Power System and Market Operations

Quantitative Energy Economics

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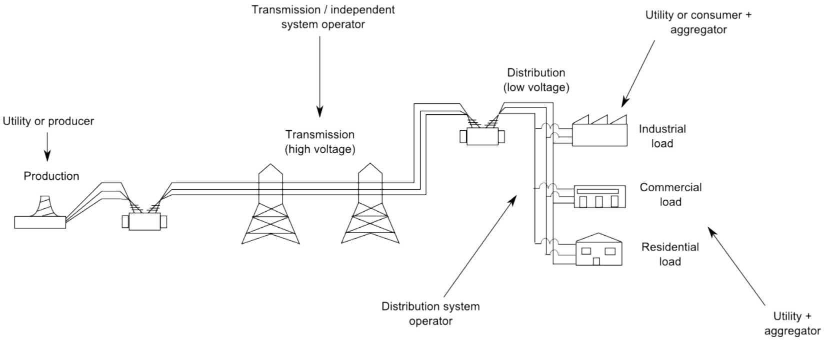
Power System and Market Operations

1. Power System Operations
2. Power Market Operations

Outline

Actors



Transmission / independent system operator
Utility or consumer + aggregator
Distribution (low voltage)
Utility or producer
Transmission (high voltage)
Industrial load
Production
Commercial load
Residential load
Distribution system operator
Utility + aggregator

Uncertainty

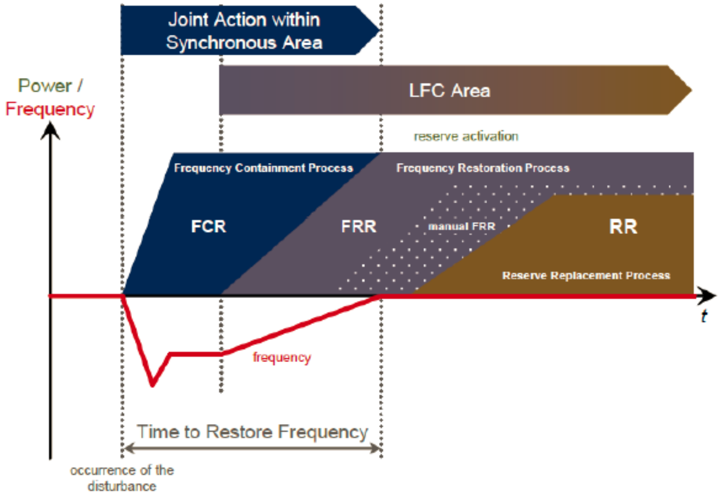
- Rainfall (affects hydro)
- Load forecast errors
- Renewable supply forecast errors
- Generator failures
- Transmission line failures
- Load failures

Contingency: failure of any system element (generator, line, transformer, load)

- Which of these uncertainties are short-term (hours-ahead or real-time)?
- Which of these uncertainties are continuous/discrete?

Frequency Control and Restoration

System frequency is an indicator of supply-demand balance



Primary Reserve

Primary reserve (a.k.a. primary control, frequency containment reserve) is the first line of defense

1. Change of inertia in generator rotors: immediate
2. Frequency-responsive governors (automatic controllers): reaction is immediate, may take a few seconds reach target
3. Automatic generation control (AGC, a.k.a. load frequency control, regulation): updated once every few seconds up to a minute

Secondary Reserve

Secondary reserve (a.k.a. automatic frequency restoration reserve, frequency responsive reserve, secondary control, operating reserve): second line of defense

