Power Systems Engineering Research Center (PSERC)

An NSF Industry / University Cooperative Research Center

PSERC

Mission

PSERC

Universities working with industry and government to find innovative solutions to challenges facing a restructured electric power industry.

- Multi-disciplinary (engineering, economics, operations research, etc.)
- Multi-university
- Collaborative
- Research and education activities

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PSERC Universities

PSERC

- Cornell University (lead university)
- Arizona State University
- University of California at Berkeley
- Carnegie Mellon University
- Colorado School of Mines
- Georgia Institute of Technology
- The University Of Illinois at Urbana
- Iowa State University
- Texas A&M University
- Washington State University
- University of Wisconsin-Madison

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Research Program

PSERC

- Three research stems
  - Markets
  - Transmission and distribution technologies
  - Systems
- Leveraged research (such as Consortium for Electric Reliability Technology Solutions)
- Public documents: www.pserc.wisc.edu

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Electric Service Reliability

Fernando L. Alvarado
Professor, University of Wisconsin

Invited Presentation
43rd NARUC Program
East Lansing, Michigan, August 15, 2001

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Outline

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- **Traditional reliability concepts**
  - **LOLP**
  - **n-1 security**
  - **Reserve margins**
- **Reliability in a market context**
  - **The Value Of Lost Load (VOLL)**
- **Some market power issues**

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Traditional reliability concepts

- Loss of load probability (LOLP)
  - Expected Demand Not Served (EDNS)
- n-1 security
- Reserve margins

Electric service reliability

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- End-user perspective:
  - Any involuntary loss of power is a reliability event
- Bulk system perspective:
  - Any system condition leading to loss of load is a reliability event
    - Only those leading to widespread or extended outages are considered true reliability events
    - The outage of a component is not an event

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Reliability Time Frames

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- The planning time frame
- The operations time frame
  - Reliability in this timeframe is sometimes called *security*
  - In this talk we will emphasize the operations time frame

Loss of load probability

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- A “planning” concept
  - Based on random outage of generators, what is the probability that the available generators will be insufficient to meet the anticipated load
    - Measured in frequency of expected outages
- EDNS extends the concept to consider energy “not served”

The n-1 security criterion

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- "The outage of any single piece of equipment shall not result in an uncontrolled loss of load"
  - A pretty universal and fundamental way of operating the system
  - Cost in not in the equation
- Sometimes n-2 and n-3 criteria are used

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Applying the n-1 criterion

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- Outage of any generator does not cause overloads or other problems
  - n-1 criterion used to establish reserve requirements
- Outage of any line or transformer should not cause any other overloads
  - If a potential problem exists, system is redispatched for "security reasons" (either via CED, via TLR, or via prices)

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Why do systems fail?

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- *Cascading* overloads
  - A simple line or transformer outage is not enough except in radial situations
    - Most distribution systems are radial
- Loss of system stability
  - Transient or dynamic
- Voltage collapse
- Insufficiency of generation

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Reserves

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- The loss of any generator shall not cause an uncontrolled loss of load
- The “area control error” (ACE) must be brought under control
  - NERC has well-defined rules for this
  - At present the rules are “voluntary”

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What is the ACE?

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- To facilitate control, the power system is divided into control areas
  - All exports and imports are monitored
  - Every area balances its energy to attain the desired exports or imports
    - It also contributes to frequency control
- The ACE is the deviation between the intended frequency+exports and the actual values

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More on reserves

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- Reserves may have to be *locational*
- They must consider time of response
  - Reserves are often classified this way
- "Sustainability" attribute of reserves has been underconsidered to date
- The cost of procuring reserves can be quite important
- Reactive reserves are important

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Reserve margins

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- "How far are we from a failure under normal conditions"
  - And how about under contingency conditions
    - A contingency is the loss of a component
  - You must also ask "in what direction"
    - *How far is the nearest gas station* is different from *how far is the next gas station*
    - Often the direction is "total system load"

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Choosing reserve margins

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- Depends on "largest credible event"
- Sometimes the probability of a triggered event is factored in
  - Play it more conservative during bad weather
- Margins often expressed in terms of size of largest generator or loss of biggest import

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Temporal classification

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- Spinning reserves
  - Fast-responding, usually instantaneously
- Supplemental reserves
  - You can bring resources on-line quickly
- Backup reserves
  - They can be brought on line after some time

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Reliability in a market context

- Reliability event occurs when demand exceeds supply
  - The supply and demand curves do not intersect!

What is reliability anyway?

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- The CAISO just disconnected you as a result of insufficient reserves
  - This is an example of a reliability event
- You had vountarily signed up for an interruptible program and got cut off
  - This is not a reliability event

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Economics 101

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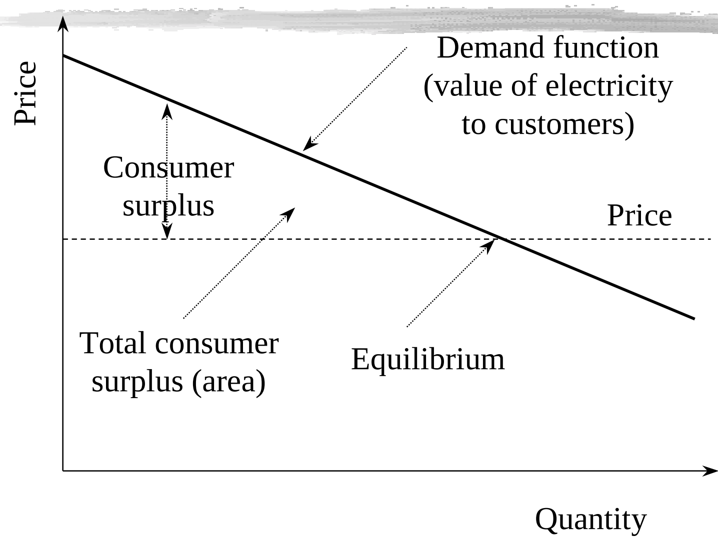
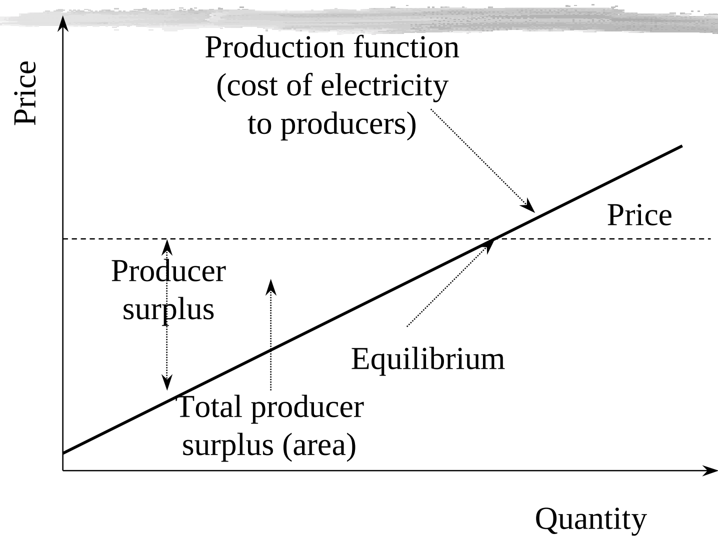
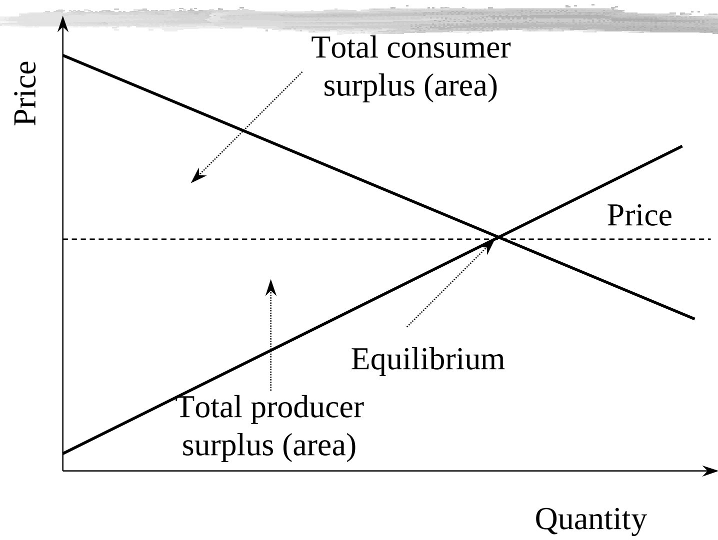


