The U.S. Electricity Industry in the 21st Century: Challenges and Opportunities

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PNNL Control of Complex Systems (CCSI) workshop at ACC

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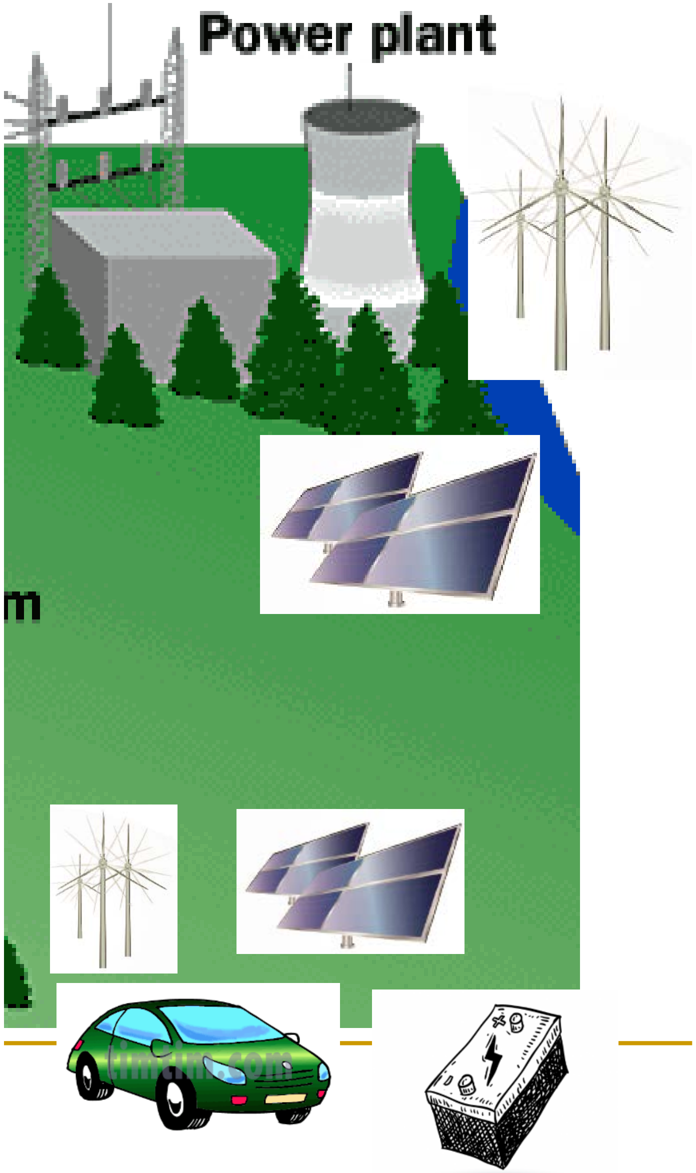

Power plant

Complexity of electricity system

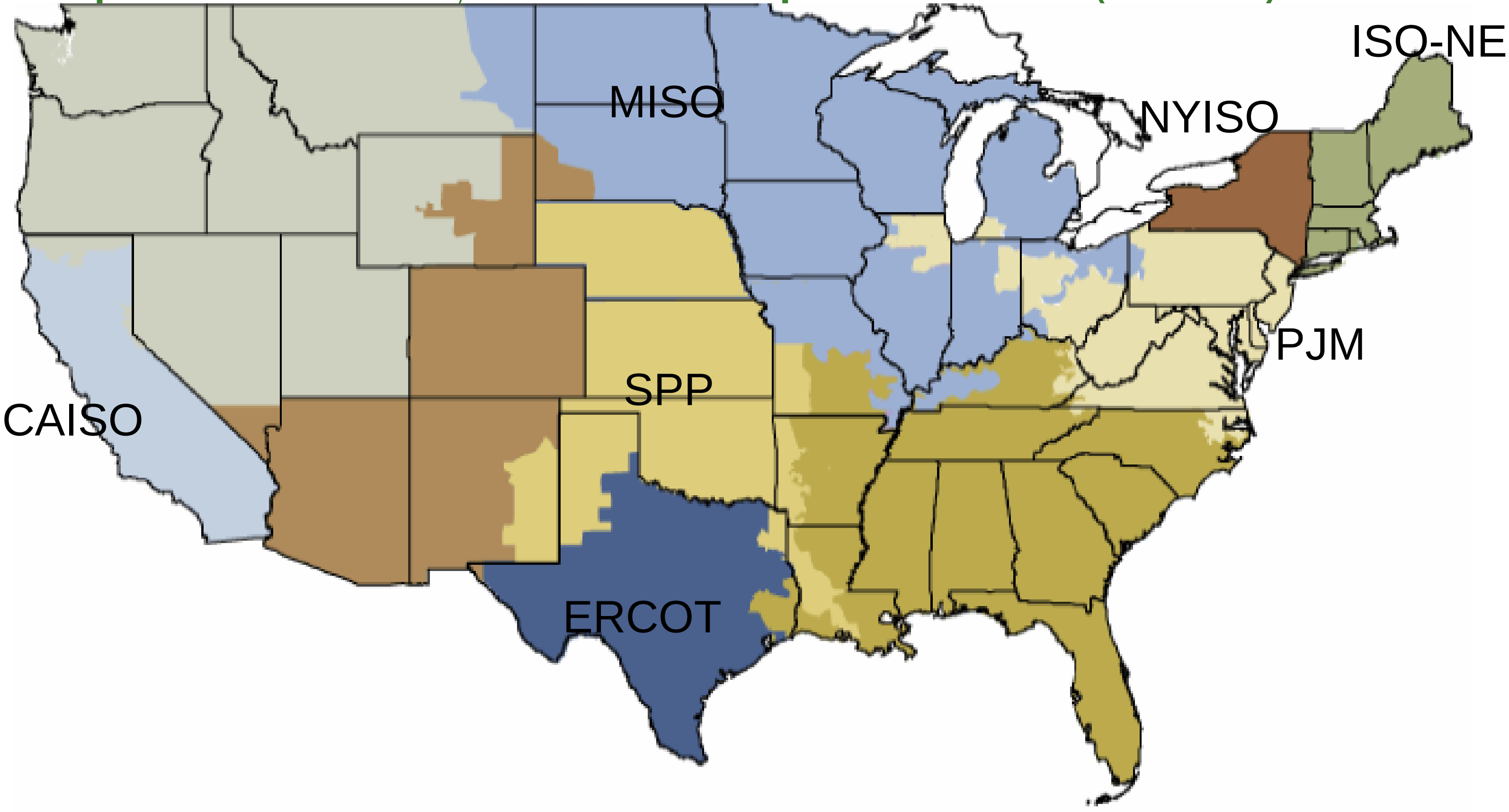
- Forecast demand is never exactly equal to real demand
- Short-term demand is almost inelastic
- Supply of some generation resources is both variable, and uncertain
- Electricity storage is still expensive (and not readily available)

Supply and demand must be balanced at all times, or system collapses

Planning this balance is hard for a vertically integrated utility

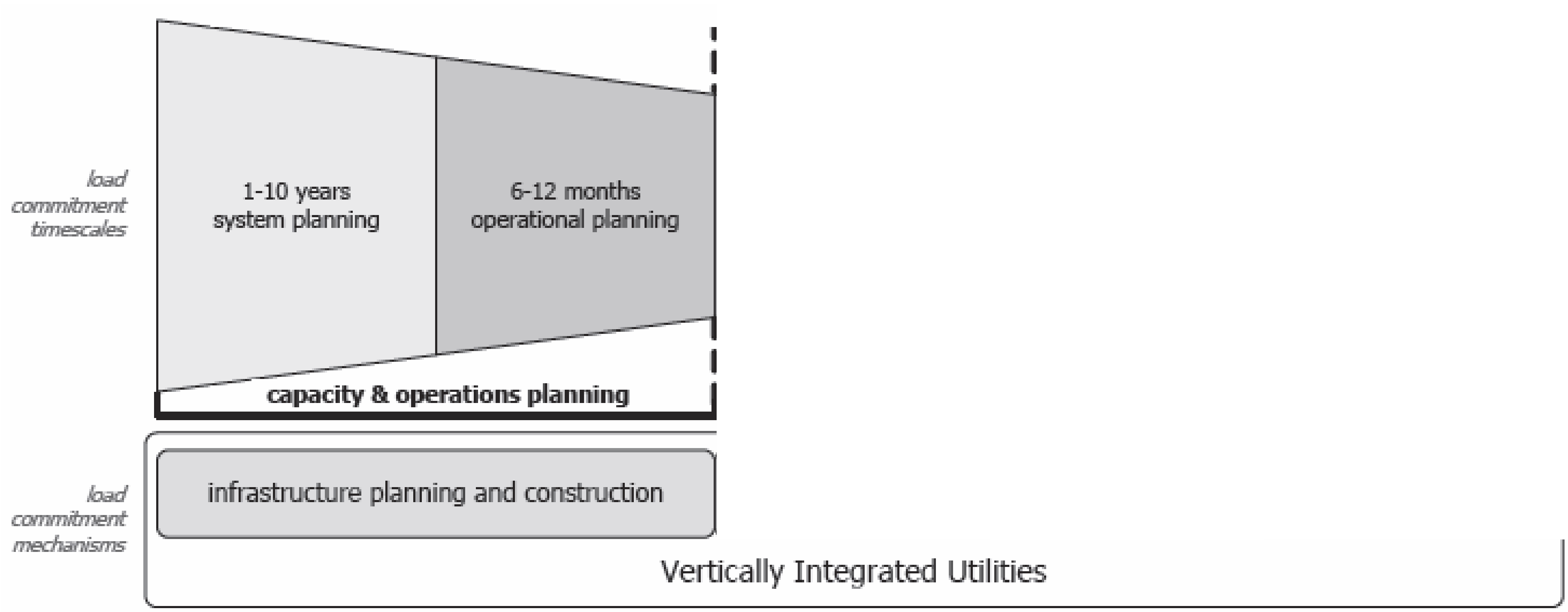
Even harder for a re-structured industry

Regional Transmission Organization (RTO) Independent Systems Operators (ISO)



http://www.ferc.gov/market-oversight/mkt-electric/overview.asp

Balancing Electricity Supply and Demand



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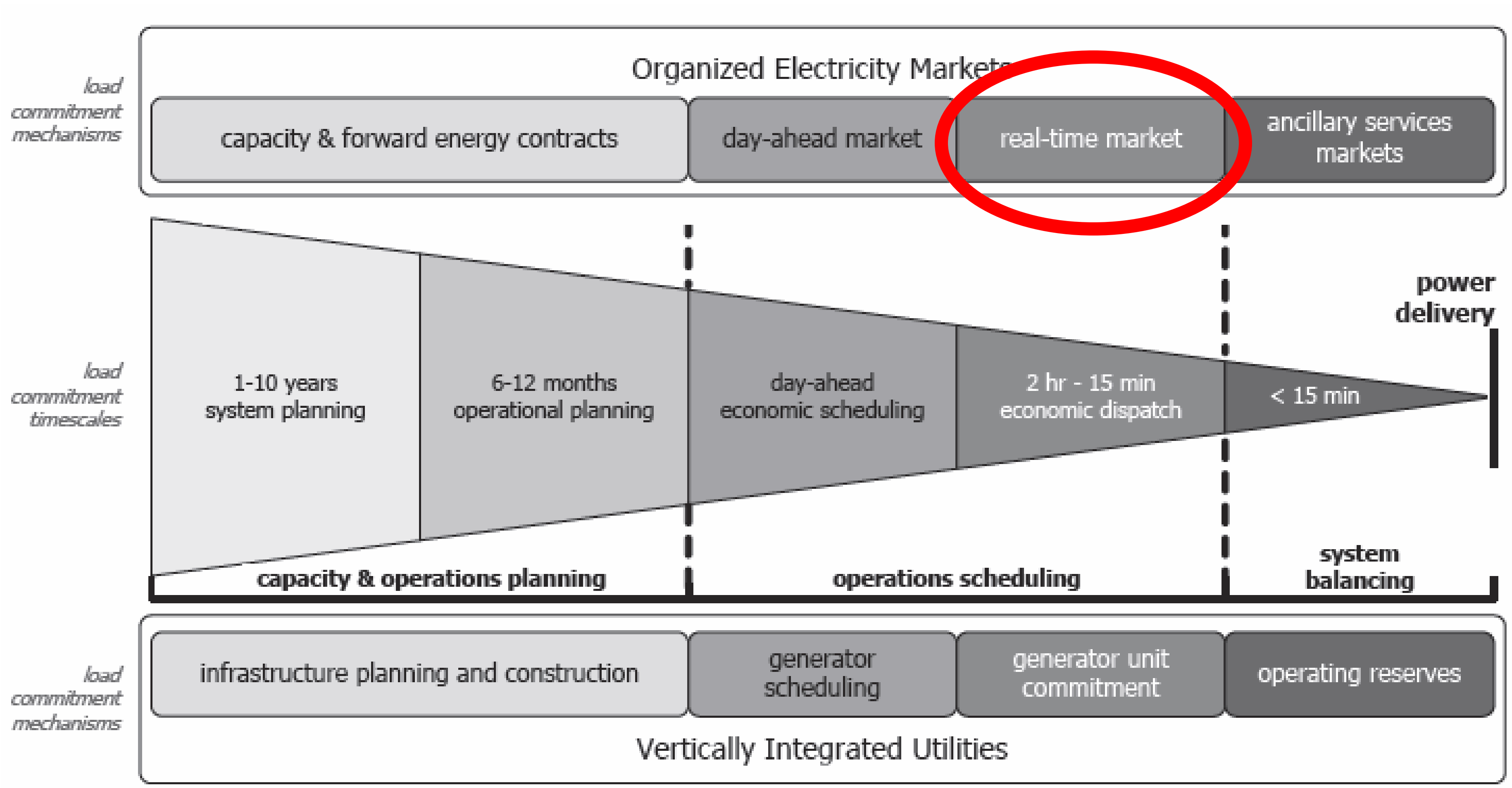


Can markets for electricity operate like any other market?