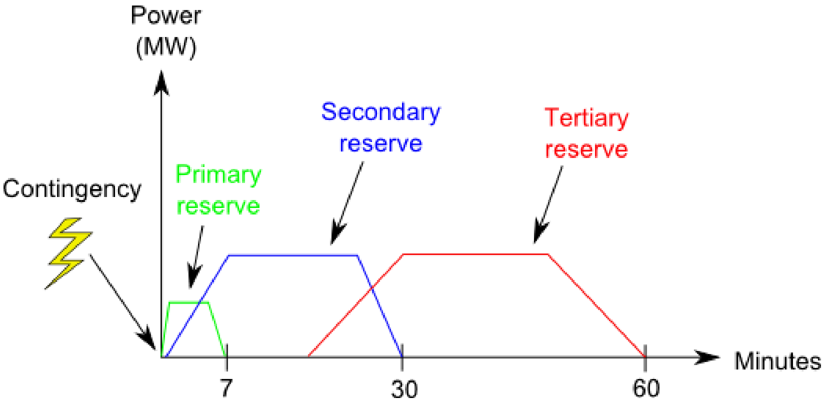
- Reaction in a few seconds, full response within 5-10 minutes
- Classified between spinning and non-spinning reserve
  - **Spinning reserve**: generators that are on-line
  - **Non-spinning reserve**: generators that are off-line but can start rapidly (or imports)
- Requirements dictated by capacity of greatest generator in the system and peak load

Tertiary Reserve

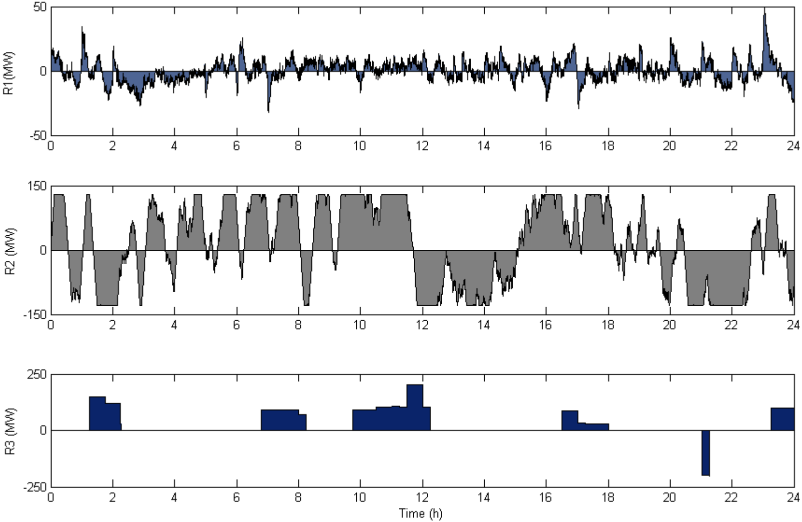
Tertiary reserve (a.k.a. manual frequency restoration services, tertiary control, tertiary reserve, replacement reserve): third line of defense