Economics 101



Economics 102



Some realities

- Demand function is closer to vertical
- Supply function tends to have steps
- Supply function does not extend to infinity

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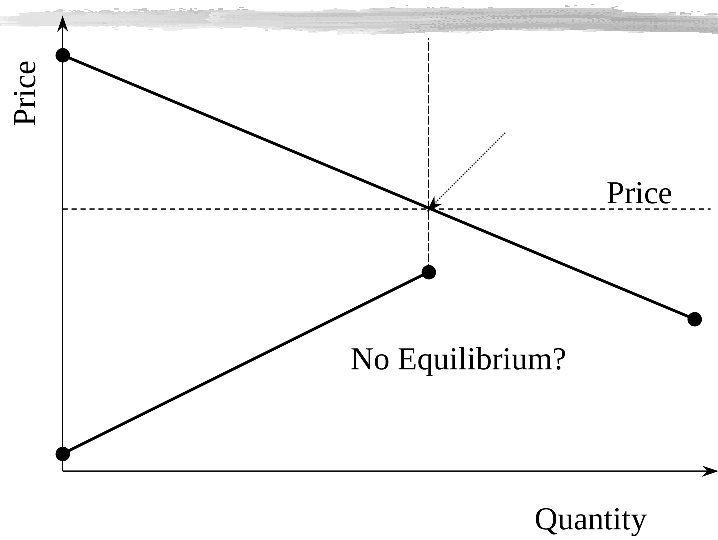
A market problem



A market failure

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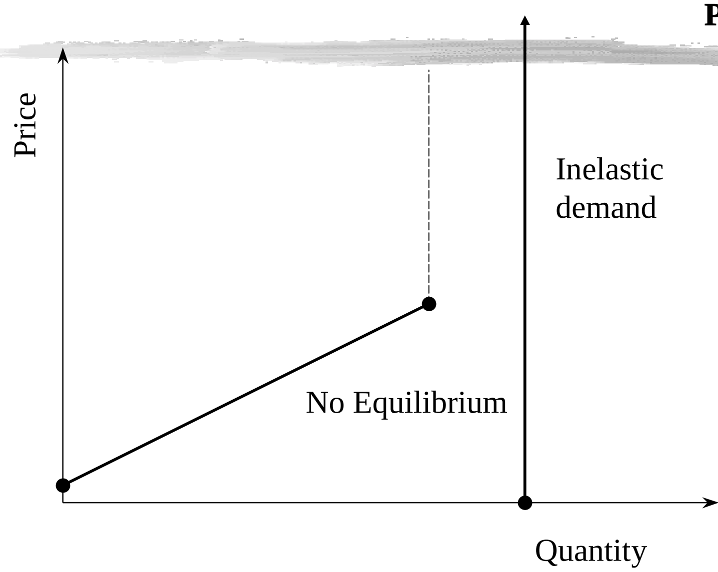

Reliability & market failure

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- Market failure ⇒ Reliability event
- Reliability event ⇒ Market failure?
  - Certain reliability events are not the result of market failure
    - There must have been a market in the first place

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Assumptions

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- Exactly two technologies
  - Each technology has a known price
- No market power
- Inelastic demand

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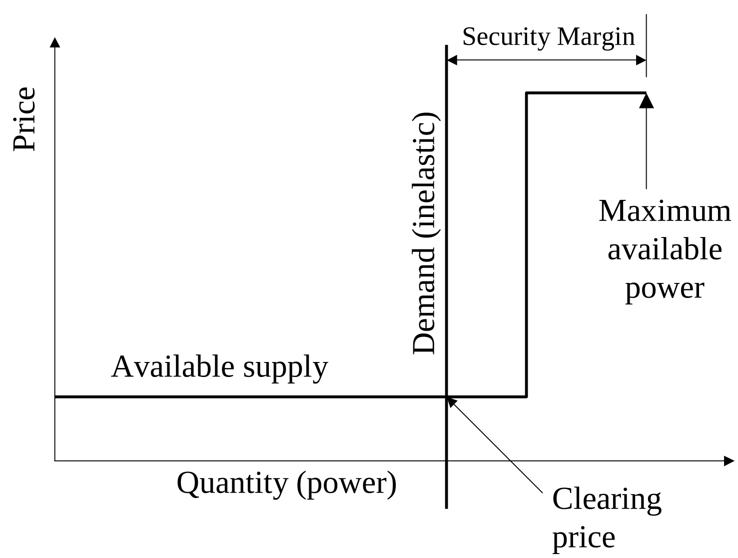
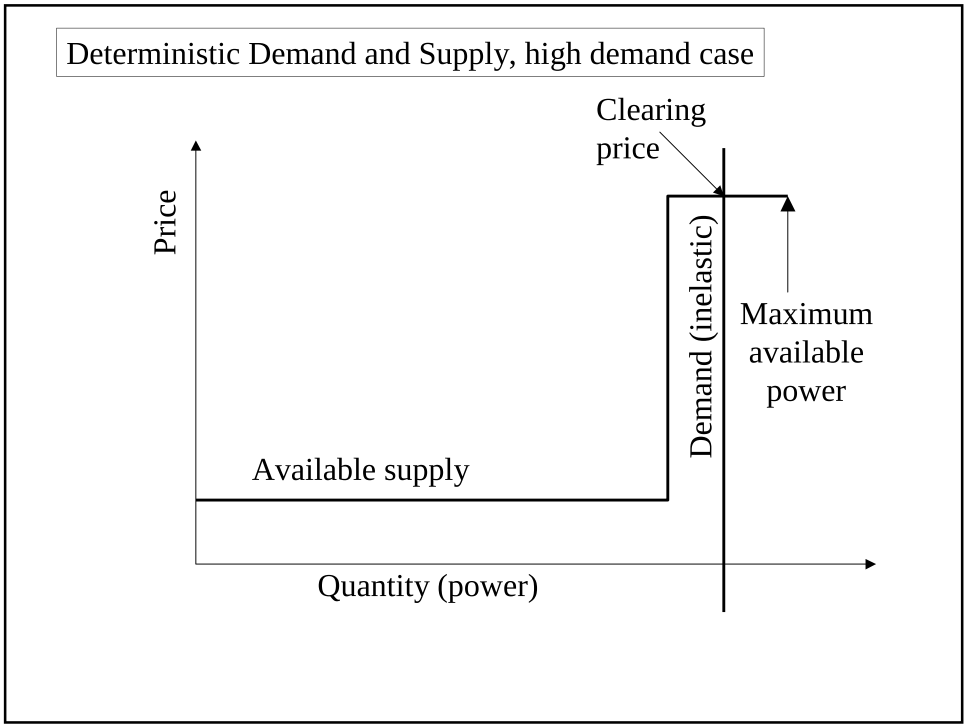
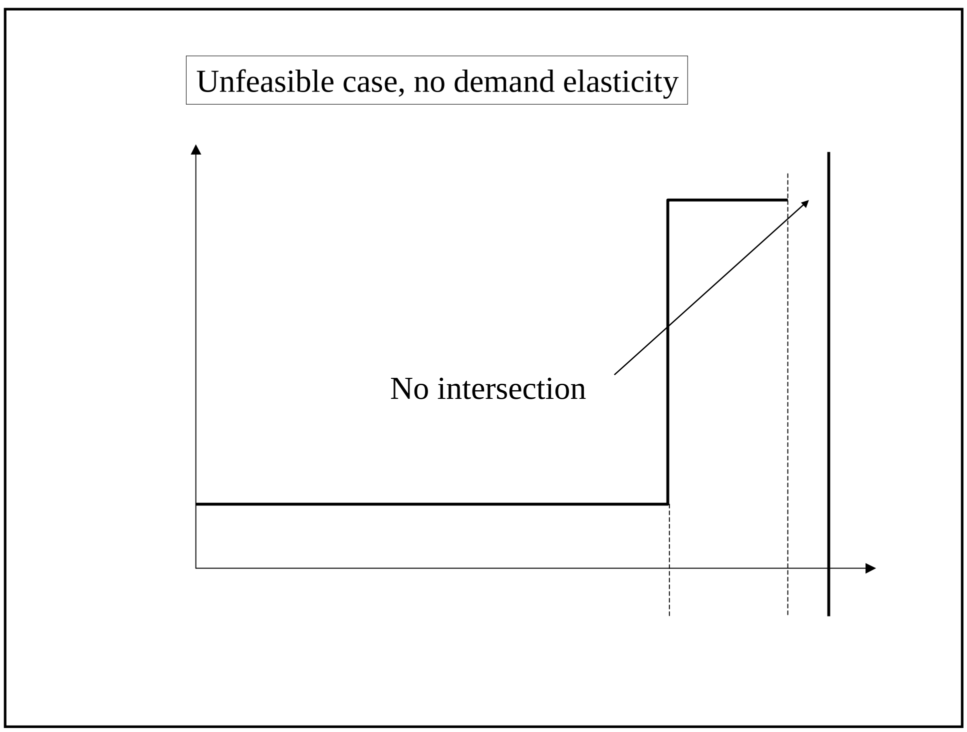
Deterministic Demand and Supply, low demand case