- Can markets reach an equilibrium in which supply is equal to demand ?

- No!!

Market needs to be managed

- A large proportion of the electricity can be traded in an unmanaged open market,

but

a managed spot market is needed to maintain reliability of the power system

Spot Market

- Spot electricity market:

market for electricity that will be generated and consumed at or very close to the time of trade

- This is in contrast with the Forward Market or Future Market
  - Forward: Physical delivery
  - Future: Only financial settlement

A **managed** spot market is a requirement of re-structuring

- Ignoring transmission constraints, once the spot market is in place, electricity can be traded like any other commodity
  - What is the commodity traded?
    - MW to be generated and consumed over a specified period of time

Example : Assume the following bids to sell and a demand forecast of 410 MW (for hour 13-14 tomorrow)

Bids to sell	Company	Quantity (MW)	Price ($/MWh)
	A	85	10
	B	285	6
	C	140	7.5
	D	90	14

Find the dispatch and market clearing price if market clears as a uniform price auction.

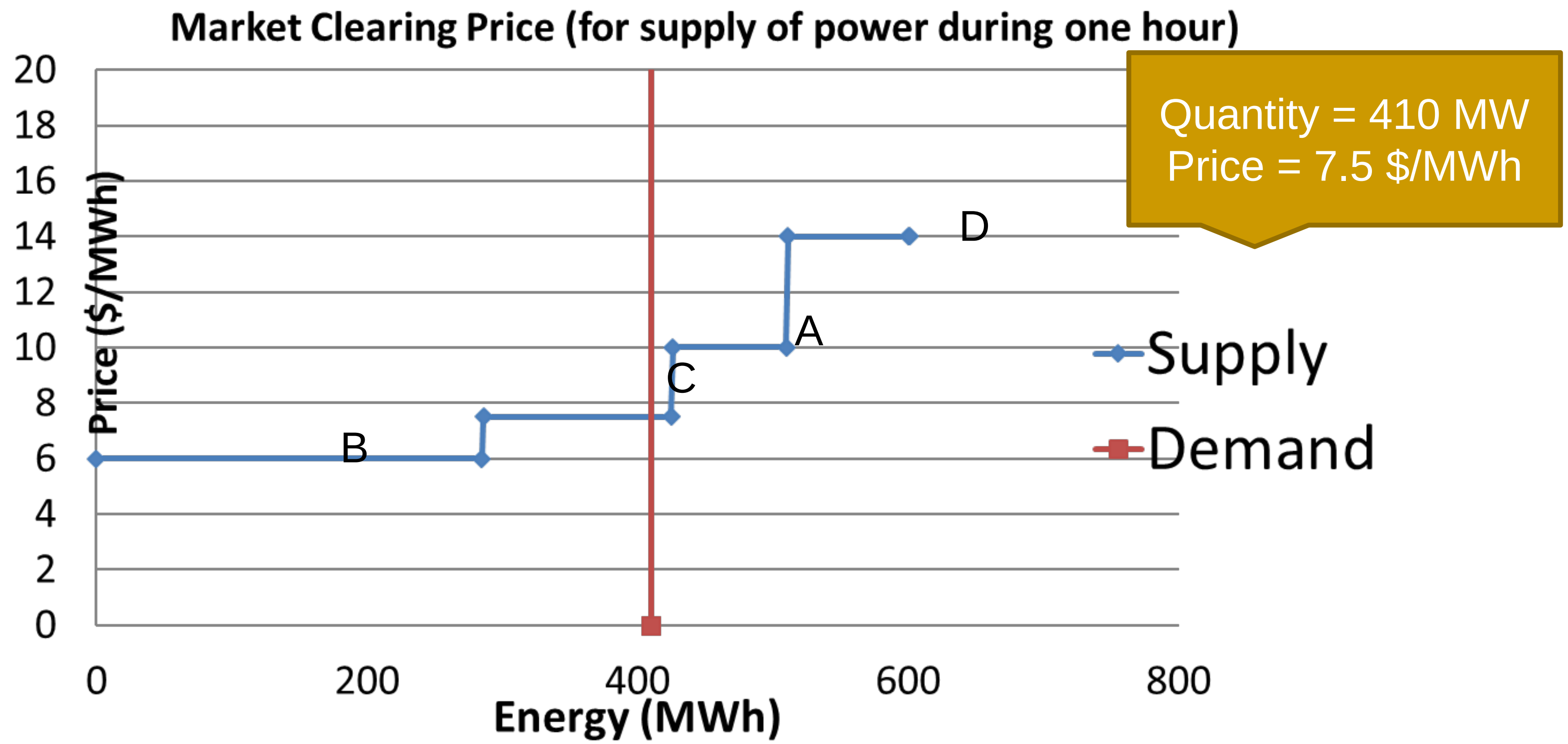
Clearing the market

1. Bids to sell: stack in ascending order by price

Bids to sell	Company	Quantity (MW)	Price ($/MWh)	Cumulative bids (MW)
	B	285	6	285
	C	140	7.5	425
	A	85	10	510
	D	90	14	600

2. Draw a supply curve
3. Draw demand curve
4. Find price and dispatch

Uniform price auction



"We must understand how the economics affect the physics and how the physics constrain the economics"

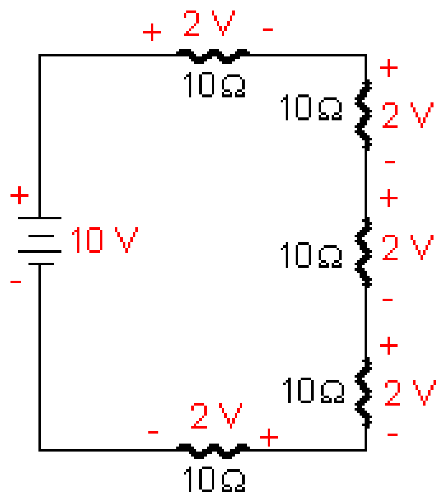
Kisrchen & Strbac

Power flow obeys kirckoff's laws, not economics!!

Kirchhoff Voltage Law (KVL)

- Sum of voltage drops around any closed loop in a circuit must equal the applied voltages

E.g. The sum of voltage drops across all the branches of any loop must be equal to zero



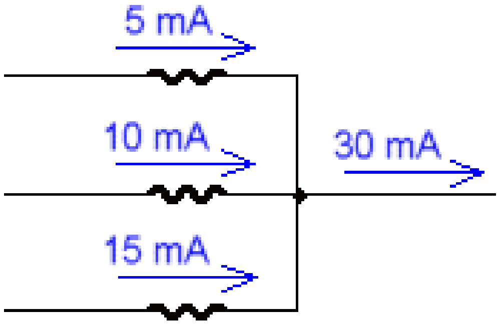
Analogy:
Closed electric loop=water fountain
Battery = water pump
rise in voltage = rise elevation

Or

- The voltage drops across parallel paths must be equal

Kirchhoff Current Law (KCL)

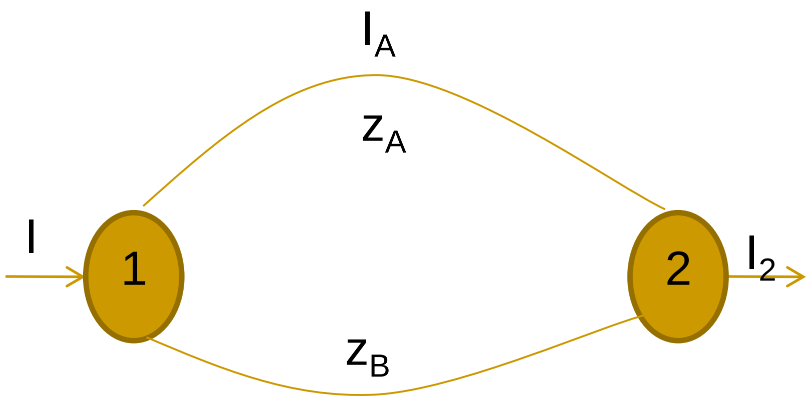
- The sum of all the currents entering a node must be equal to the sum of all the currents leaving this node
- Active and reactive power must be in balance at each node:
  - Generation + Imports – Exports – Consumption = 0



Example 1: Find current flow across each branch

1. KCL→ Sum of all currents entering a node = the currents exiting the node:

$$I = I_A + I_B$$



2. Ohm's law for AC systems

$$V_m = I_m Z$$

3.KVL→ Voltage drops across parallel paths are equal:

$$V_{12} = I_A Z_A = I_B Z_B$$

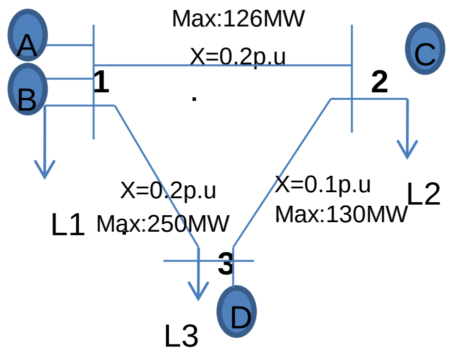
Substituting 1 into 3 we find

$$I_B = I \frac{Z_A}{Z_A + Z_B}$$

$$I_A = I \frac{Z_B}{Z_A + Z_B}$$

Power flow is equal to injected power times the reactance of the complementary path divided by the total reactance of all paths

Now consider the grid



Generator	Marginal Cost ($/MWh)	Maximum Generating Capacity (MW)
A	7.5	140
B	6	285
C	14	90
D	10	85