- Available within 15 minutes

Sequenctial Activation of Reserves



Reserves in Belgium



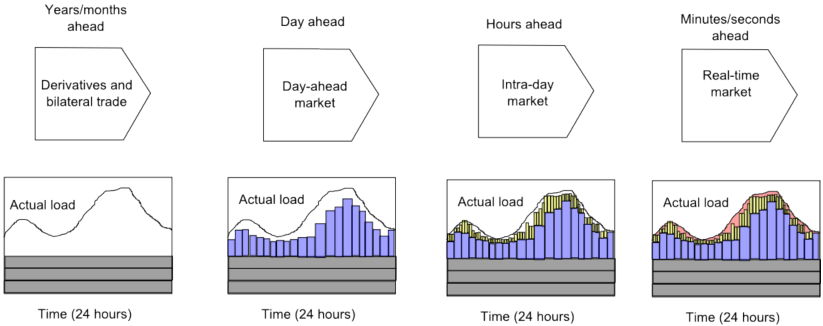
Cost Minimization with Reserves

Consider n generators, operating cost f_i, capacity C_i, power demand D

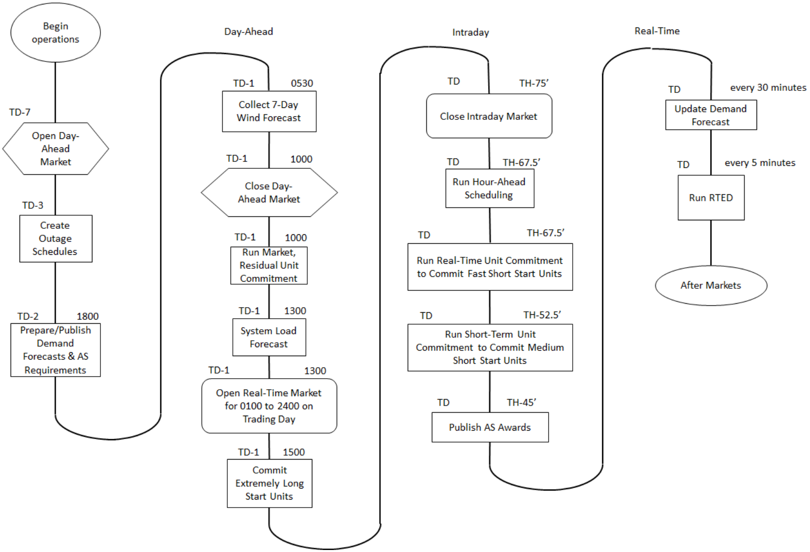
$$
\begin{aligned}
\min \sum_{i=1}^{n} f_i(p_i) \\
\text{s.t. } p_i + r_i \leq C_i \\
\sum_{i=1}^{n} p_i = D \\
\sum_{i=1}^{n} r_i \geq \max_{i=1,\dots n} C_i \\
p_i, r_i \geq 0
\end{aligned}
$$

What have we ignored?

Sequential Electricity Markets



Flow Chart of Operations



Analyzing the Flow Chart

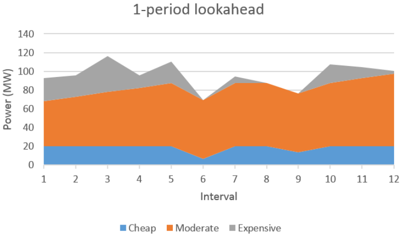
- Which decisions are binding before day-ahead/in the day-ahead/in real time?
- What happens if system operator demand forecast is much higher than traded power in day-ahead market?
- What parts of the supply chain are *not* actively controlled, according to the flow chart?
- Where would demand response enter in this flow chart?
- How many optimization models are shown in the flow chart?
- What would happen if each optimization model ignored future time periods?

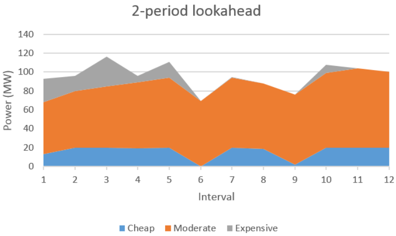
Example: Looking Ahead in Operations

Consider the following example with three generators:

- Real-time economic dispatch: solved every 5 minutes for the next 5 minutes
- Initial conditions: 50 MW from expensive and 50 MW from moderate
- Demand: Gaussian with mean 100 MW, standard deviation 15 MW

Generator	Marg. cost (\$/MWh)	Max (MW)	Ramp (MW/min)
Cheap	0	20	$+\infty$
Moderate	10	$+\infty$	1
Expensive	80	$+\infty$	5





- Cost 5-minute lookahead: 1738 $
- Cost 10-minute lookahead: 1406 $

Why is the second policy doing better?

Outline

The Motivation for Markets

- Information: each agent uses only private information
- Short-run efficiency (Adam Smith's 'invisible hand'): profit-maximizing agents behave optimally from a global point of view if 'the price is right'
- Long-run efficiency: correct investment incentives

Degree of Centralization

Bilateral (least centralized) $\rightarrow$ Exchange $\rightarrow$ Pool (most centralized)

- Bilateral trade: traders exchange in pairs
- **Exchanges**: traders submit simple bids to **auctions** with simple rules
- **Pools**: traders submit multi-part bids to auctions with complex rules