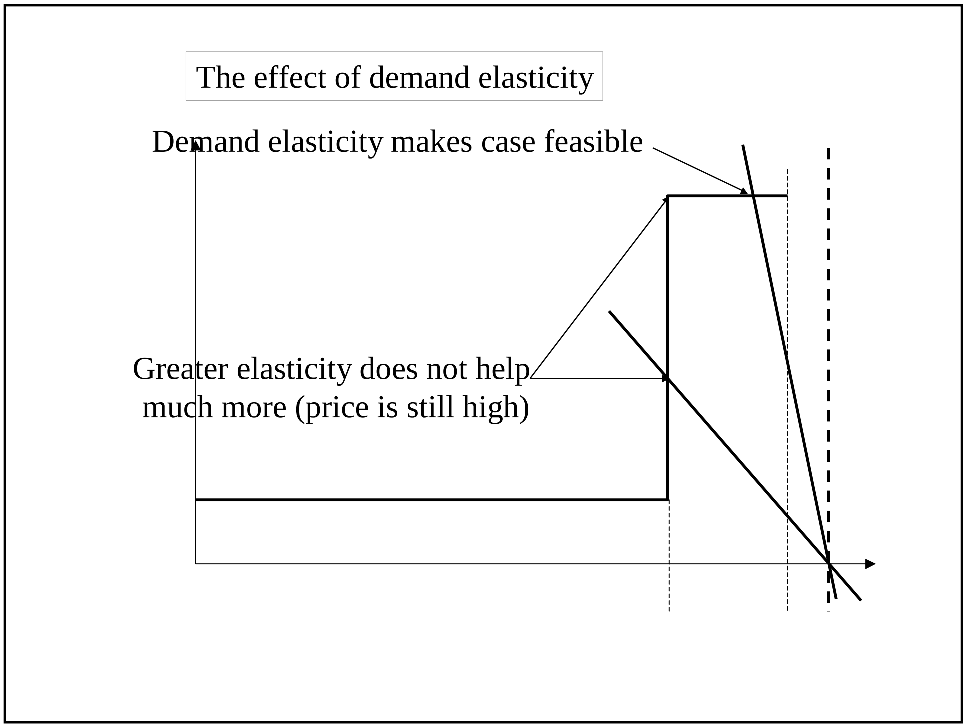


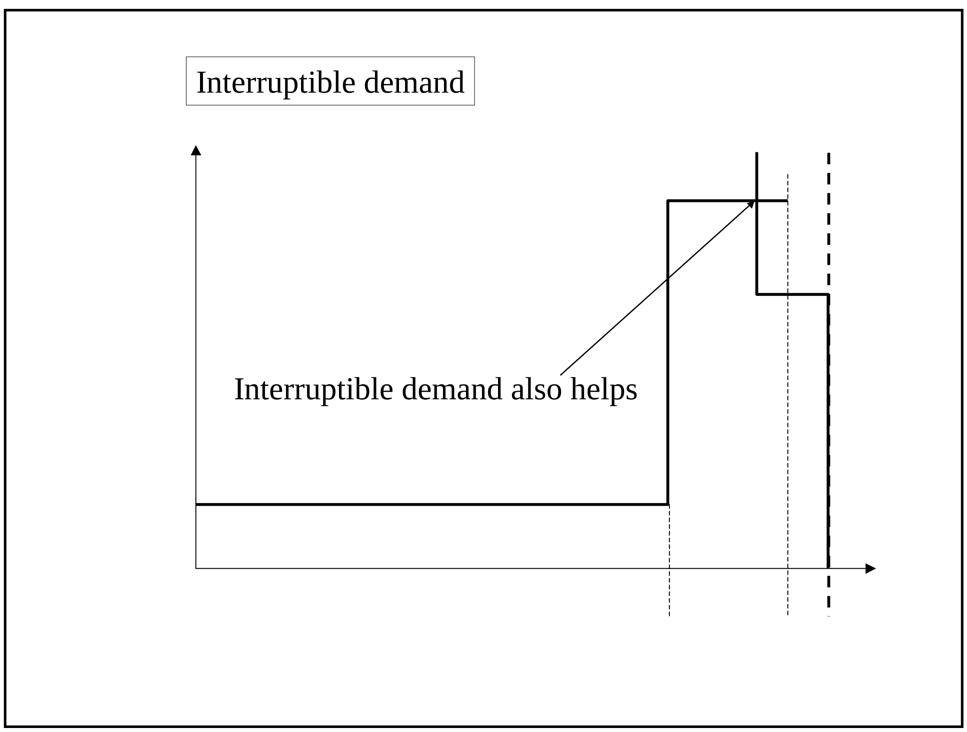


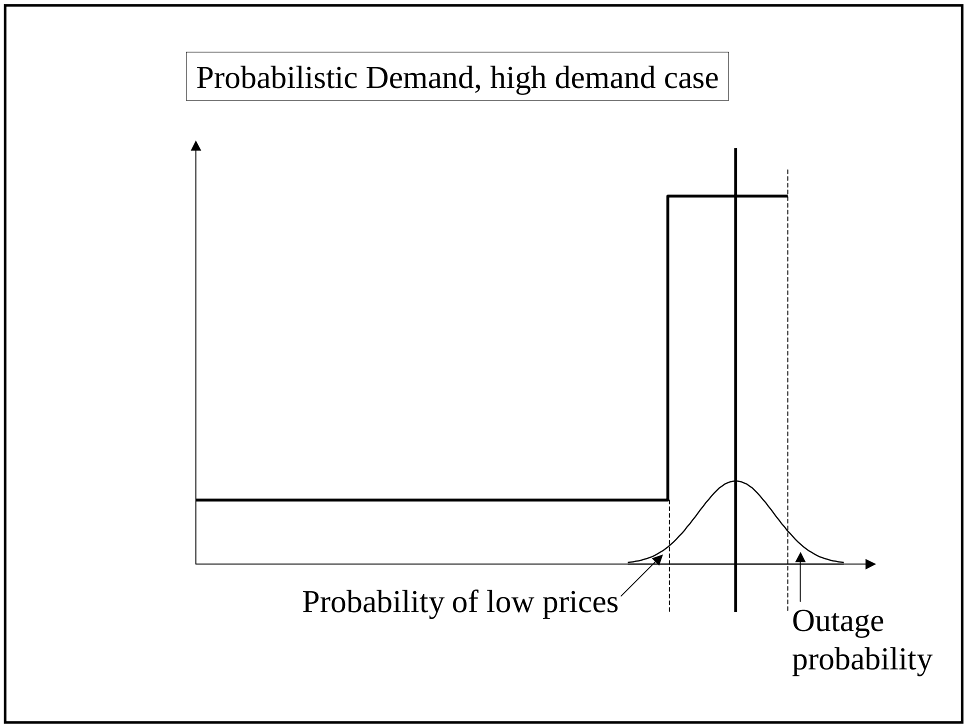
Deterministic Demand and Supply, high demand case
Clearing
price
Price
Demand (inelastic)
Maximum
available
power
Available supply
Quantity (power)