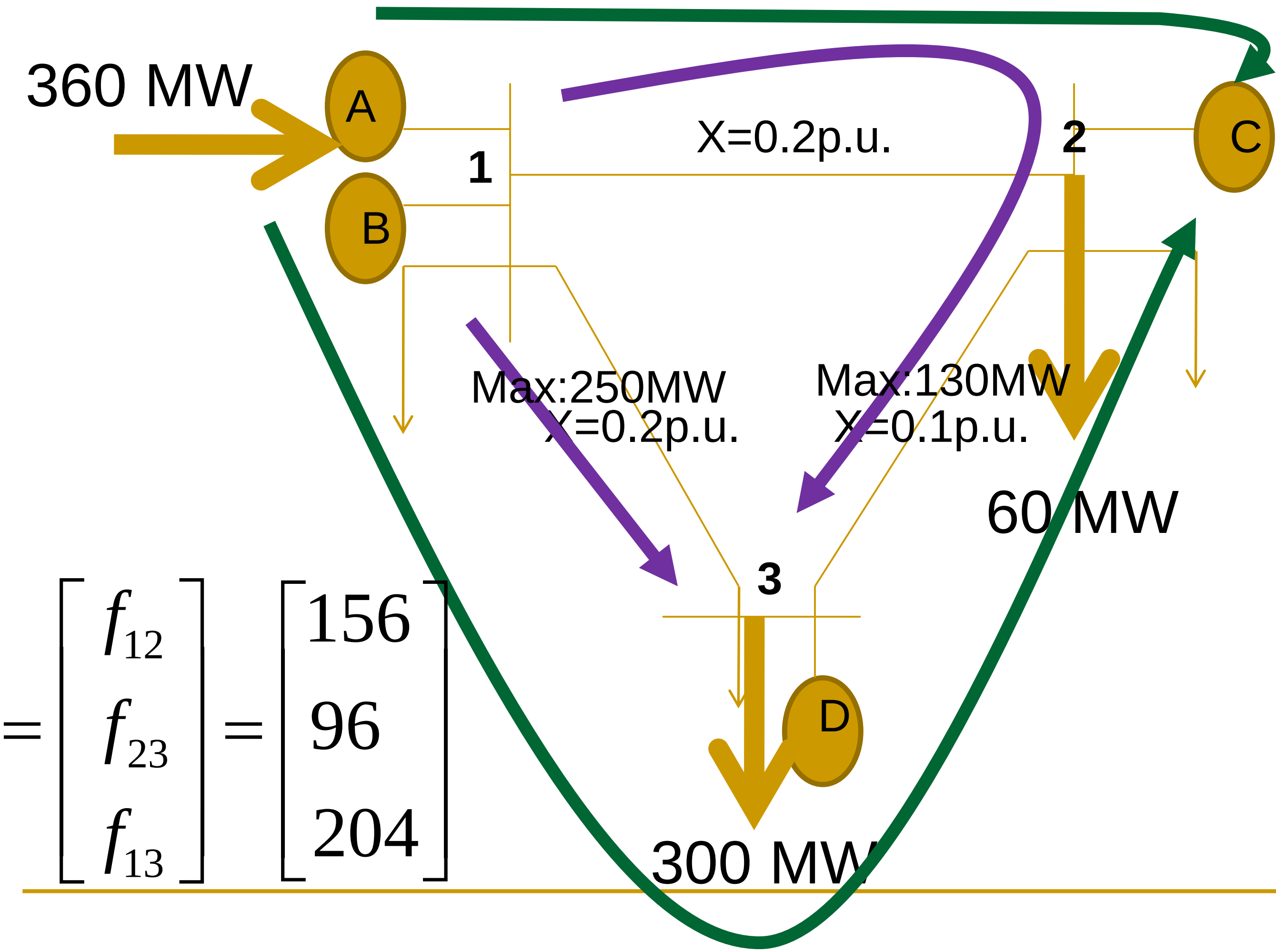
Unconstrained dispatch:
-Generate 285MW from B
-Generate 125MW from A

Price: $7.5/MWh at all nodes

Feasible? We need to find flows

Assume:
L1 = 50MW
L2 =60MW
L3 = 300MW
a) What is the unconstrained dispatch? What is the price if? Is it feasible?
b) What is the security constrained economic dispatch? What is the price?

Example 4: find Power Flow corresponding to unconstrained dispatch



$$X = \begin{bmatrix} f_{12} \\ f_{23} \\ f_{13} \end{bmatrix} = \begin{bmatrix} 156 \\ 96 \\ 204 \end{bmatrix}$$

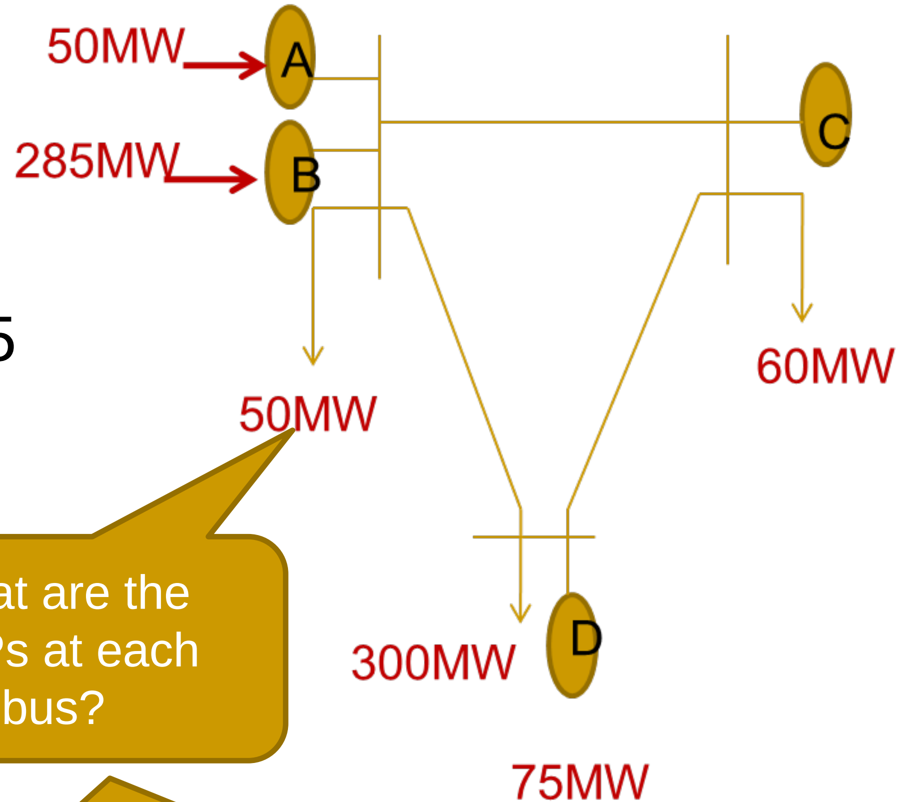
Locational Marginal Price (LMP)

- LMP = the minimum cost of supplying an additional MW of electricity at that node
- Loads pay the LMP at their node of withdrawal
- Generators are paid the LMP at their node of injection
- What happens to the difference ?

Security constrained economic dispatch:

- Injection at node 1: 285
- Withdrawal at node 2: 60
- Withdrawal at node 3: 225

- Generation B: 285
- Generation A: 50
- Generation C: 0
- Generation D: 75



What are the LMPs at each bus?

They are no longer 7.5$/MWh at each node because there are transmission constraints

Need to learn definition of **Marginal Generator**

Definition: Marginal generator

Characteristics

1. A partially loaded generator

2. Could vary output to make feasible supply of the next MW of load demanded in the system
   - Increase output
   - Or decrease output to alleviate transmission congestion

- How many marginal generators ?
  - If m binding constraints then m+1 marginal generators

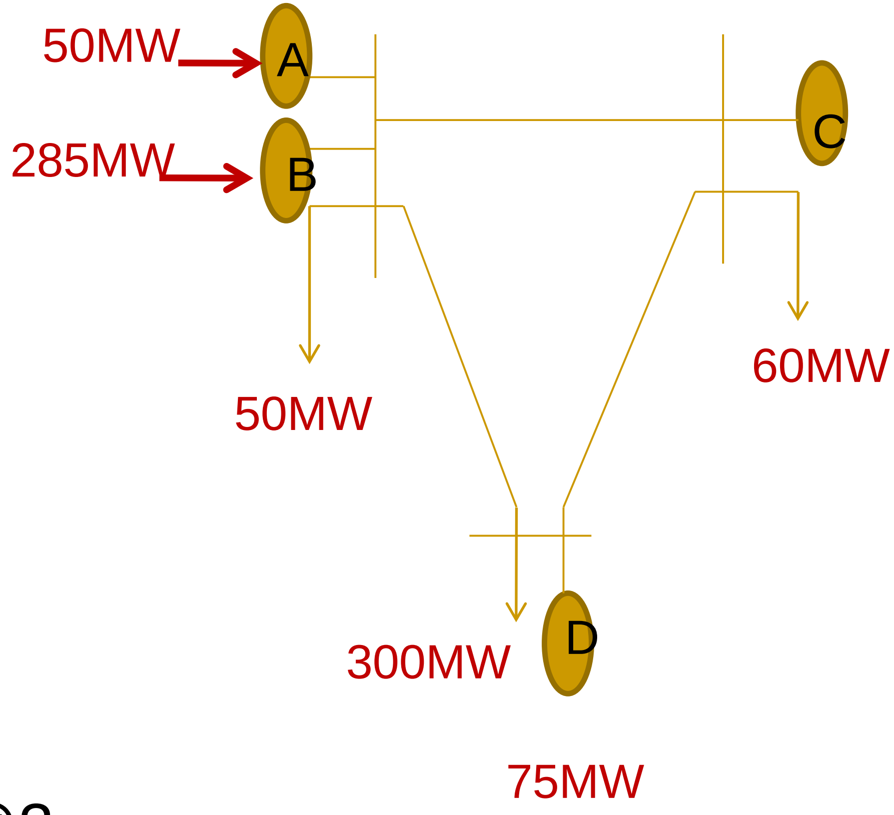
Calculating LMP

- Nodes with a marginal generator
  - LMP = Marginal cost of the marginal generator

- Nodes without a marginal generator
  - LMP = Linear combination of the LMP at other nodes
  - Since next MW at node might be produced by increasing production at some marginal generators and decreasing it at others, LMPs can be lower than the MC of the marginal generators

Calculating LMPs

- Marginal generators:
  - A, D



- LMPs=?
- LMP @ 1: 7.5 $/MWh
- LMP @ 3: 10 $/MWh
- LMP @ 2 = ?
- Linear combination of
  - LMP @ 1 and LMP @3
  - Find cheapest way to meet next MW of load at 2 without increasing flow on congested line

Solution: Calculation of LMP at Node 2:

To provide 1MW at bus 2 without violating capacity limits of the congested line 1-2 we need to:

- Increase Generation at 3 by 1.5MW,
- decrease generation at 1 by 0.5MW

LMP @ 2:

1.5*10$/MWh - 0.5*7.5$/MWh =
11.25 $/MWh

Method 2: Using optimization to find power flows

This is called:
Optimal Power Flow (OPF)

- Decision variables?
  - Generation — $G_{A,}\ G_{B,}\ G_{C,}\ G_D$
  - Power flow on each line — $f_{12,}\ f_{23,} f_{13}$
- Objective function?
  - Minimize cost: $\min \sum_{i=1}^{N_G} C_i(G_i)$
- Constraints?
  - Total Generation equals total load
  - Generation is within limits → for all generators
  - Power bus balance equation→ for all buses — $G_i - L_i - \ldots + \ldots = 0$
  - KVL around the loop — $x_{12}f_{12} + x_{23}f_{23} - x_{13}f_{13} = 0$
  - Flows on lines do not exceed capacity →for each line

Calculation of LMPs accounting for thermal losses

- Why should losses be considered?
  - Losses increase with
    - Longer lines
    - Lower voltages
    - Higher current (higher load)
  - A *security constrained economic dispatch* that does not consider losses is less than optimal

PJM implemented *marginal losses LMP pricing* in 2007

LMP = generation marginal cost + transmission congestion cost + marginal losses cost