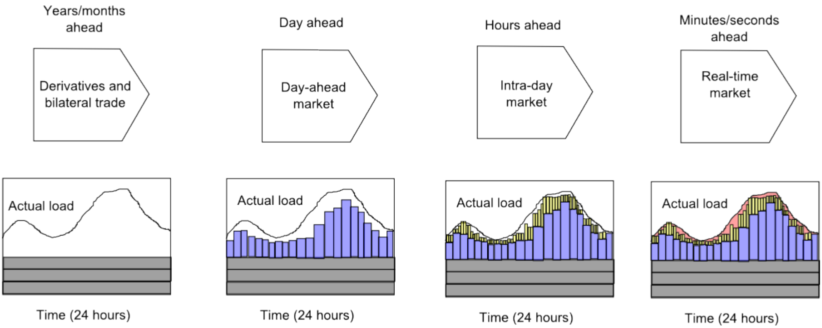
Can electricity be traded bilaterally in real time?

Example: Exchange Versus Pool

Consider generator with startup cost of 2400 \$, capacity of 10 MW, fuel cost of 20 \$/MWh who wants to sell energy for 24 hours

- Exchange: at least how much should the generator bid in order not to lose money?
- Pool profit for energy price P: $\max((P - 20) \cdot 10 \cdot 24 - 2400, 0)$ \$
- Pool side payment: $\max(2400 - (20 - P) \cdot 10 \cdot 24, 0)$ \$

Degree of Centralization in Different Time Frames



As we move to real time, markets become more centralized

Uniform-Price Auctions

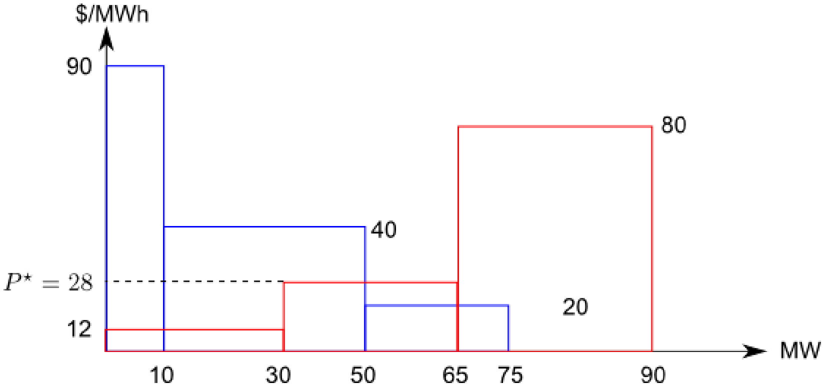
- Generator bids: price-quantity pairs (P, Q), representing price P at which suppliers are willing to produce quantity Q
- Consumer bids: price-quantity pairs (P, Q) representing price P consumers are willing to pay for quantity Q
- Obligations and payoffs
  - Market clearing price $P^\star$: intersection of supply and demand curves
  - *In the money* supply bids: produce and receive $P^\star$ \$/MWh
  - *In the money* demand bids: consume and pay $P^\star$ \$/MWh

Example

The following bids are submitted for *5-minute* power in a uniform price auction

- Supplier 1: 30 MW at 12 $/MWh
- Supplier 2: 35 MW at 28 $/MWh
- Supplier 3: 25 MW at 80 $/MWh
- Consumer 1: 10 MW at 90 $/MWh
- Consumer 2: 40 MW at 40 $/MWh
- Consumer 3: 25 MW at 20 $/MWh

- What is the uniform price?
- What is each supplier's profit?
- What is each consumer's profit?
- How much money is left to the auctioneer?