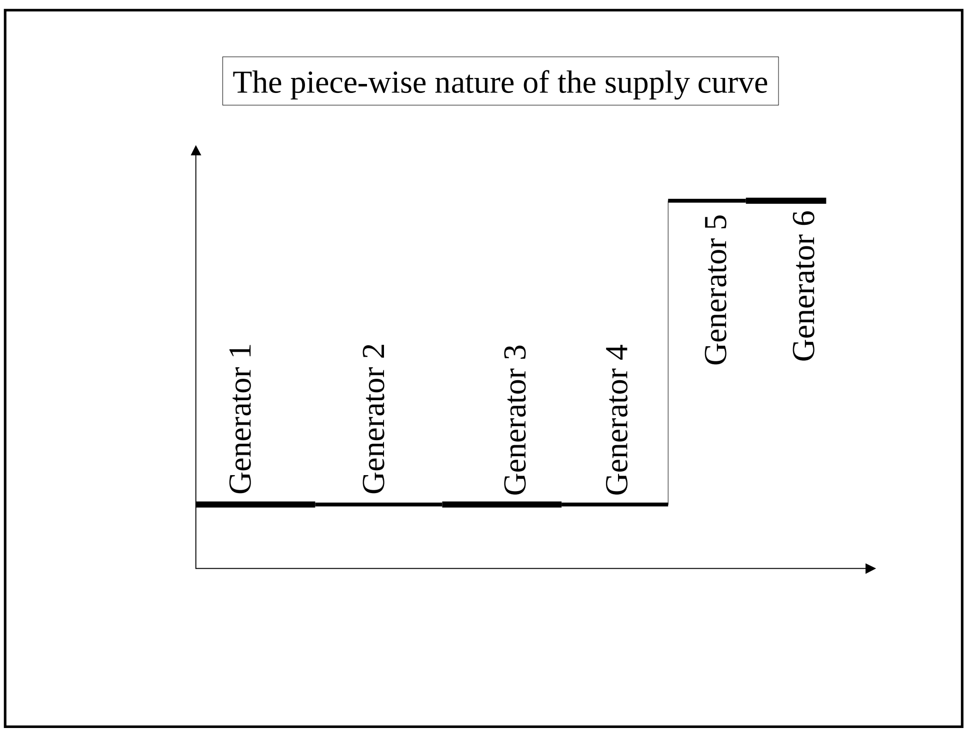


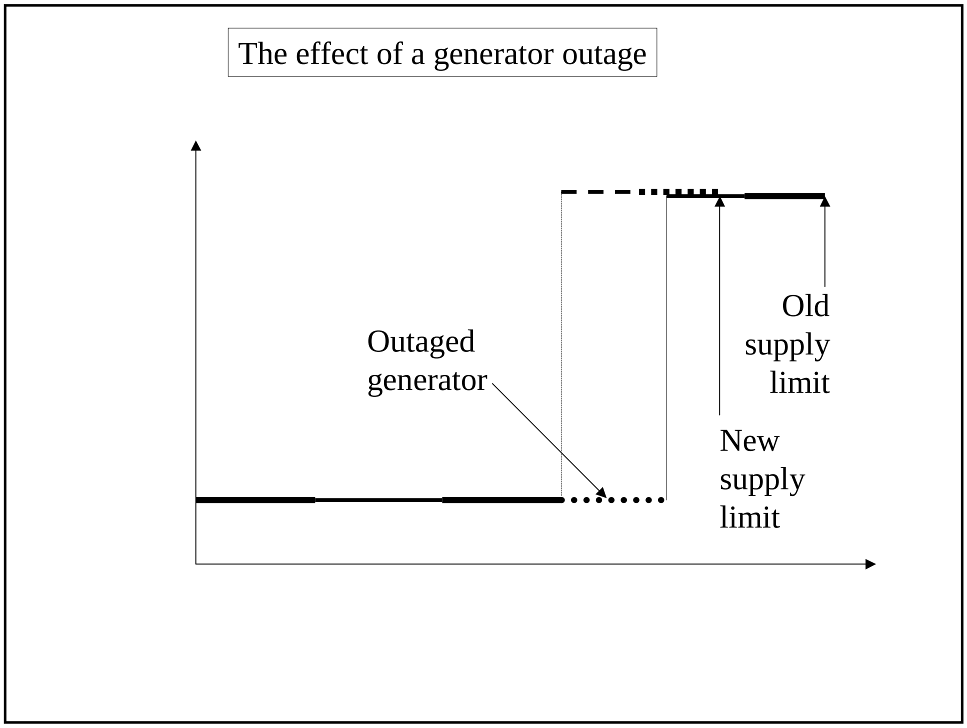
Unfeasible case, no demand elasticity
No intersection

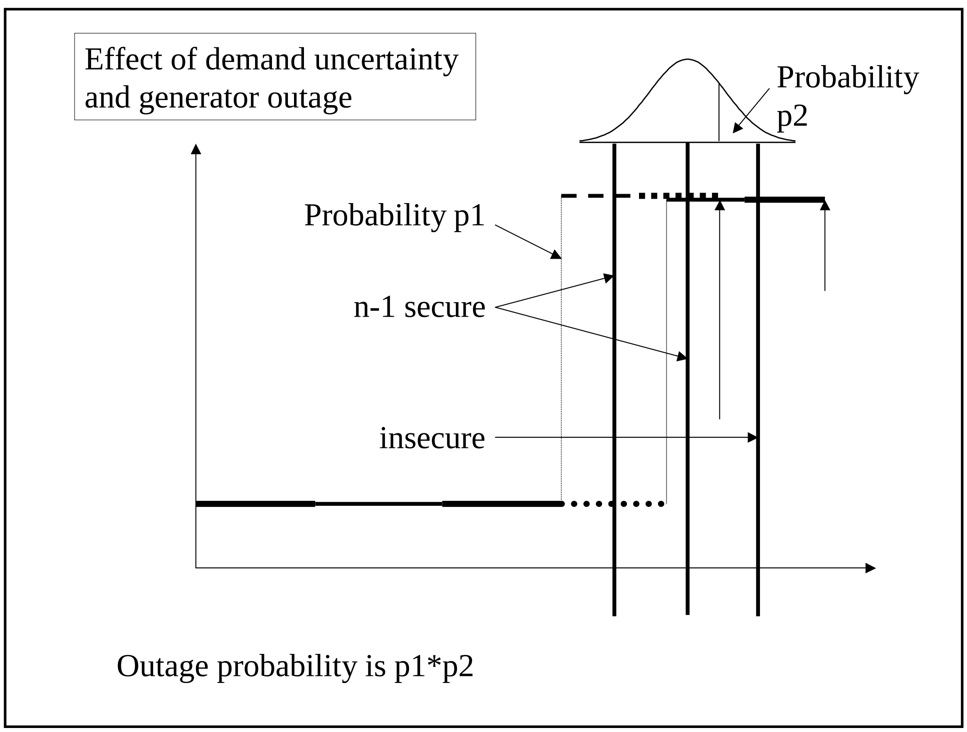

The effect of demand elasticity
Demand elasticity makes case feasible
Greater elasticity does not help much more (price is still high)

