain adjustments in generation or load.
- These adjustments translate into purchases and sales of electrical energy that can be settled at a spot price reflecting the market's willingness to provide or absorb extra energy.
- Any party that is willing to adjust its production or consumption should be allowed to do so on a competitive basis.

The Functionality of a Generic Spot Market

Obtaining Balancing Resources



- What are the balancing resources?
  - Increase or decrease in generation
    - Can be offered by generators.
    - Generating units that are not fully loaded can submit bids to increase their output.
    - A generating unit can also offer to pay to reduce its output.
      - A generating unit that submits such an offer is in effect trying to replace its own generation by cheaper power purchased on the spot market.
  - Increase or decrease in demand
    - A consumer could offer to reduce its consumption:
      - If the price it would receive for this reduction is greater than the value it places on consuming electricity during that period.
    - Can be offered by consumers
    - Can be implemented immediately.

The Functionality of a Generic Spot Market

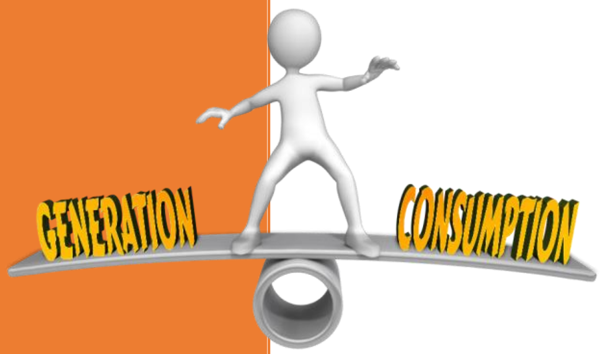
Obtaining Balancing Resources

- The units of energy that are traded to keep the system in balance do not have the same value.
- A megawatt obtained by increasing slightly the output of a large thermal plant costs considerably less than a megawatt of load that must be shed to prevent the system from collapsing.
- To be able to keep the system in balance at minimum cost, the system operator should have access to a variety of balancing resources.
- When producers and consumers bid to supply balancing resources, their bids must specify not only a quantity and a price but also what constraints limit their ability to deliver a change in power injection.

The Functionality of a Generic Spot Market

Obtaining Balancing Resources

- Balancing resources can be offered either for:
  - a specific period
    - Offered by market participants on the spot market after the forward market for that period has closed.
  - On a long-term basis
    - To reduce the risk of not having enough balancing resources or of having to pay a very high price for these resources.
    - The supplier is paid a fixed price (often called the option fee) to keep available some generation capacity.
    - The contract also specifies the price or exercise fee to be paid for each megawatt-hour produced using this capacity.
    - The system operator would call upon this contract only if the exercise fee is lower than what it would have to pay for a similar balancing resource offered on a short-term basis.