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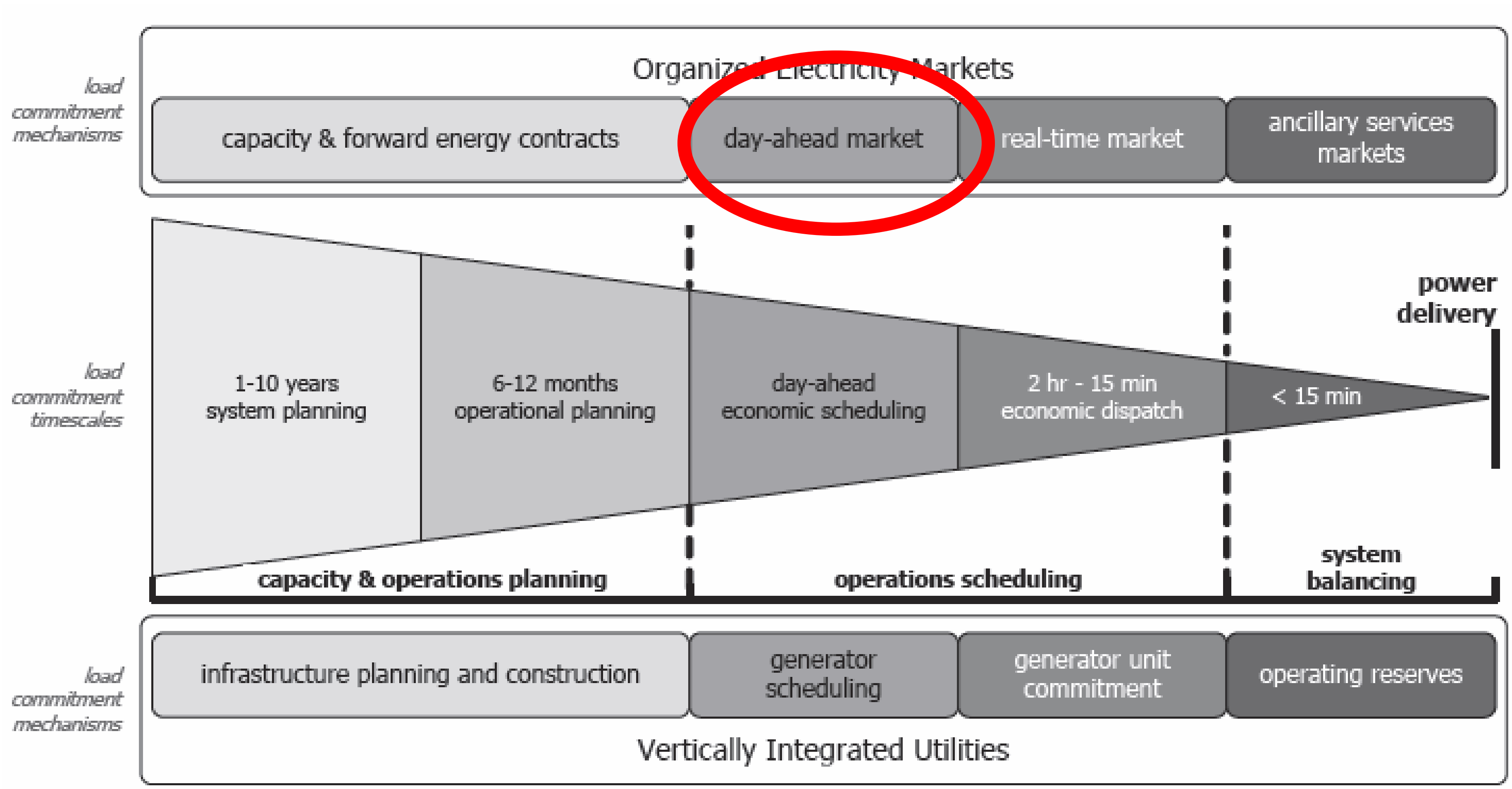
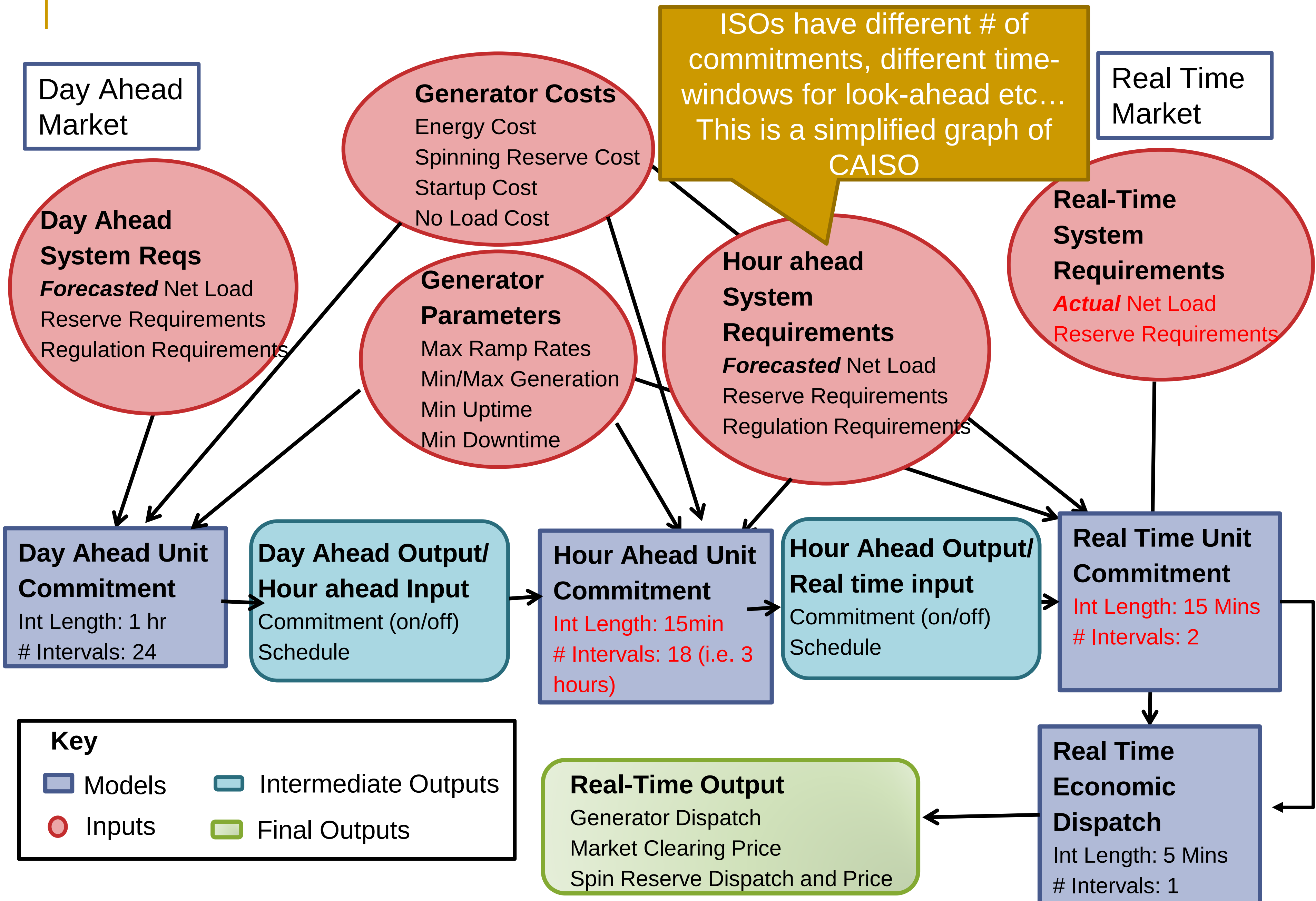


Market Clearing: Unit Commitment/Economic Dispatch Model



Market Clearing – Day Ahead Unit Commitment

Planning Period: 24 hours

Decision variables:

- Planned Hourly Generator Schedules for each hour of the planning period:
  - Commitment (on/off)
  - Energy Produced
  - Spinning Reserves Provided

Minimize:

Energy Costs + Spinning Reserve Costs + Startup Costs + Fixed Costs + OverGenerationPenalty + UnderGeneration Penalty + Scarcity of Reserves Penalty

Subject to:

- DispatchableGen + Stochastic(wind and solar)Gen +UnderGen - OverGen-= Forecasted Load
- Reserves Available >= Reserves Required
- Generator constraints
  - Ramp rates
  - Min up/down time
  - Min/Max Generation

Market Clearing – Day Ahead Economic Dispatch

Planning Period: 24 hours
Assume units are on or off as prescribed by the Unit Commitment
Decision variables:

- Planned Hourly Generator Schedules for each hour of the planning period:
  - Energy Produced
  - Spinning Reserves Provided

Minimize:

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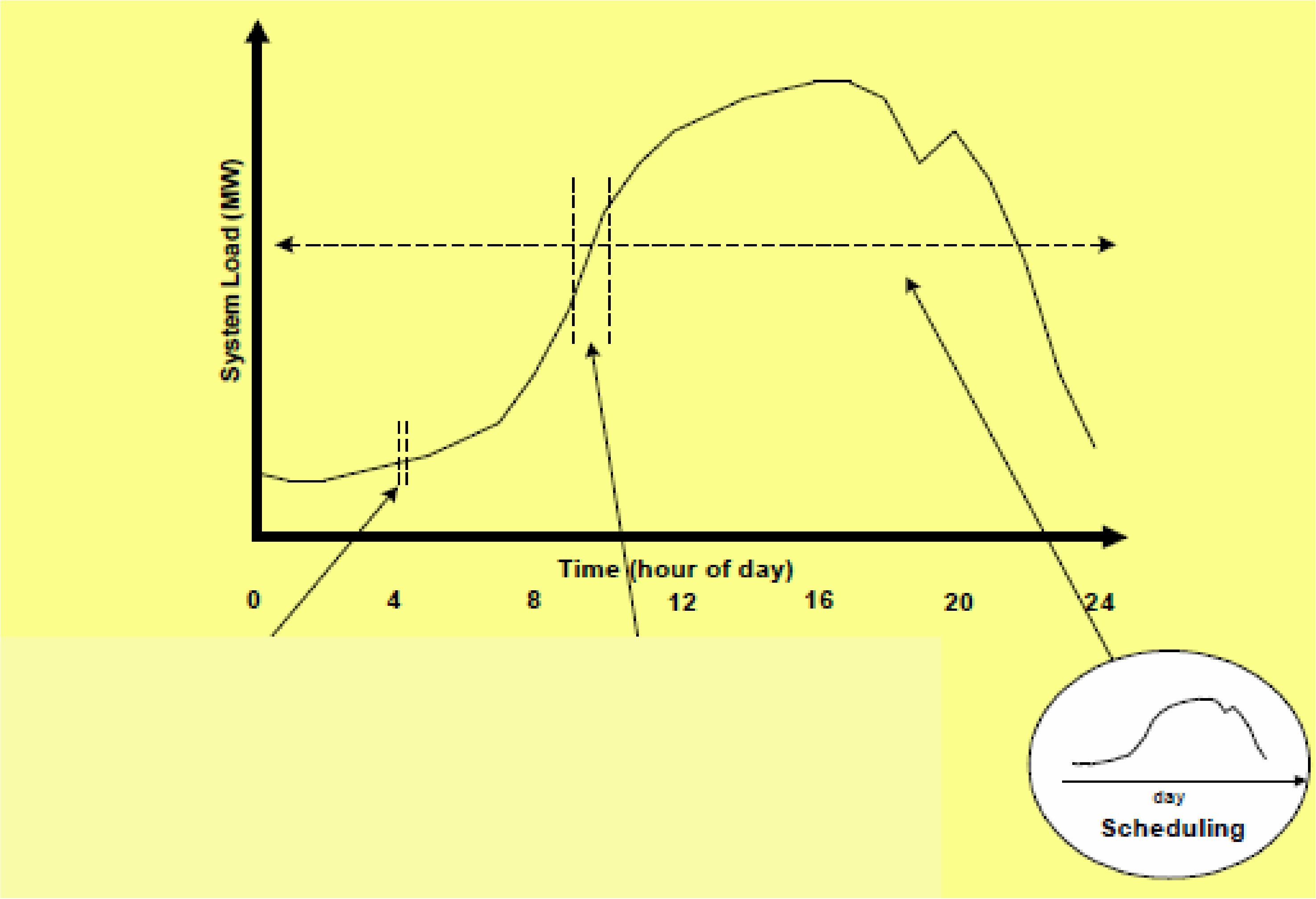
There is a power balance constraint for each node

Shadow price of each is LMP

Balancing Electricity Supply and Demand



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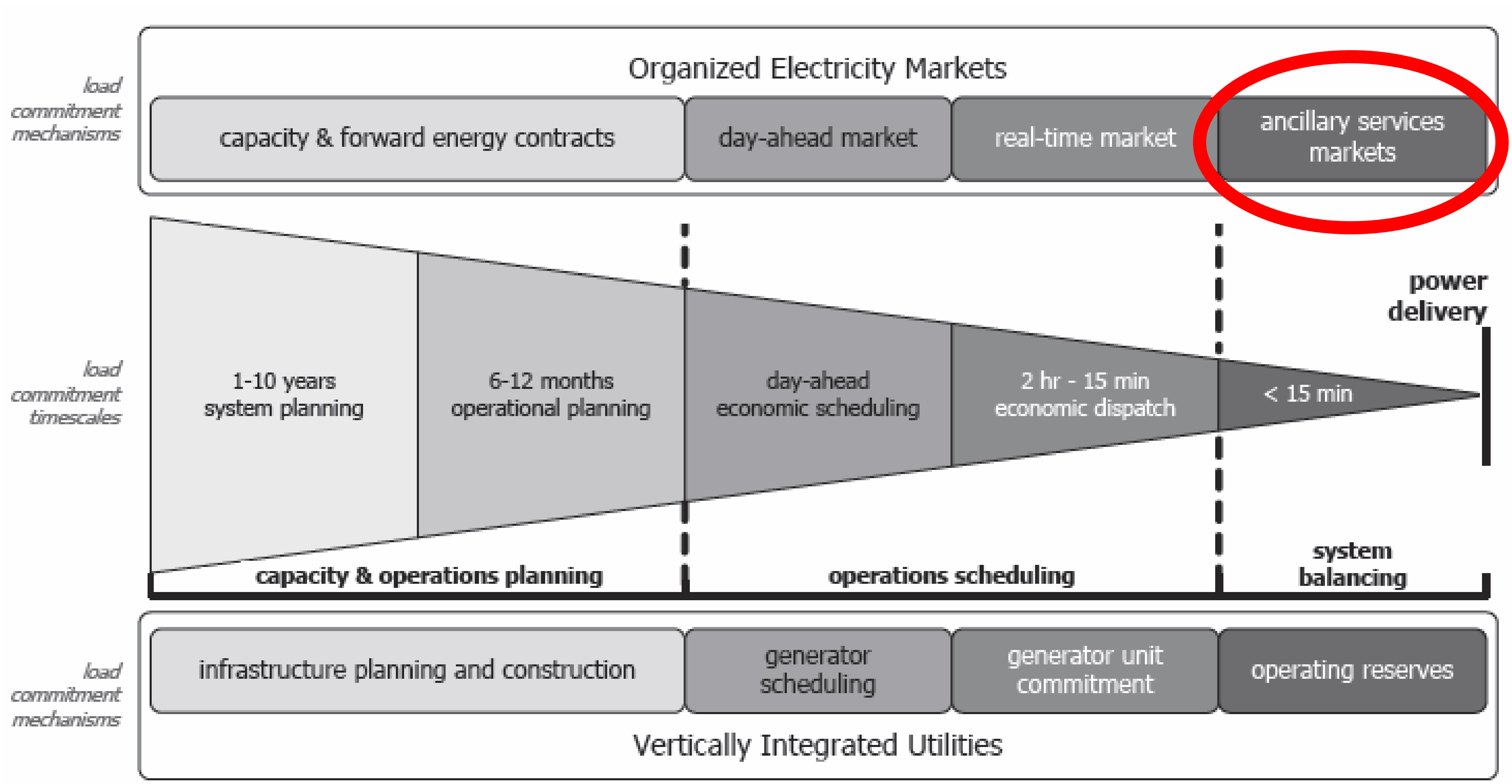