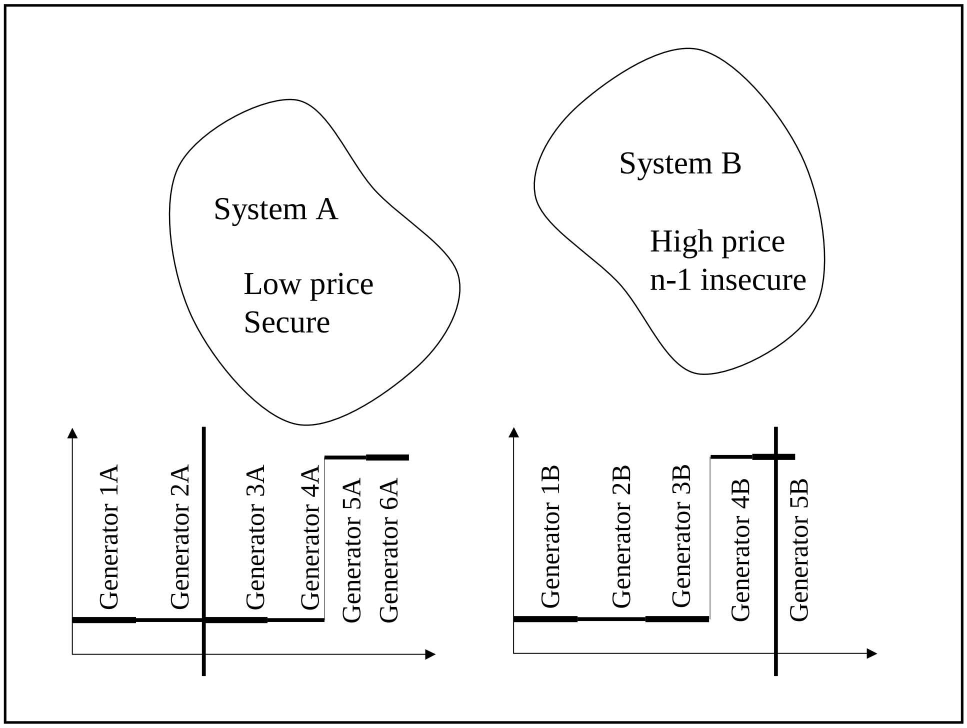

Interruptible demand
Interruptible demand also helps

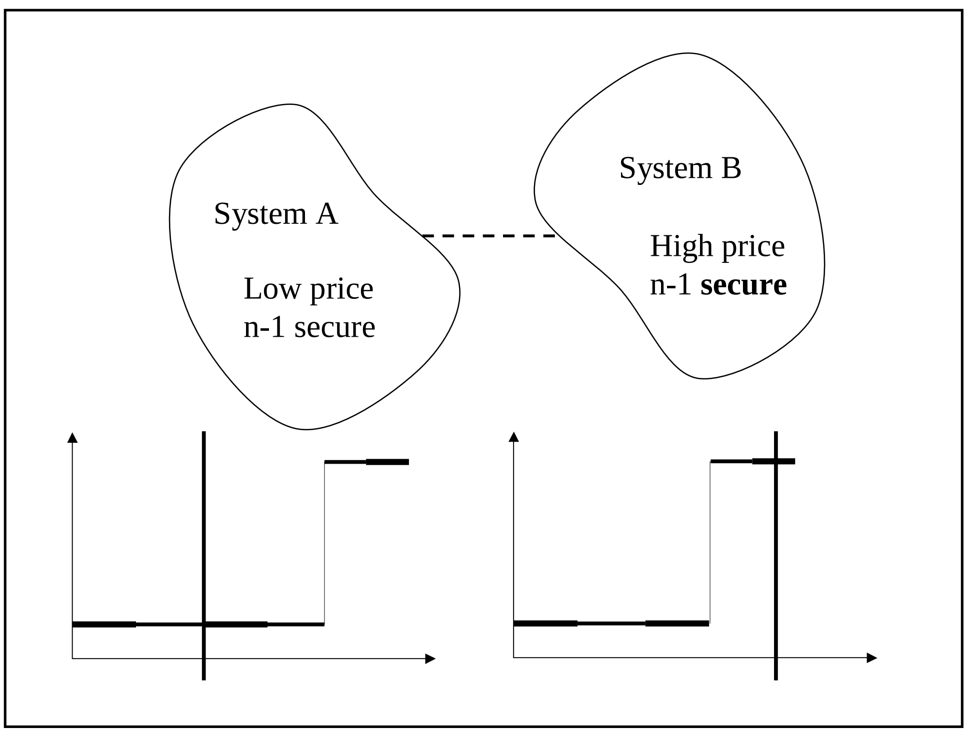

Probabilistic Demand, high demand case
Probability of low prices
Outage
probability

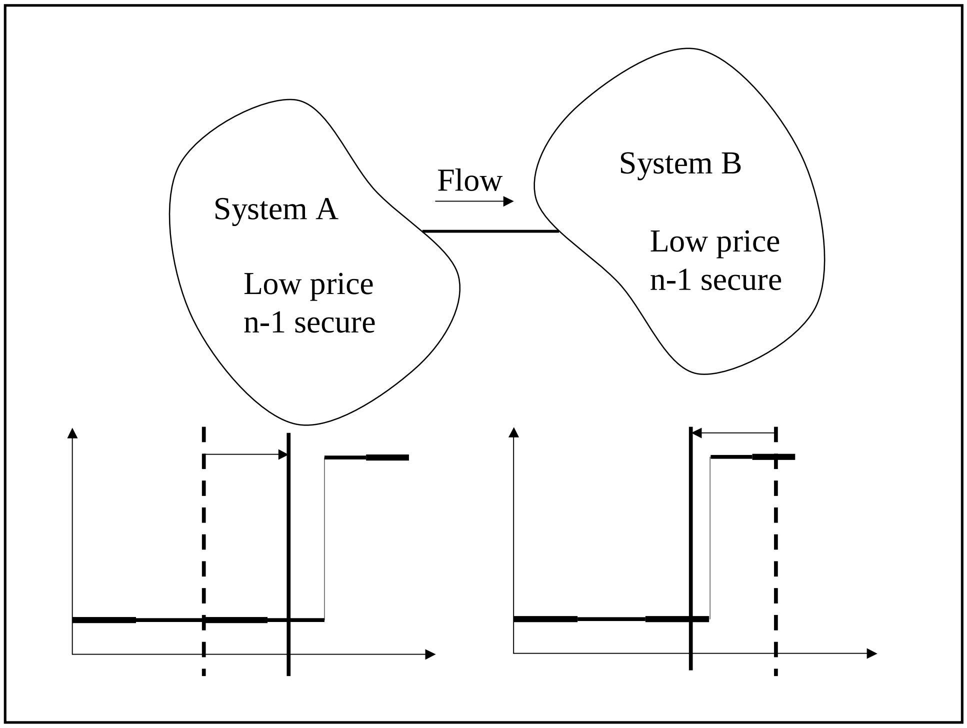

The piece-wise nature of the supply curve
Generator 1
Generator 2
Generator 3
Generator 4
Generator 5
Generator 6

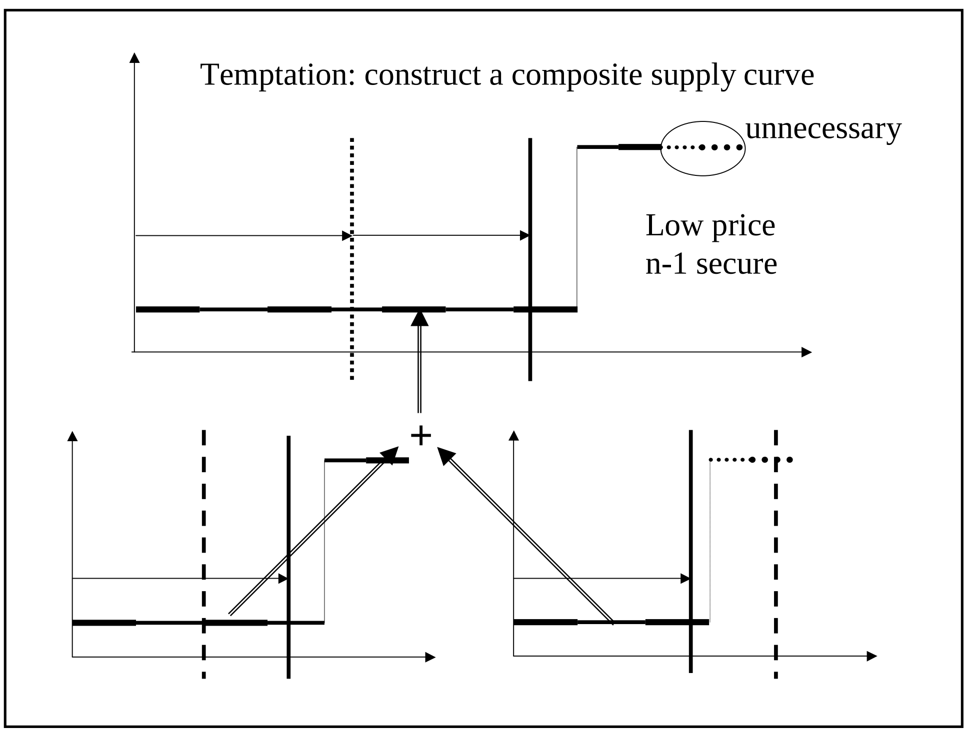

The effect of a generator outage
Outaged
generator
Old
supply
limit
New
supply
limit