$/MWh
90
80
40
$P^\star = 28$
20
12
MW
10
30
50
65
75
90

Second-Price Auctions

Auctions for selling one item

- Lowest bidder (supplier) paid for supplying the auctioned item
- Supplier is paid price bid by cheapest losing bidder

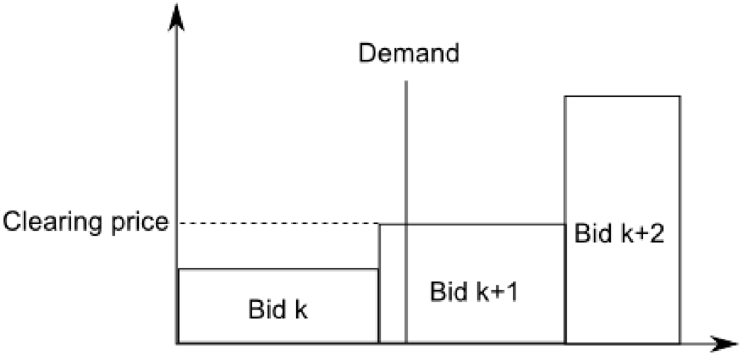
Induces truthful bidding

- Why would you want to understate cost?
- Why would you want to overstate cost?

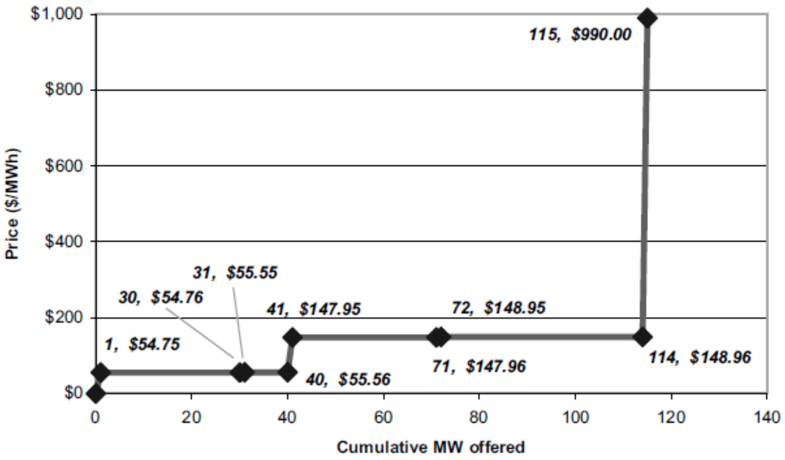
William Vickrey: 1996 Nobel prize in economics

From Second-Price Auctions to Uniform Price Auctions

Uniform prices are a natural generalization of second-price auctions to multiple items, 'losing' bid is $k + 1$



Hockey Stick Bidding



Meanwhile, in Texas (February 24, 2013)

Pay-As-Bid Auctions

Pay-as-bid pricing: Bids are accepted in order to maximize benefit from trade, each agent pays/receives the price they bid.

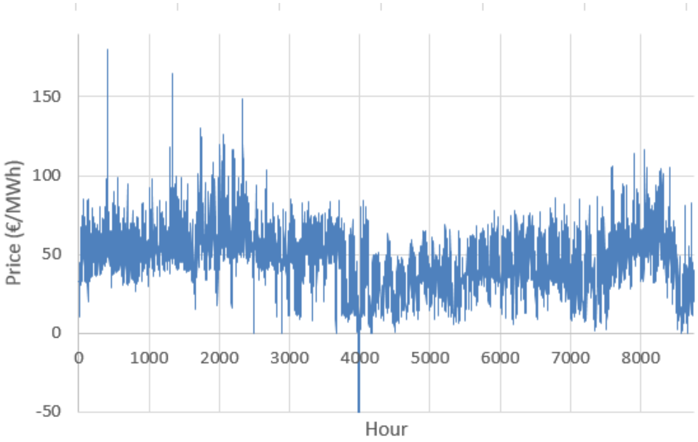
Criticisms of uniform pricing:

- Price volatility
- Hockey-stick bidding
- Unfair profit margins for infra-marginal suppliers. This argument is wrong.

Criticisms of pay-as-bid pricing:

- Discriminatory (different price for the same product)

Price of Energy in CWE (2013)



Is this a uniform or pay-as-bid auction?