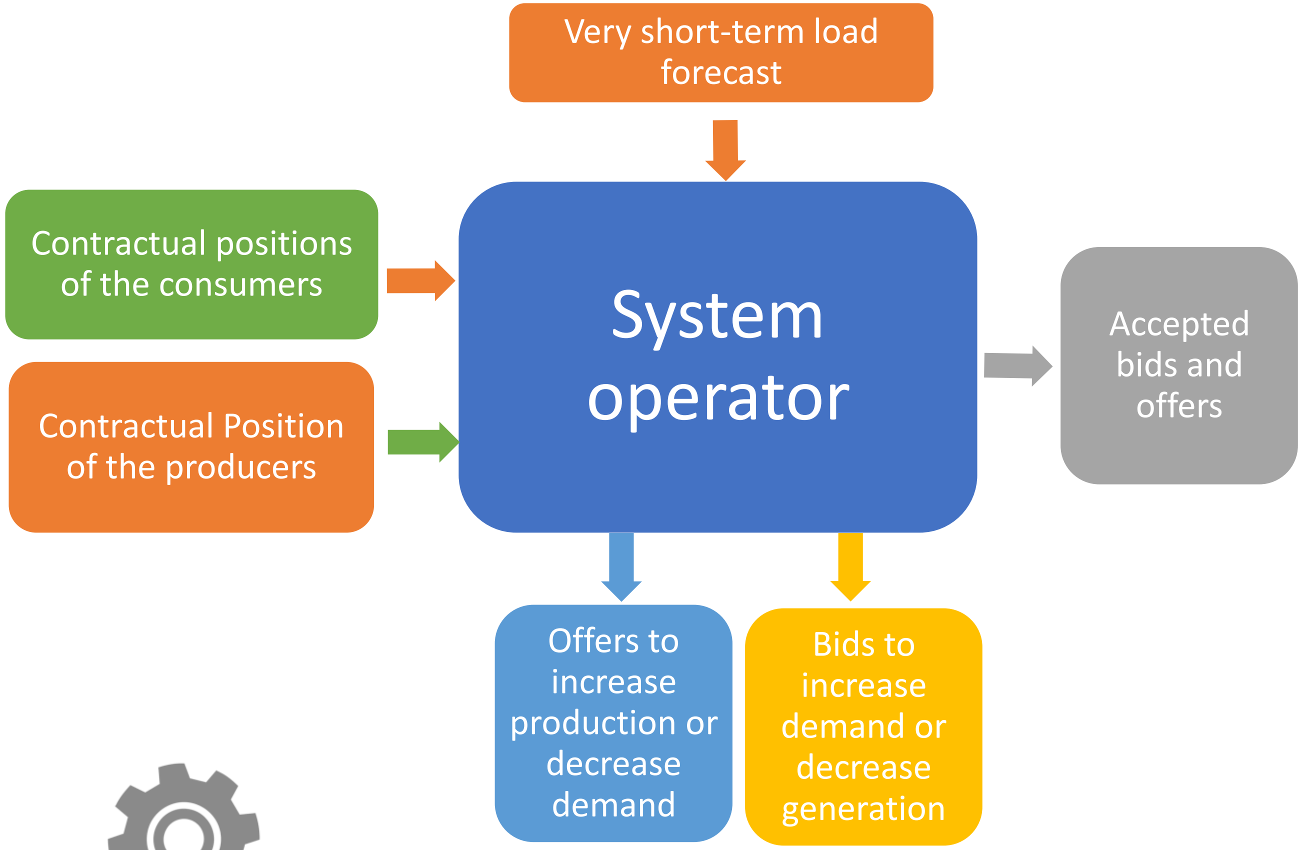


The Functionality of a Generic Spot Market

Gate Closure

- Forward markets must close at some point before real time.
- How much time should elapse between this gate closure and real time?
  - System operators prefer a longer interval.
  - it gives them more time to develop their plans.
    - bring on-line a large coal-fired plant to make up a deficit in generation.
  - Generators and retailers prefer a shorter interval.
    - It reduces their exposure to risk.
    - to match their contractual position with their anticipated load or production
    - A load or wind generation forecast calculated 1h ahead of real time is usually much more accurate than a forecast calculated 4h ahead.
  - Market participants would therefore prefer to trade electronically up to the last minute.
  - traders prefer dealing on a true market that is driven solely by market forces rather than on a spot market that is heavily influenced by complex considerations about the operation of the power system.

Operation of a managed spot market for electricity



The functionality of a generic spot market

Operation of the Spot Market

- At gate closure, the producers and the consumers must inform the system operator of their contractual positions, i.e. how much power they intend to produce or consume during the upcoming trading period.
- The system operator combines that information with its own forecast of the total load to determine by how much the system is likely to be in imbalance.
- If generation exceeds the load, the system is said to be long. If the opposite holds, the system is short. The system operator must then decide which balancing bids and offers it will use to cover the imbalances.

Example

- When the gate closes for bilateral trading, Borduria Power from the previous example has contracted to produce a net amount of 580 MWh for the period under consideration. The company intends to produce this amount as follows:

Generating unit i	Scheduled Production (MW)
A	500
B	80
C	0

Example

- The characteristics of Borduria Power's generating units

Generating unit i	Scheduled Production (MW)	Pmin(MW)	Pmax(MW)	MC($/MWh)
A	500	100	500	10.0
B	80	50	80	13.0
C	0	0	50	17.0

Example

- Bids and offers are likely to maximize Borduria Power's profit:

Type	Identifier	Price ($/MWh)	Amount (MW)
Bid	SMB-1	17.50	50
Offer	12.50	12.50	12.50
Offer	9.50	9.5	400

Interactions Between the Spot Market and the Forward Market

- If the spot price is low, purchasers buy slightly less than they need in forward markets.
- If the spot price is high, these same purchasers will push up the price in the forward market.
- Electricity is a commodity whose spot price is highly volatile.
  - a megawatt-hour sold on the spot market is produced by a flexible plant.
  - The amount of energy is low, they need to charge higher prices to recover their costs causing sharp spikes in the prices.
  - Price spikes occur because for a short time the number of participants able to provide this energy is very small and because consumers are not able or not willing to reduce their demand at short notice.
  - Price spikes represent a risk for companies.
  - The forward prices are thus artificially inflated by the need to generate a small fraction of the total energy demand at short notice.

The Settlement Process

The settlement process

There are always inaccuracies in the completion of the forward contracts.

For other commodities, the buyer withhold part of the payment or pay additional amount of the delivered quaintly is less or more than the amount contracted.

For electricity, any differences must be settled to ensure the reliability of the system and that the demand always meet the supply.

In electricity markets, the system operator buy the decifict and sell the excess in the spot market.

The parties that are responsible for the imbalances pay the cost of these balancing activities.

The Settlement Process

Determining the net position og every market player.

Each generator must report to the settlement system the net amount of energy that it had contracted to sell for each period.

This amount is subtracted from the amount of energy that it produced.

- If the result is positive, the generator is deemed to have sold this excess energy to the system.
- If the result is negative, the generator is treated as if it had bought the difference from the system.

All large consumers and retailers must report the net amount of energy that they had contracted to buy for each period.

This amount is subtracted from the amount of energy actually consumed.

- If the sign of the result is positive , the consumer or retailer is deemed to have sold energy to the system.
- If the sign is negative, or the consumer or retailer is deemed to have bought energy from the system.

These imbalances are charged at the spot market price.

Example - Position of Borduria Power's

Borduria Power's position:

Unit	P^{sched} (MW)	P^{min} (MW)	P^{max} (MW)	MC ($/MWh)
A	500	100	500	10.0
B	80	50	80	13.0
C	0	0	50	17.0

Borduria Power's spot market bids:

Type	Unit	Price ($/MWh)	Amount (MW)
Bid (increase)	C	17.50	500
Offer(decrease)	B	12.50	80
C (decrease)	A	9.50	50

Spot market assumed imperfectly competitive
Bids/offers can be higher/lower than marginal cost

Example of settlement

- 11 June between 2:00 pm and 3:00 pm
- Spot price: 18.25 $/MWh
- Unit B of Borduria Power could produce only 10 MWh instead of 80 MWh
- Borduria Power thus had a deficit of 70 MWh for this hour
- 40 MW of Borduria Power’s spot market bid of 50 MW at 17.50 $/MWh was called by the operator

Example of settlement- Borduria Power trading account

Market	Type	Amount [MWh]	Price [$/MWh]	Revenues [$]	Expenses [$]
Futures and Forwards	Sale	200	12.50	2,500.00	
	Sale	250	12.80	3,200.00	
	Sale	100	14.00	1,400.00	
	Purchase	-30	13.50		405.00
	Sale	50	13.80	690.00	
Power Exchange	Sale	20	13.50	270.00	
	Sale	30	13.30	399.00	
	Sale	10	13.25	132.50	
	Purchase	-20	14.40		288.00
	Purchase	-20	14.30		286.00
	Purchase	-10	14.10		141.00
Spot Market	Sale	40	18.25	730.00	
	Imbalance	-70	18.25		1,277.50
Production Cost	Unit A	-500	10.00		5,000.00
	Unit B	-10	13.00		130.00
	Unit C	-40	17.00		680.00
Total		0		9,321.50	8,207.50

In short

- Pool trading:
  - Market operator collects from consumers
  - Market operator pays producers
  - All energy traded at the pool price
- Bilateral trading:
  - Bilateral trades settled directly by the parties as if they had been performed exactly
- Managed spot market:
  - Produced more or consumed less → receive spot price
  - Produced less or consumed more → pay spot price


QUESTIONS