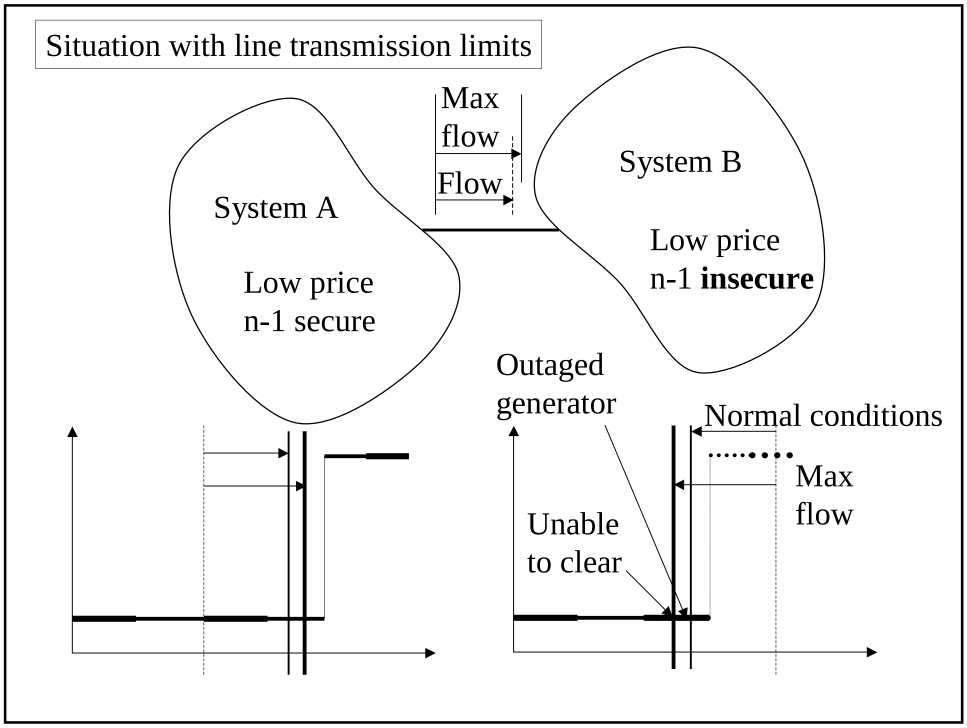

Effect of demand uncertainty
and generator outage
Probability
p2
Probability p1
n-1 secure
insecure
Outage probability is p1*p2

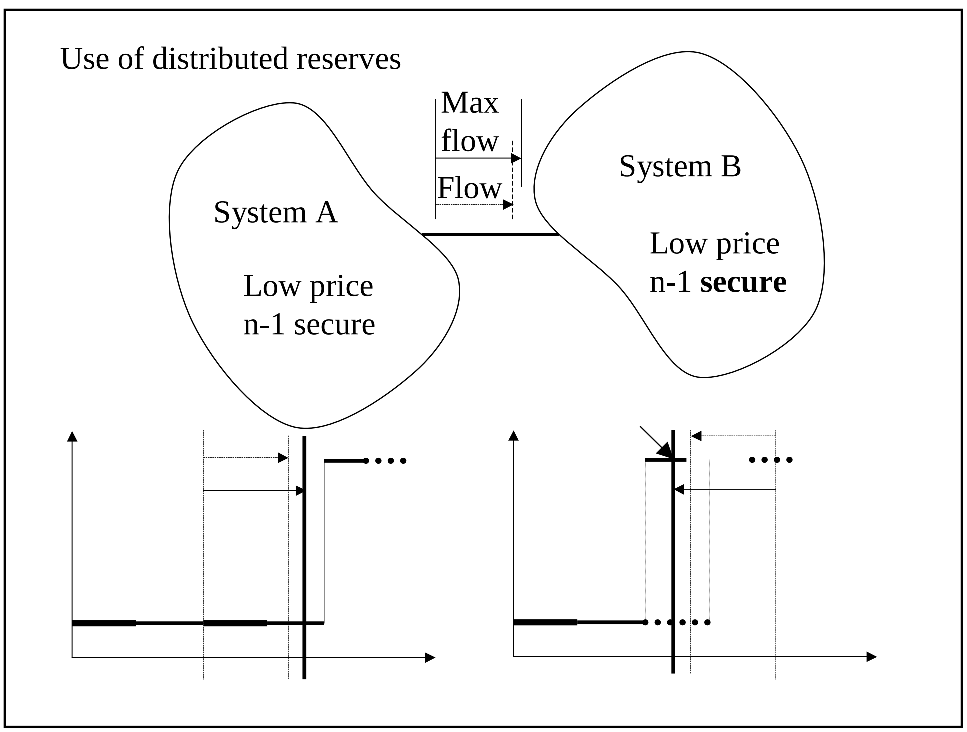

System A
Low price
Secure
System B
High price
n-1 insecure
Generator 1A
Generator 2A
Generator 3A
Generator 4A
Generator 5A
Generator 6A
Generator 1B
Generator 2B
Generator 3B
Generator 4B
Generator 5B


System A
Low price
n-1 secure
System B
High price
n-1 **secure**


System A
Low price
n-1 secure
Flow
System B
Low price
n-1 secure


Temptation: construct a composite supply curve
unnecessary
Low price
n-1 secure
+


Situation with line transmission limits
Max flow
Flow
System A
Low price
n-1 secure
System B
Low price
n-1 **insecure**
Outaged generator
Normal conditions
Max flow
Unable to clear


Use of distributed reserves
Max flow
Flow
System A
Low price
n-1 secure
System B
Low price
n-1 **secure**

Reality

- Many flowgates
- Networked sysyem
- Demand can be elastic
- Time delays important
- Generators have fixed (investment) costs and restrictions
- Load is uncertain
- Transmission outages exacerbate problems
- If one firm dominates a technology, market power occurs (next)
- If one firm dominates a location, market power results

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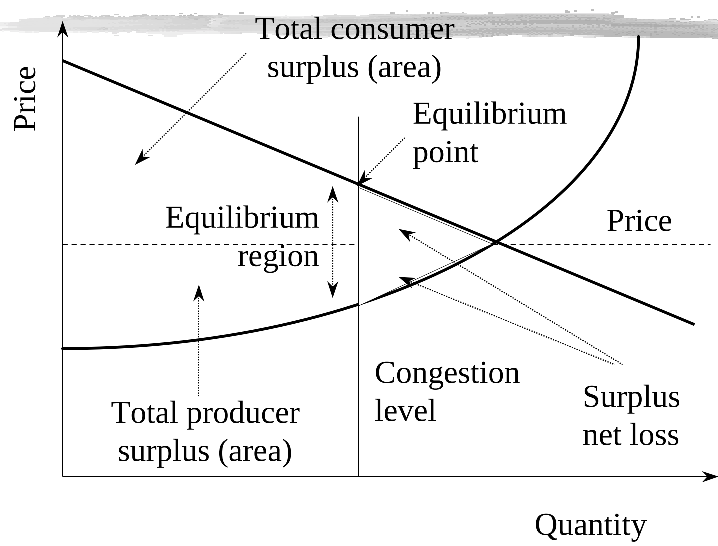
The effect of congestion