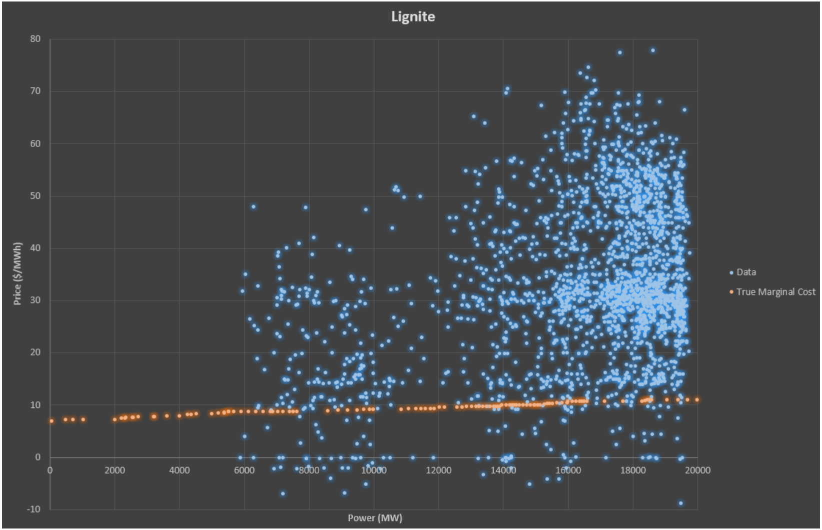
Example

The following bids are submitted for *5-minute* power in a pay-as-bid auction

- Supplier 1: 30 MW at 12 $/MWh
- Supplier 2: 35 MW at 28 $/MWh
- Supplier 3: 25 MW at 80 $/MWh
- Consumer 1: 10 MW at 90 $/MWh
- Consumer 2: 40 MW at 40 $/MWh
- Consumer 3: 25 MW at 20 $/MWh

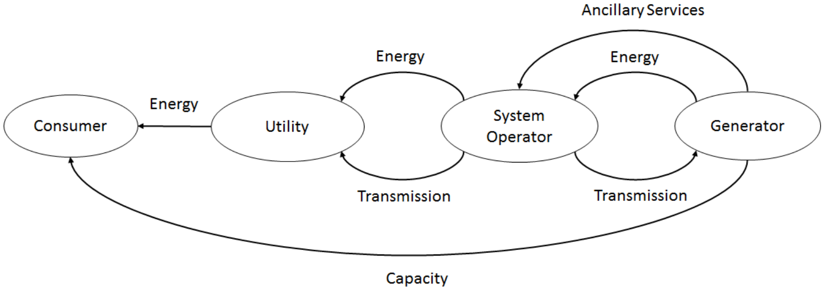
- What is the price?
- What is each supplier's profit?
- What is each consumer's profit?
- How much money is left to the auctioneer?

Lignite Dispatch in Germany (May -December 2014)



- Which of the blue dots are losing money?
- Which of the blue dots would be suspect of keeping power out of the market?

Blueprint of an Electricity Market



Blueprint Variants

What would the following mean?

- an ‘Energy’ arrow from generators to utilities
- an ‘Ancillary Services’ arrow from system operator / generators to utilities
- a ‘Capacity’ arrow from generators to utilities
- an ‘Ancillary Services’ arrow from utilities to the system operator

Example: California and Central Western Europe

- Pool versus exchange
- Coordination
- Nodal versus zonal pricing

Day-Ahead Market

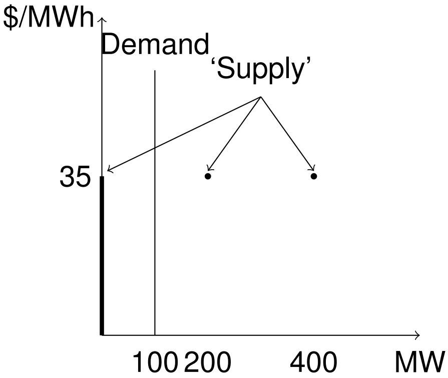
California:

- Pool: detailed bids and uplift payments
- Uniform price for energy (different between nodes)
- Each generator bids individually
- Determines energy, reserve, transmission usage simultaneously

Central-Western Europe:

- Exchange: simple bids
- Uniform price for energy (different between zones)
- Each firm (not generator) bids individually
- Determines energy, cross-border transmission usage (not reserve)
- Ignores Kirchhoff's laws (for the time being)

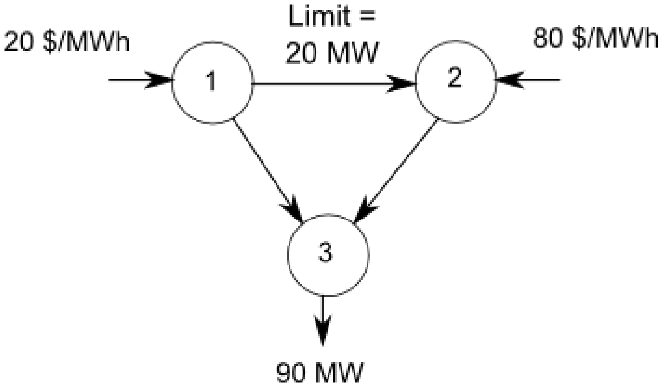
A System Without a Market-Clearing Price [Stoft, 2001]



- Fixed demand: 100 MW
- Identical generators
  - Startup cost: 3000 $
  - Marginal cost: 20 $/MWh
  - Capacity: 200 MW

Ignoring Kirchhoff's Laws

All lines have identical characteristics



What is the optimal dispatch if we ignore Kirchhoff? if we account for Kirchhoff?

Real-Time Operations

California:

- Real-time market: replica of day-ahead market model with certain decisions fixed
- Uniform price

Central and Western Europe:

- Re-dispatch: change of generator schedule in order to prevent violation of transmission constraints
- Balancing: use of reserve in order to correct forecast errors/contingencies (pay-as-bid)

Nodal Pricing Versus Zonal Pricing

California

- **Node:** physical connection point of the network
- **Nodal pricing**: transmission capacity is bought indirectly by differentiating price of energy at each *node*

Central and Western Europe

- **Zone**: collection of nodes at which electric energy is sold at the same price
- **Zonal pricing**: motivation is to simplify the trading of energy by reducing the number of markets

Nodal Pricing in PJM (February 15, 2014)

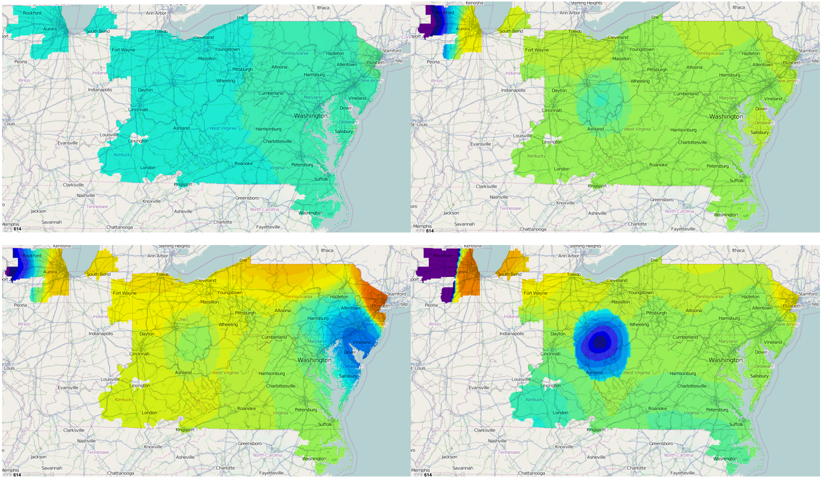


Figure: 05:40 (upper left), 08:40 (upper right), 09:20 (lower left), 09:55 (lower right).

Zonal Pricing