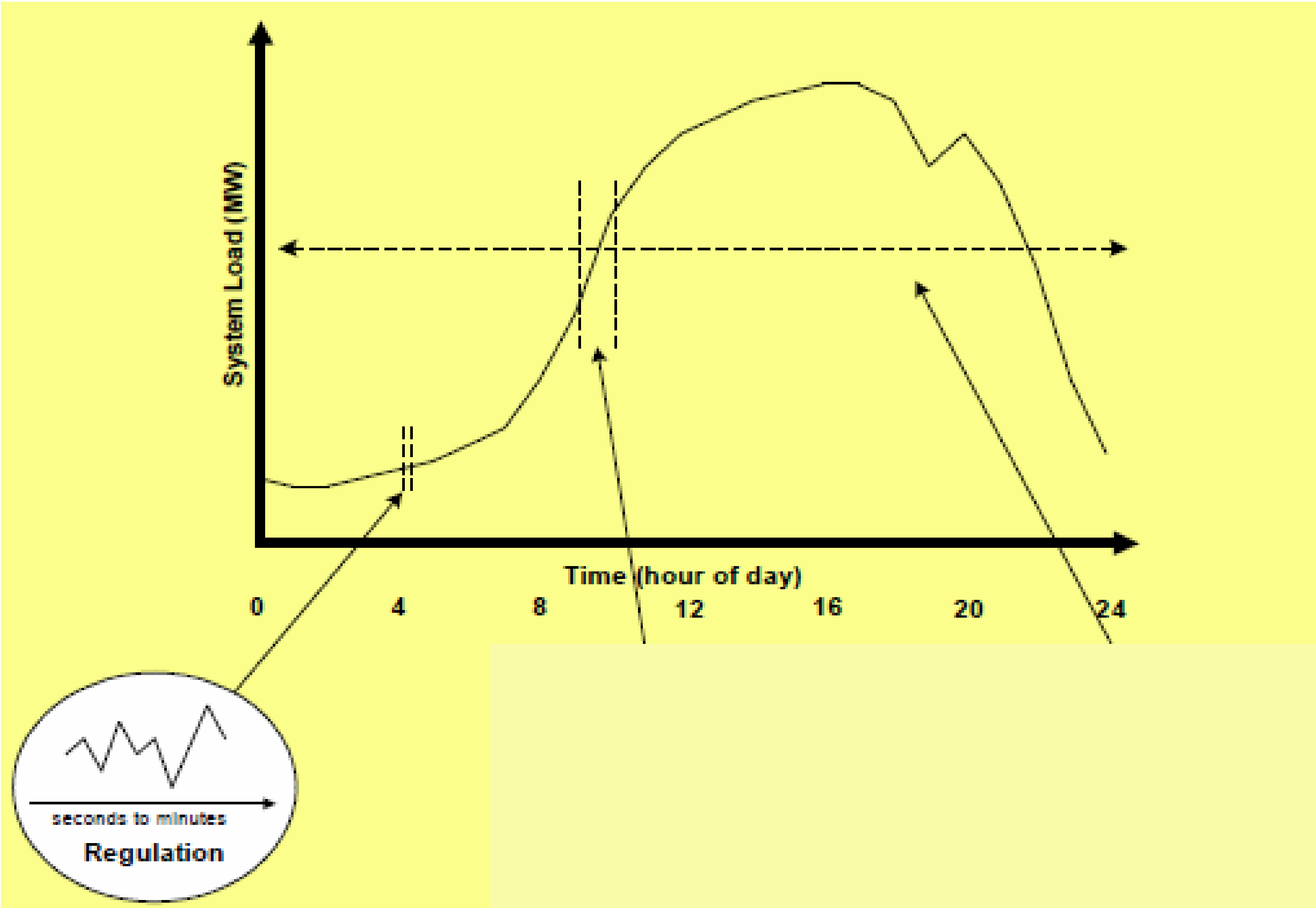
Ancillary services

- Preventive services
  - Frequency Regulation
  - Load following
- Reserve services
- Emergency
  - Black start-capability

Regulation service

- Handles:
  - Sudden fluctuations in the load
  - Small unintended variations in generation
- Keeps frequency close to normal
- Provided by units that have an AGC

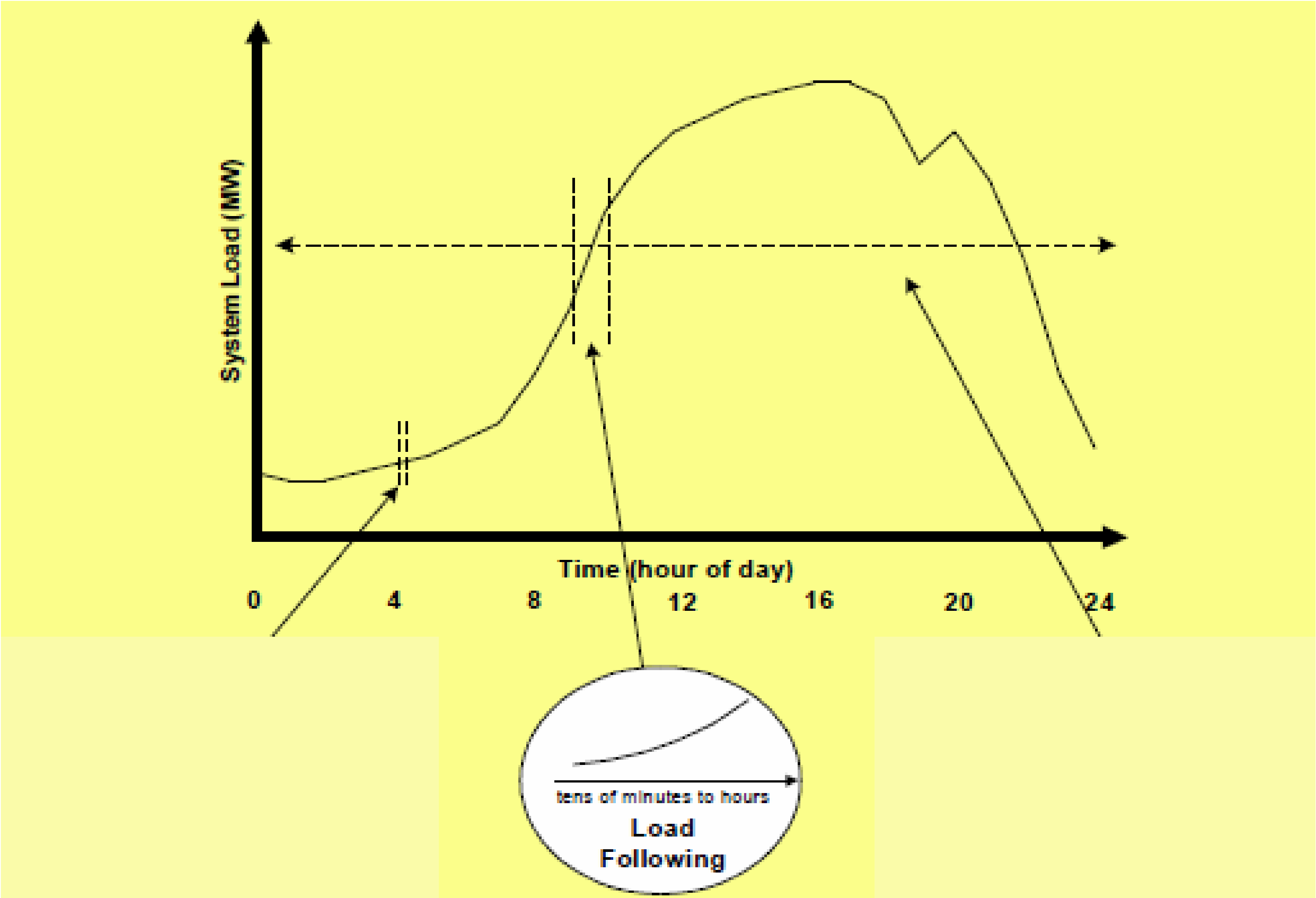
Balancing Electricity Supply and Demand



Load following service

- Handles
  - Slower fluctuations in load
  - Intra period load fluctuations (that are usually neglected by the energy market)
- Provided by generating units (or storage facilities) with fast ramp-rates
  - Spinning reserves
  - Supplemental reserves

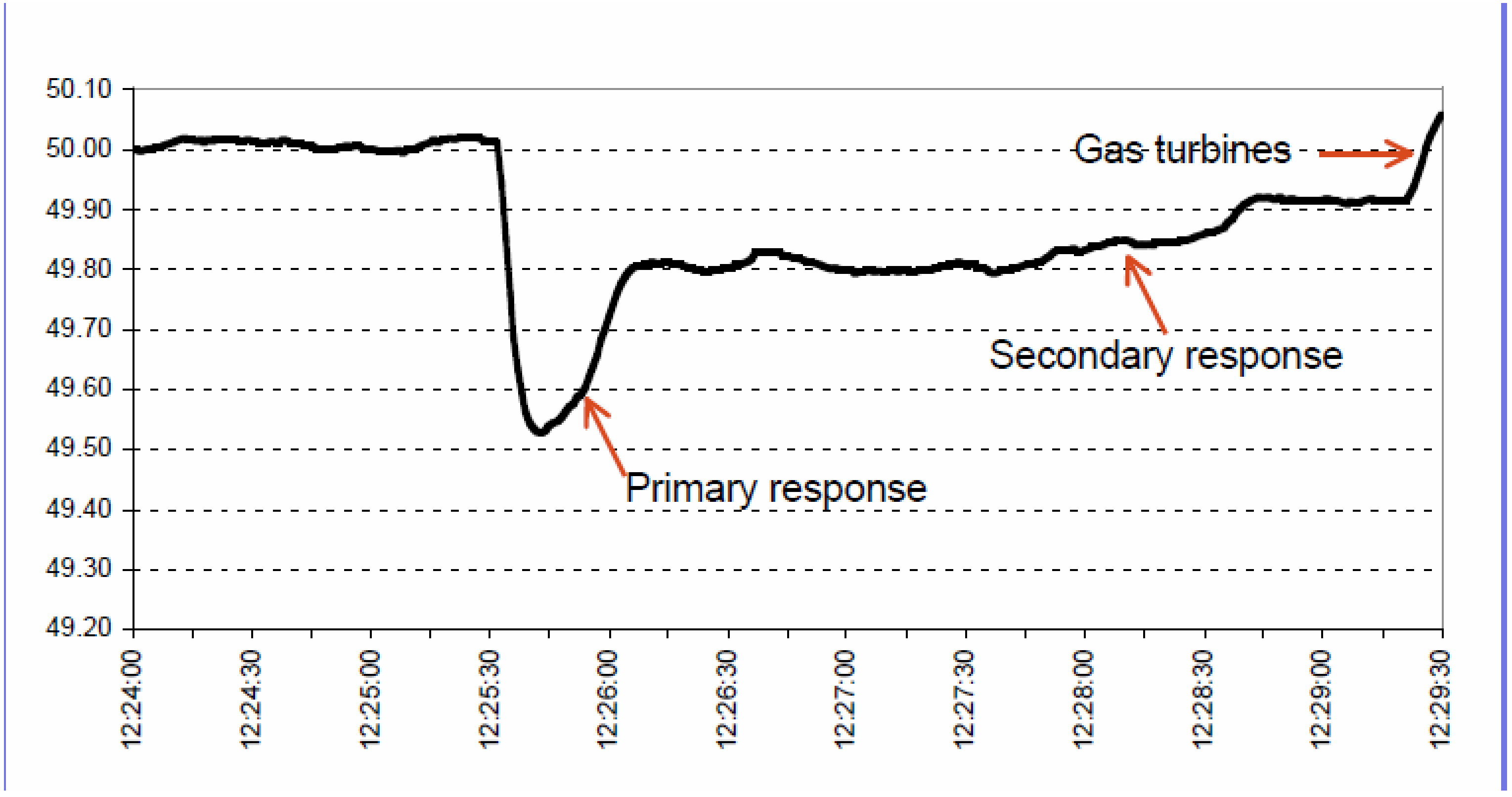
Balancing Electricity Supply and Demand



Reserve services

- Handle
  - Large and unpredictable generation deficits (generators and transmission outages)
- Types of reserves
  - Spinning reserves
    - Primary: Available withing10secs and sustainable for 20secs
    - Secondary: Available within 30secs and sustained for 30 min
  - Supplemental reserve: can replace spinning