Who gets what

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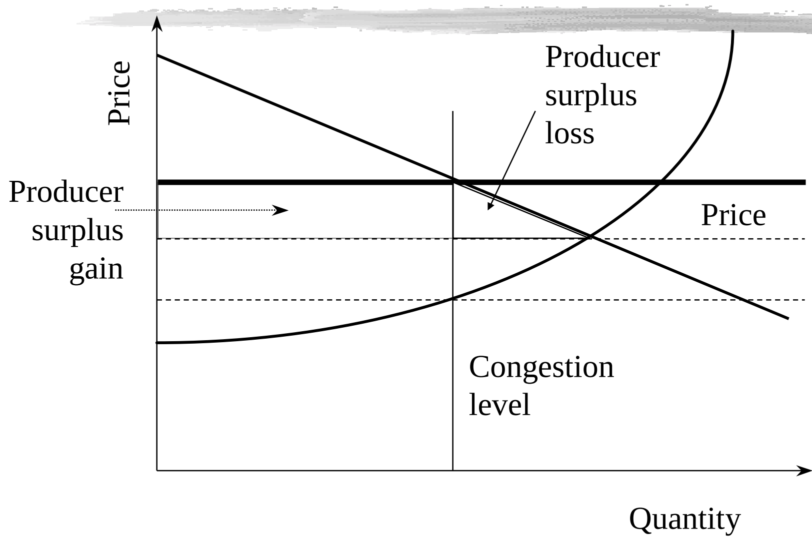

Who gets what, part II

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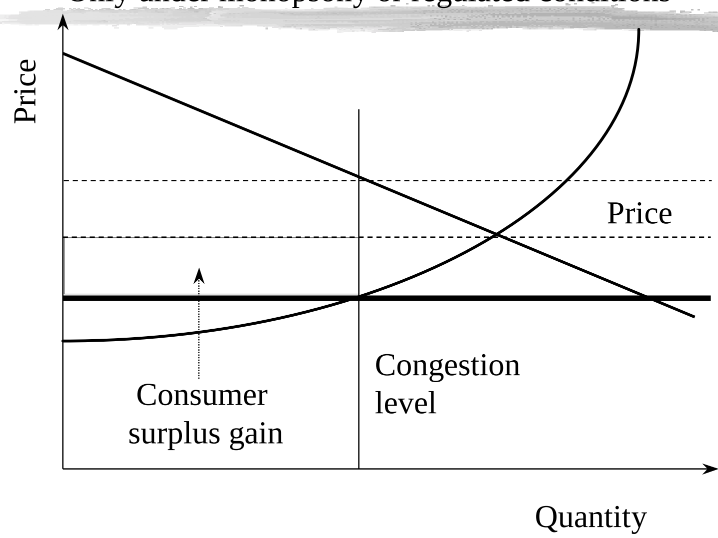
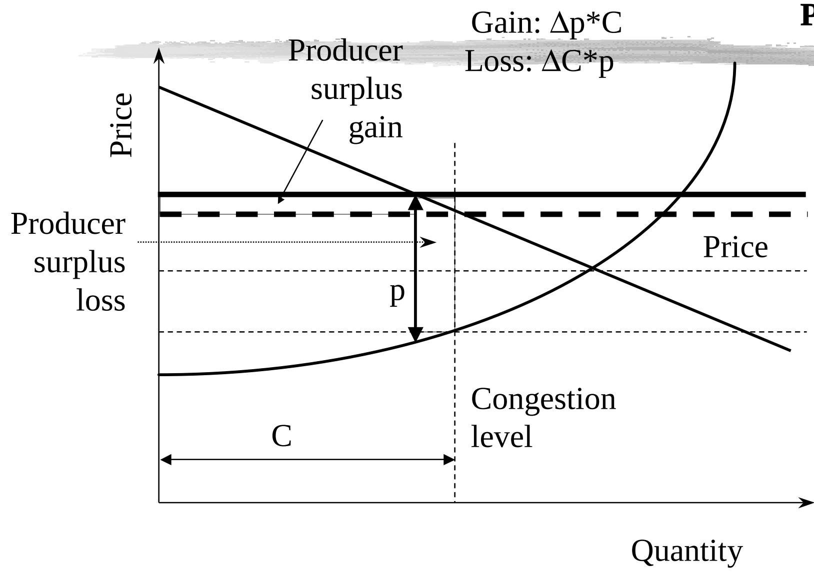
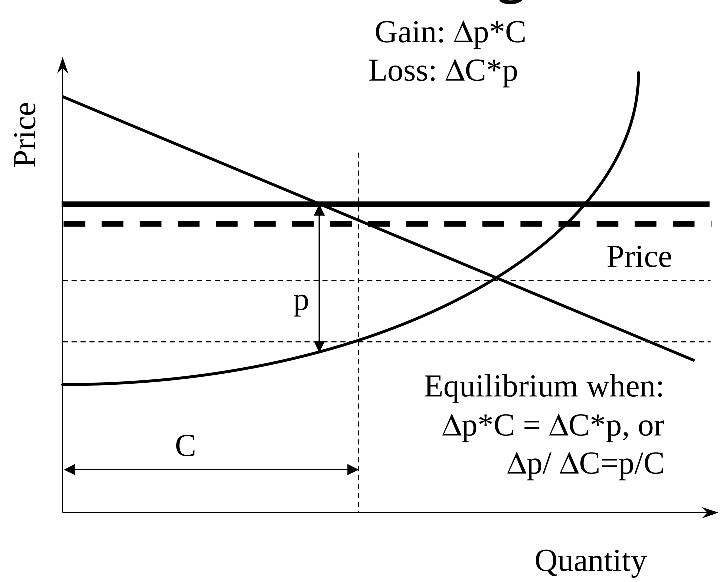
"Only under monopsony or regulated conditions"



The incentive to congest



Equilibrium with congestion



The effect of congestion

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- Congestion creates “gaming” opportunities
  - Producers have an incentive to congest
    - (Up to a point)
- The only unambiguous way to characterize the effect of congestion is to look at net surplus loss
  - Translated: when we compute congestion costs, we do not care who incurs them

Additional remarks

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- Two-technology suppliers can lead to higher than marginal prices as the knee of the supply curve is approached
- Larger number of suppliers reduces this effect
- Market power studies should consider investment recovery issues
- Transmission congestion makes matters worse!!

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Features of the example

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- Only two areas (one flowgate)
- Radial
- Demand is inelastic
- Time delays are not an issue
- Generators have no startup/shutdown costs or restrictions or minimum power levels

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Observations

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- Demand elasticity is important
- Locational aspects of reserves matter
  - LMP for reserves
- Ramping rates matter
- In deregulated markets only units explicitly committed to reserves are available
  - In regulated markets and in PJM all units are
- Reliability requires that we increase supply
  - Standby charges tend to reduce supply (Tim Mount)

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Reliability and price spikes*

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- **What has happened in California?**
  - **Price caps have come down**
  - **Average prices have increased**
  - **Price volatility has decreased**
  - **There have been involuntary curtailments**