System Response to a generator outage



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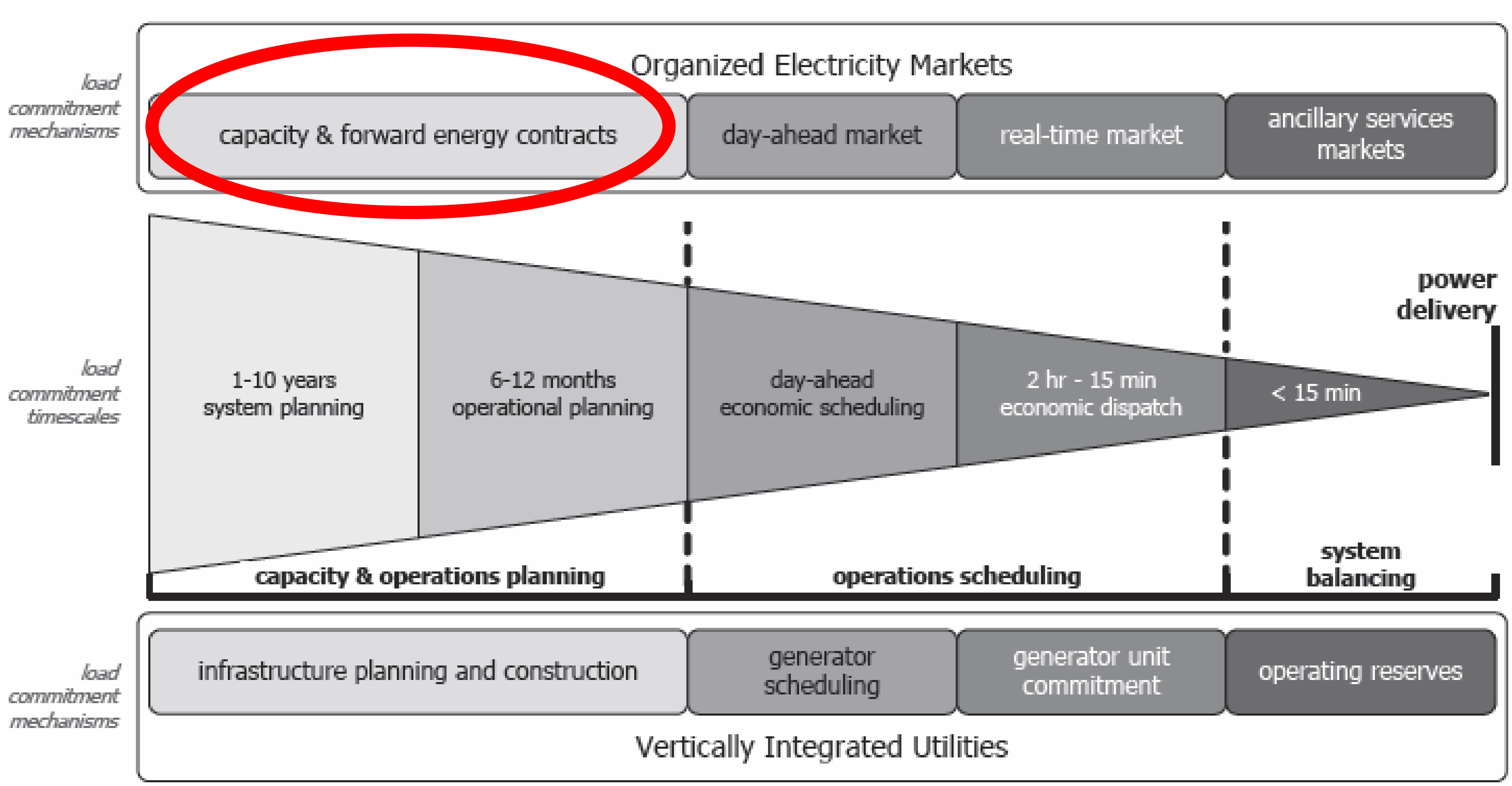
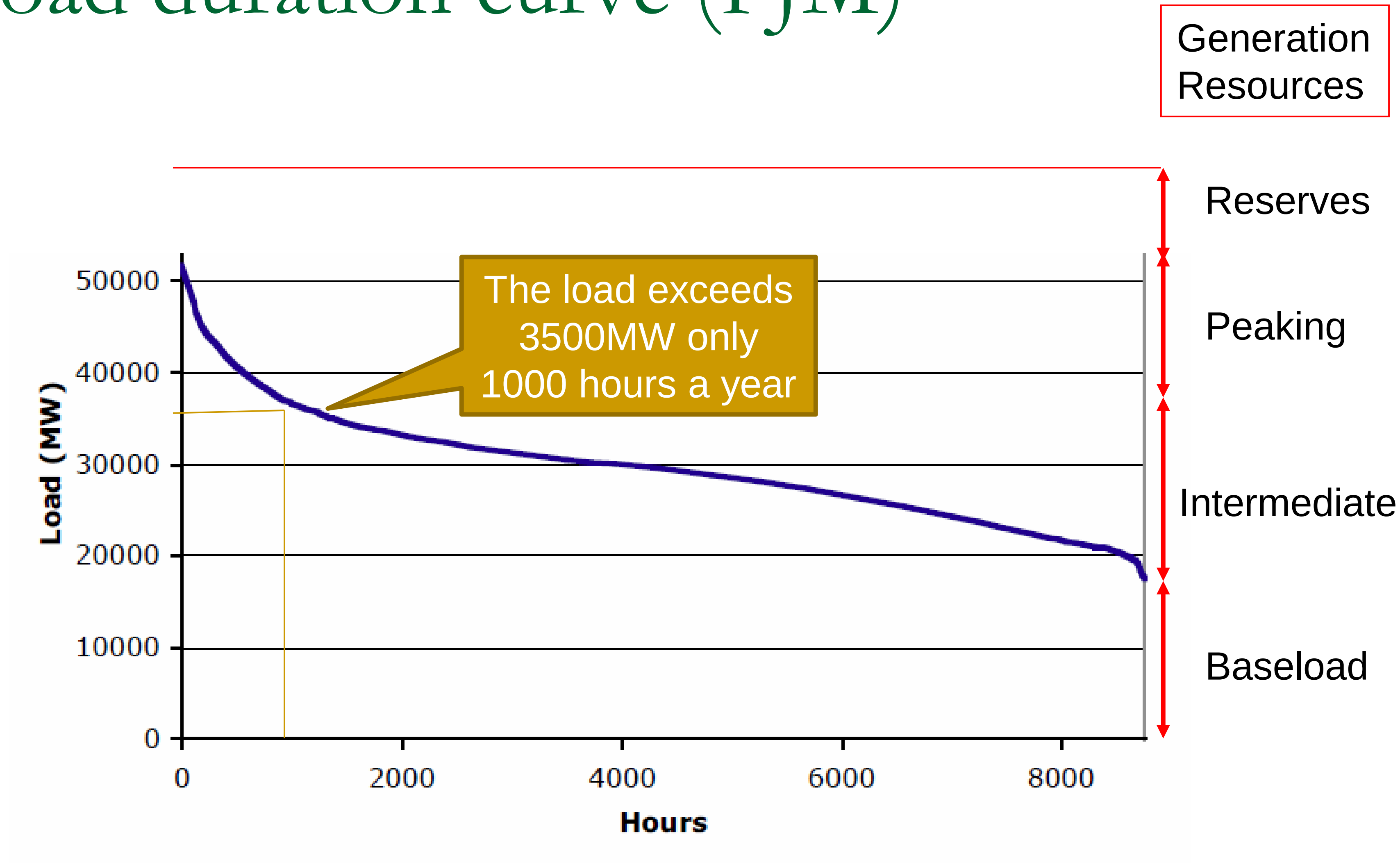
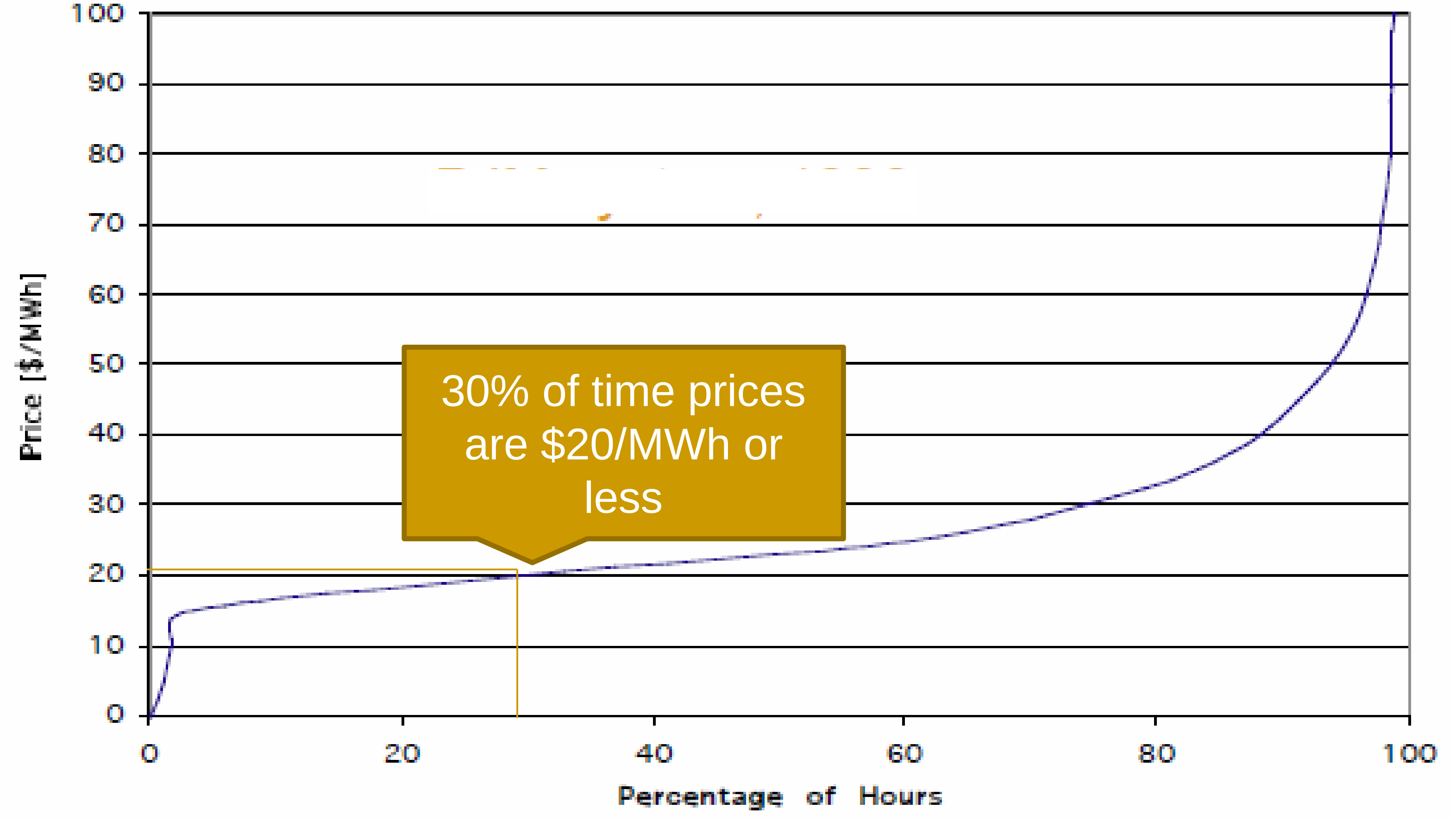


Load duration curve (PJM)



Price duration curve



Implications of the load duration curve

- Market price is set by the marginal cost of marginal generator
  - This is the most expensive generator needed at that hour to meet demand
- Infra marginal generators collect an economic profit because their marginal cost is less than the market price
  - Economic profit pays the fixed costs
- Marginal generator will not recover its fixed cost if price = MC
  - So it needs to incorporate them in its bid (Price=MC+Fixed cost)
  - This is why there are price spikes
- To avoid very high price spikes…
  - Price caps are implemented by ISOs
- But, price caps do not allow marginal generators to recover their Fixed costs So to ensure generation resource adequacy .. .NEED capacity payments !!
- Or need to allow for an scarcity adder to the real time energy price (ERCOT ORDC)

Without any of these, there will not be adequate investment in generation capacity!!

Capacity Market

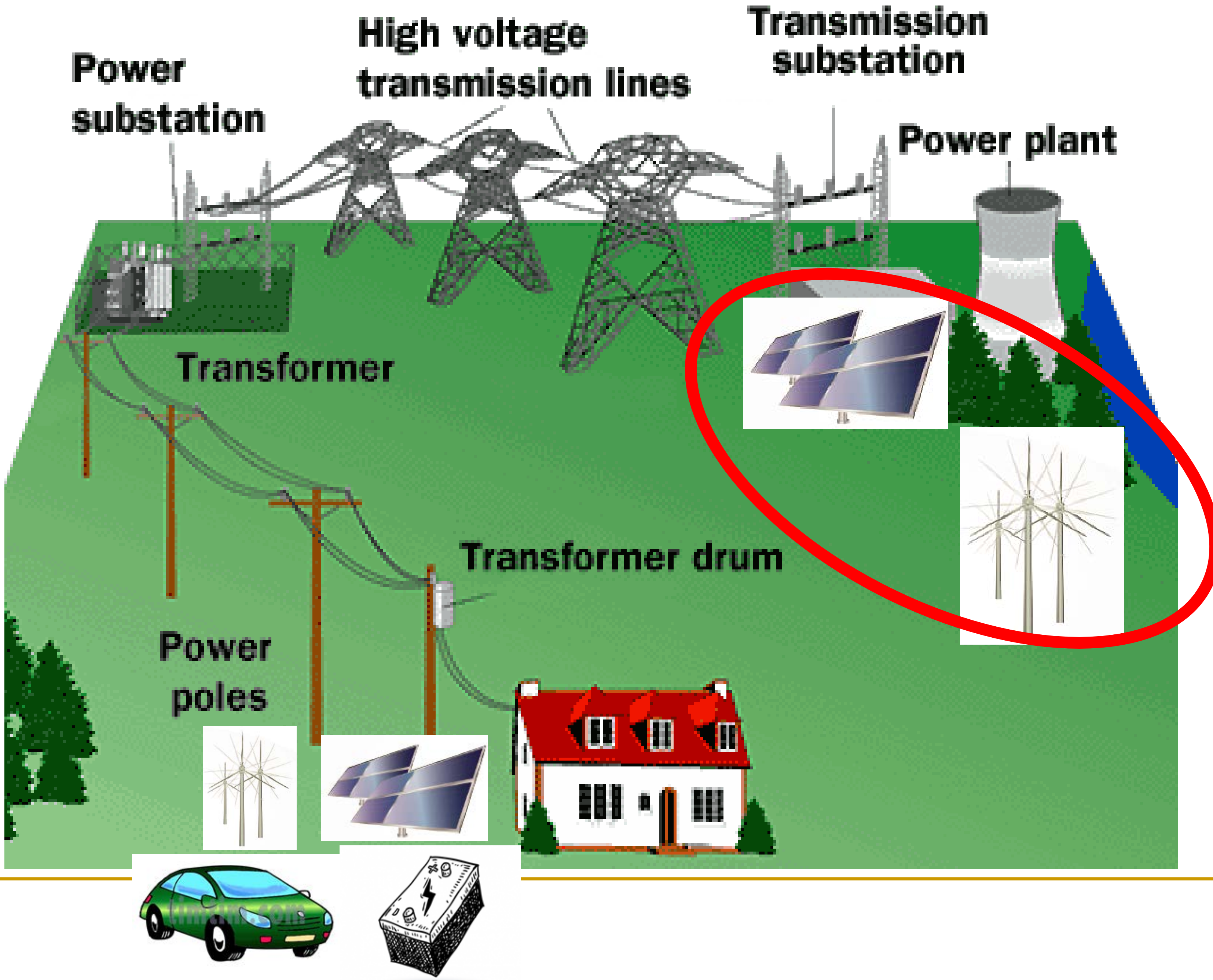
- Capacity target is administratively determined
  - Regulator determines the generation capacity required to meet a reliability target
- Consumers (LSEs) must all “buy” their share of this capacity
- Generators bid to provide this capacity
- Price paid depends on how much capacity is offered

Generators recover their fixed costs by

- Participating in the energy market as non-marginal generators
  - Paid in $/MWh at the energy market clearing price
- Participating in the capacity market
  - Paid in $/MW

New challenges

- Increased penetration of Variable Energy Resources (such as wind and solar)
  - Connected at transmission level
- Increased penetration of Distributed Energy Resources (DERs)
  - Resources connected to the distribution network


Power substation
High voltage transmission lines
Transmission substation
Power plant
Transformer
Transformer drum
Power poles

Balancing demand and supply becomes harder at all time scales!

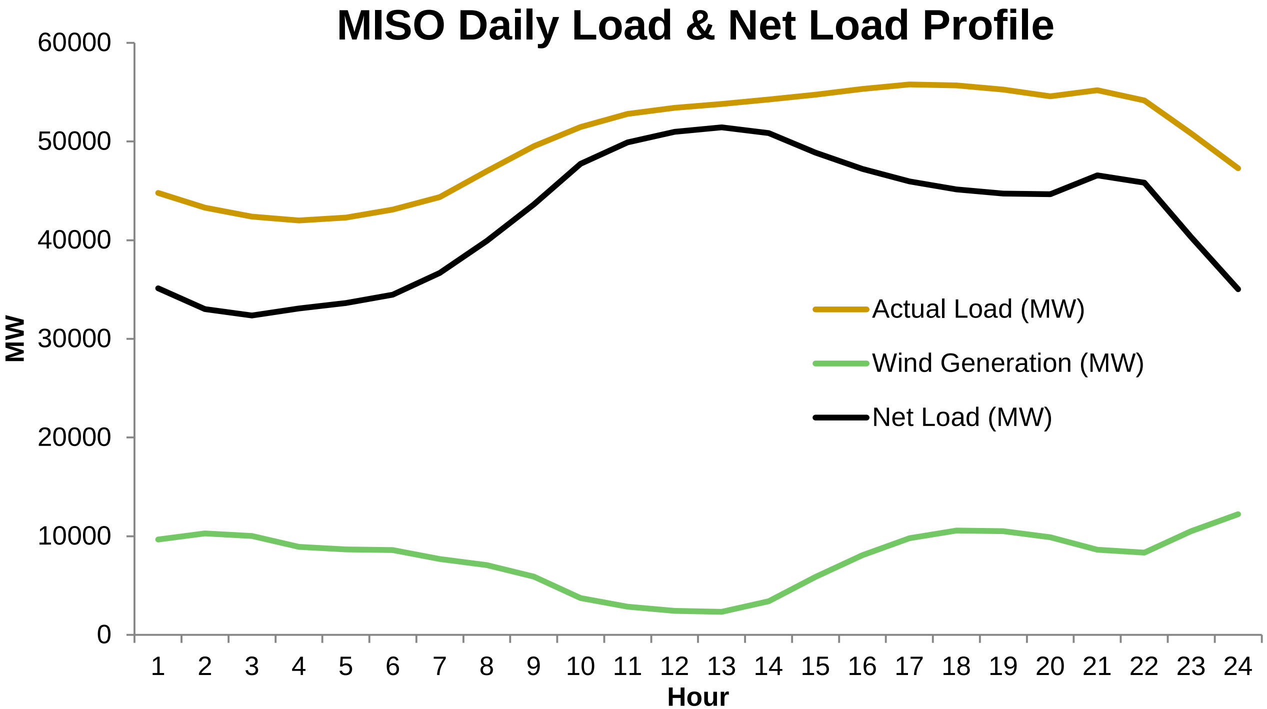
- Milliseconds to seconds
  - System dynamic stability studies
- Seconds to Minutes
  - Regulation
- Minutes to Hours
  - Load following
- Days, months, years
  - Capacity adequacy

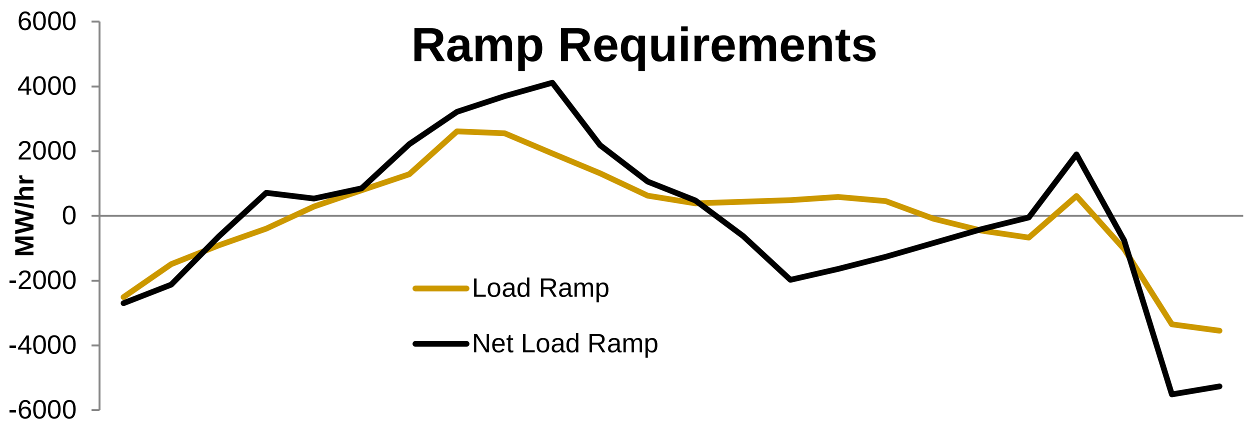
Geographic aggregation helps

New wind turbine technology and batteries help

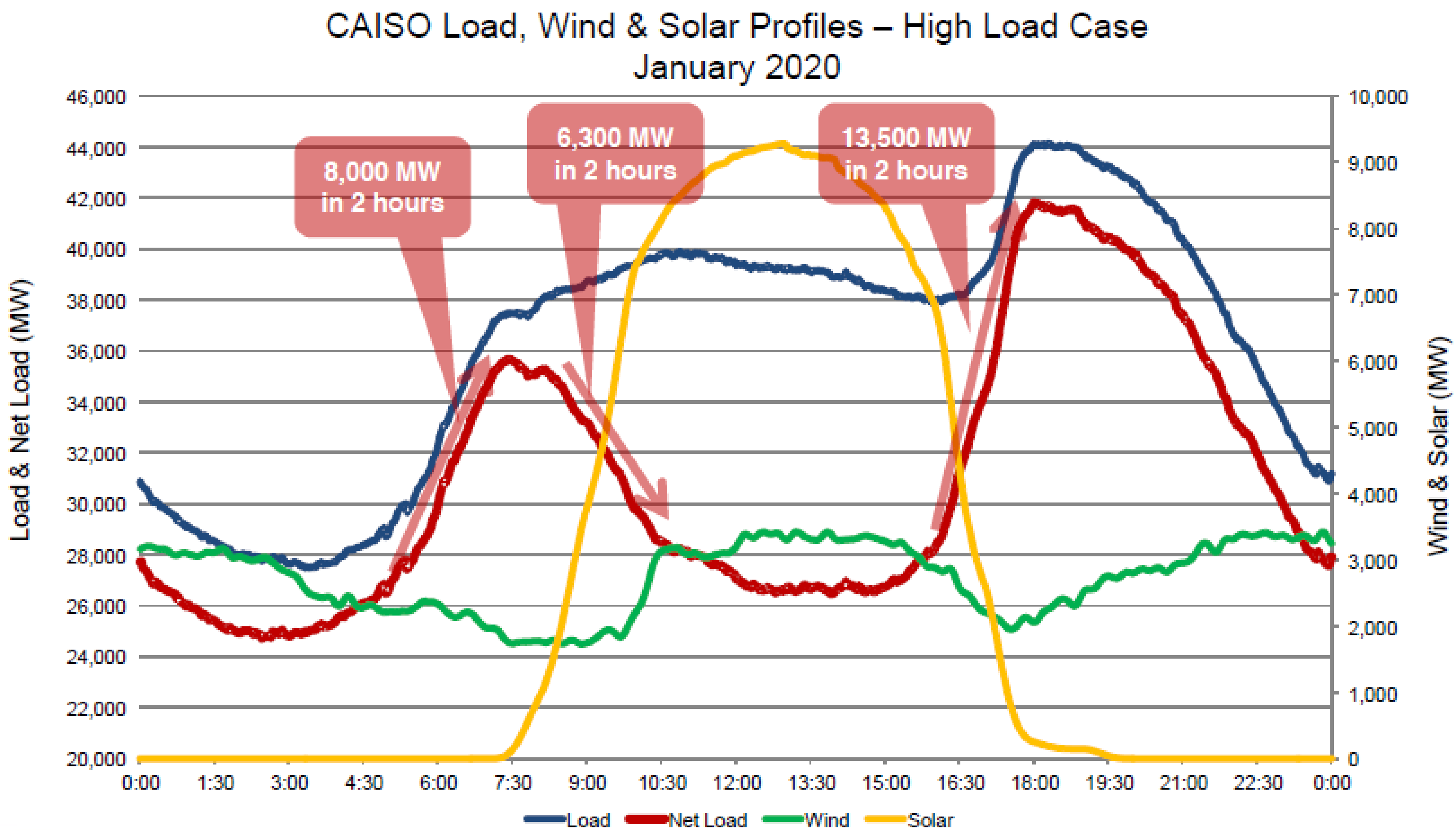
Implies higher costs and emissions

With wind balancing the system is harder





CAISO 2020: A lot of fast ramping conventional generation needed



Possible ways to deal with ramping shortages

- Increase the requirements for other ancilla
  - Commit more resources to provide fr
    - Use regulation resources to ramp **up** and ramp **down** a
  - Increase *spinning reserve* requirements
    - Use them to ramp **up**

But increases costs because resources are paid twice !

- Use a *time-coupled multi-interval dispatch* r
  - I.e. implement a dispatch that “looks ahead”
- Modify Day Ahead UC-ED and Real Time E
  - explicitly ensure ramp capability is provisioned
  - to estimate the opportunity cost of ramp capability and compensate generators accordingly (Navid and Rosenwald, 2012,2013)

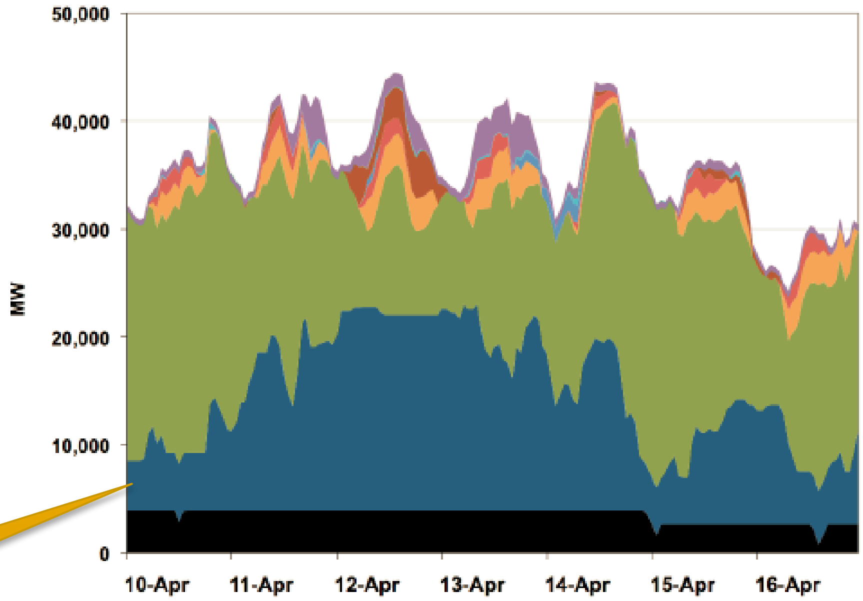
Will provide all the ramp needed with perfect forecast, but

1. Does not account for uncertainty
2. does not separate energy prices from ramp prices

Fossil-fired power plants will *cycle* more

2016: mid April

Future: 35% of wind



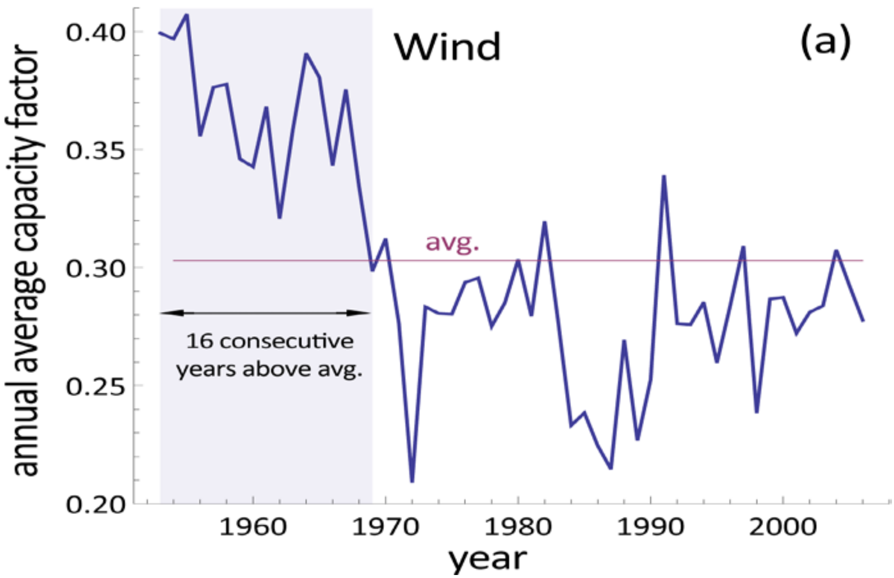
Coal plants will accelerate, shut-down and start-up more often than before

How will their emissions change?

Balancing demand and supply becomes harder at all time scales!

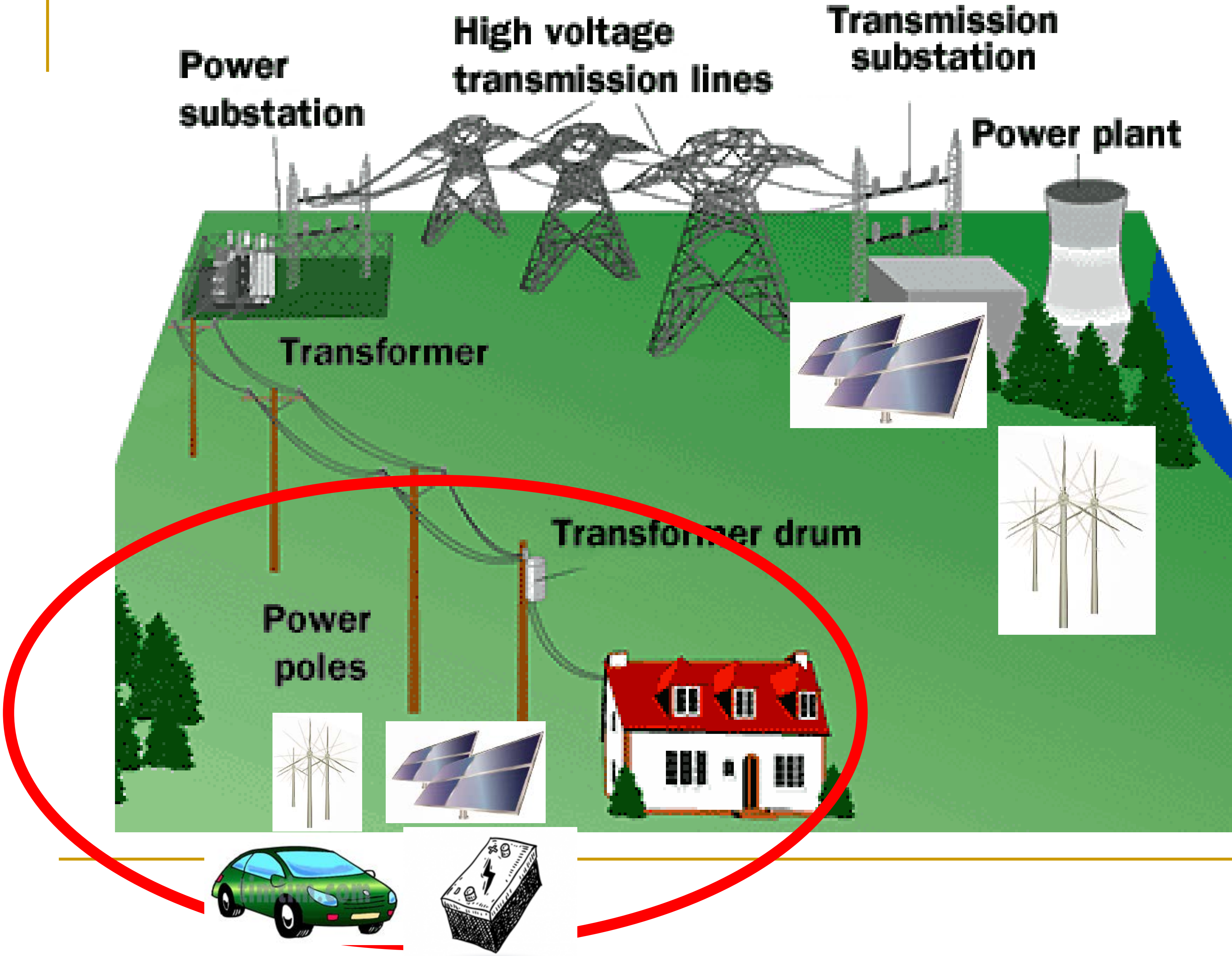
- Milliseconds to seconds
  - System dynamic stability studies
- Seconds to Minutes
  - Regulation
- Minutes to Hours
  - Load following
- Days, months, years
  - Capacity adequacy

long term variability



New challenges

- Increased penetration of Variable Energy Resources (such as wind and solar)
  - Connected at transmission level
- Increased penetration of Distributed Energy Resources (DERs)
  - Resources connected to the distribution network
    - Gas-fired generation
    - Solar PV
    - Small an mid size wind
    - Electric vehicles
    - Energy storage
    - Demand-side management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Proliferation of DERs implies the end of today's power system paradigm

- No more exclusive power flow from central generators to distribution systems
  - Large supply can be generated at the distribution level
    - And if not consumed locally will need to find its way to other markets through the transmission network

Proliferation of DERs implies the end of today's power system paradigm

- Need to reconsider today's distinction between transmission and distribution levels
  - Physical
  - Organizational
  - Regulatory / economic

- What will be the roles of the operators of the transmission system (ISO/TSO) and the operators of the distribution system (DSO)?
- How will DSOs be regulated?

Proliferation of DERs implies the end of today's power system paradigm

- There will be a multitude of agents,
  - consuming,
  - generating,
  - storing
  - and trading electricity
- How to ensure an efficient economic outcome?

by instituting a system that provides the right economic signals throughout the entire grid

Economic signals to ensure efficiency with DERs should:

- Value each service provided by a DER and a central generator
  - At the place it is provided
  - At the time it is provided

- Account for the effects of DER and central oeprators
  - on network thermal losses
  - on grid's technical constraints

- Allowing DERs to compete and collaborate in the provision of services

Services: all need to be priced to allow peaceful co-existence of DERs and the central grid

- Energy
  - Generation Capacity
  - Load following
  - Frequency reg
  - Black-start
  - Reserves
- Network
  - Transmission capacity
  - Voltage control
  - Reduction of thermal losses
  - Reduction of network constraints

Paradigm shift to allow DER market participation and reap its benefits

Today's markets

- Almost all costumers pay a flat rate
  - No locational variation
  - No temporal variation
  - No customer response!

Lots of opportunities to do this right!!

The future

- DSOs clear markets
  - Distributed LMPs are charged/paid to all end-nodes
  - Automated custumer's devices respond to DLMPs
- DSO coordinates with ISO

Thank you!

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