(*) Some of this material comes from Tim Mount at Cornell

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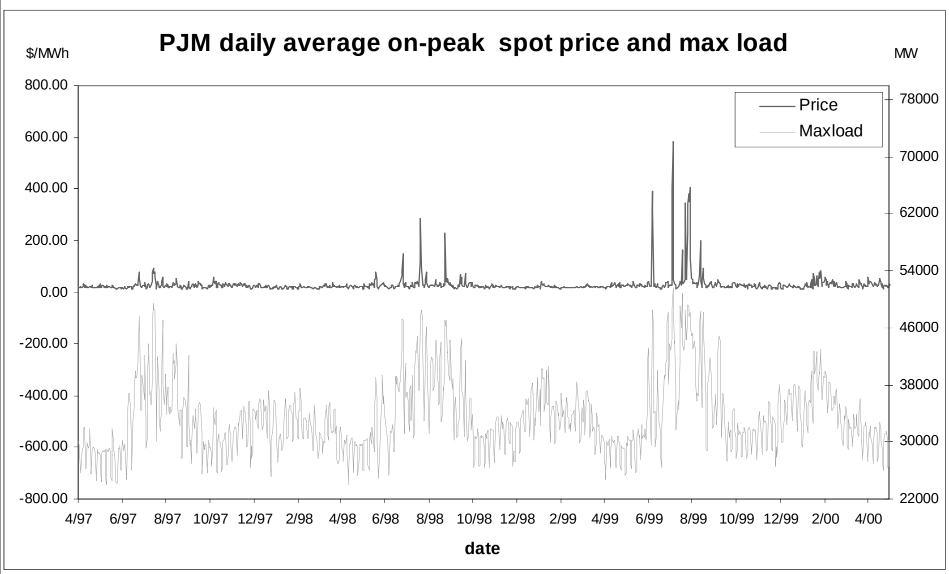
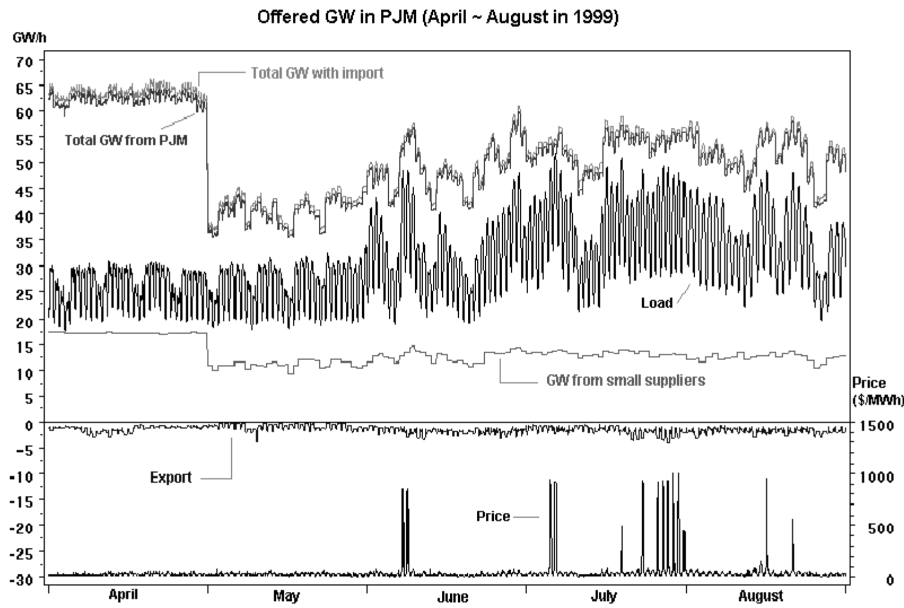
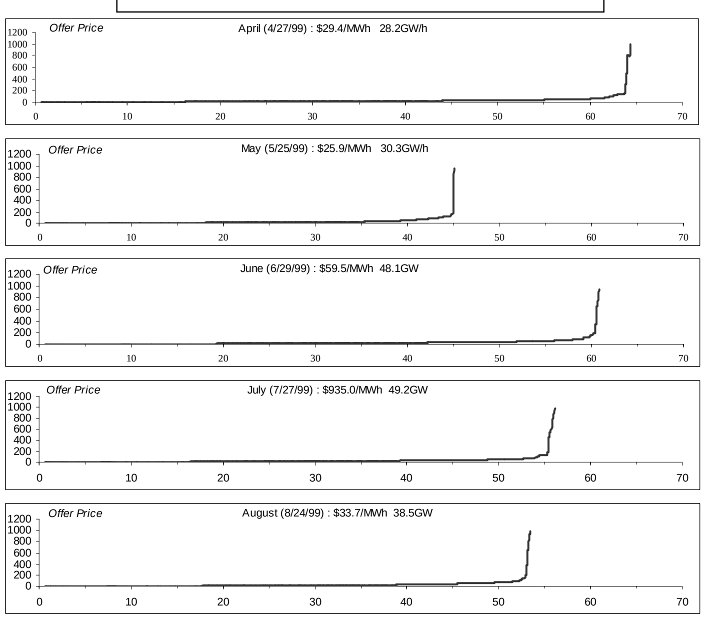




Assorted PJM offer curves



Observations

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- Price spikes have developed not so much under high load conditions as under tight reserve conditions
- For suppliers that own more than one technology, there are strong incentives to withhold capacity
- There is a strong connection between reserves and reliability (and market power)

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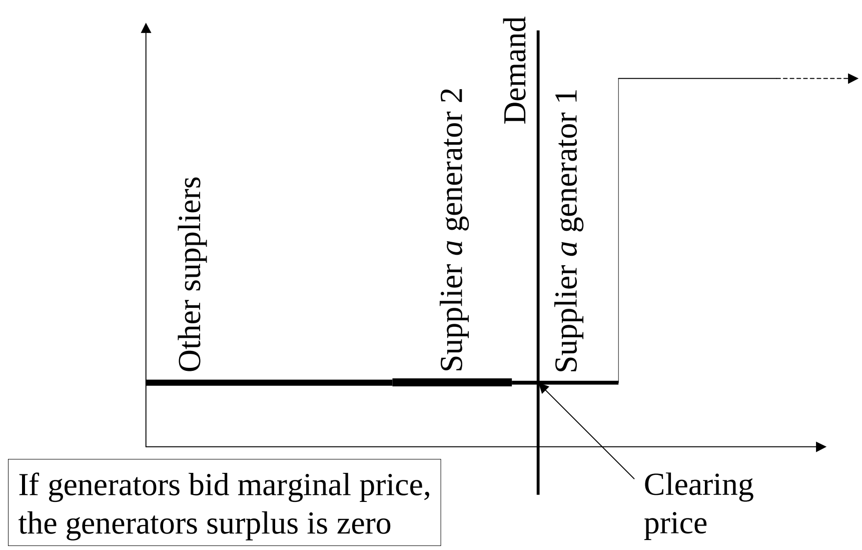
Market Power?

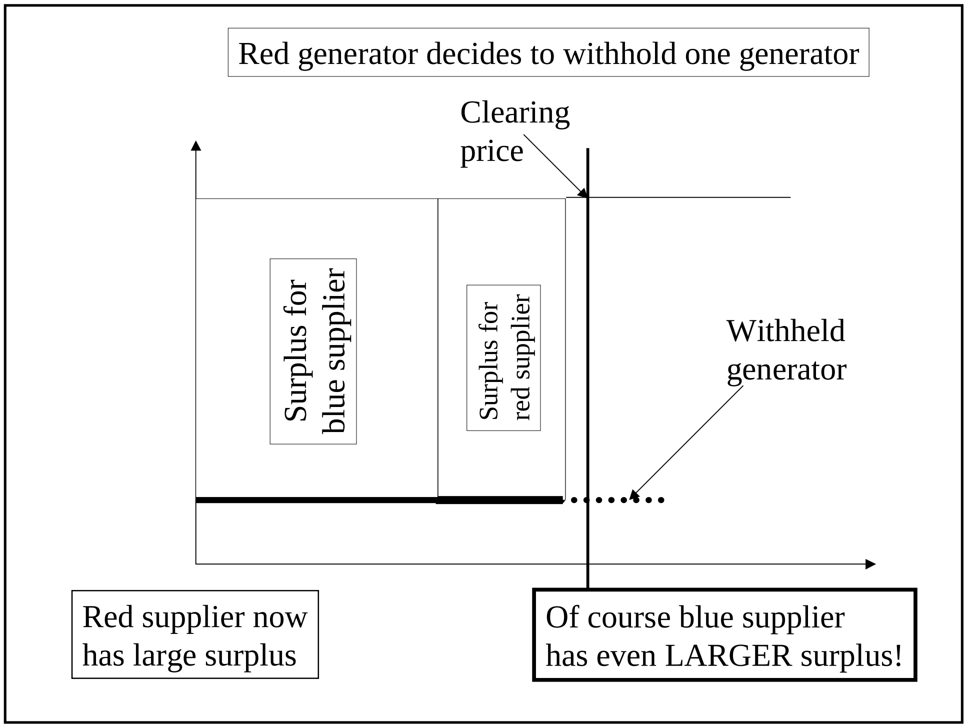
- The ability to raise prices significantly above the efficient economic equilibrium
- Disclaimer: the slides that follow are not really a market power study but rather they represent a simplified illustration of how higher prices could result as a result of market concentration.

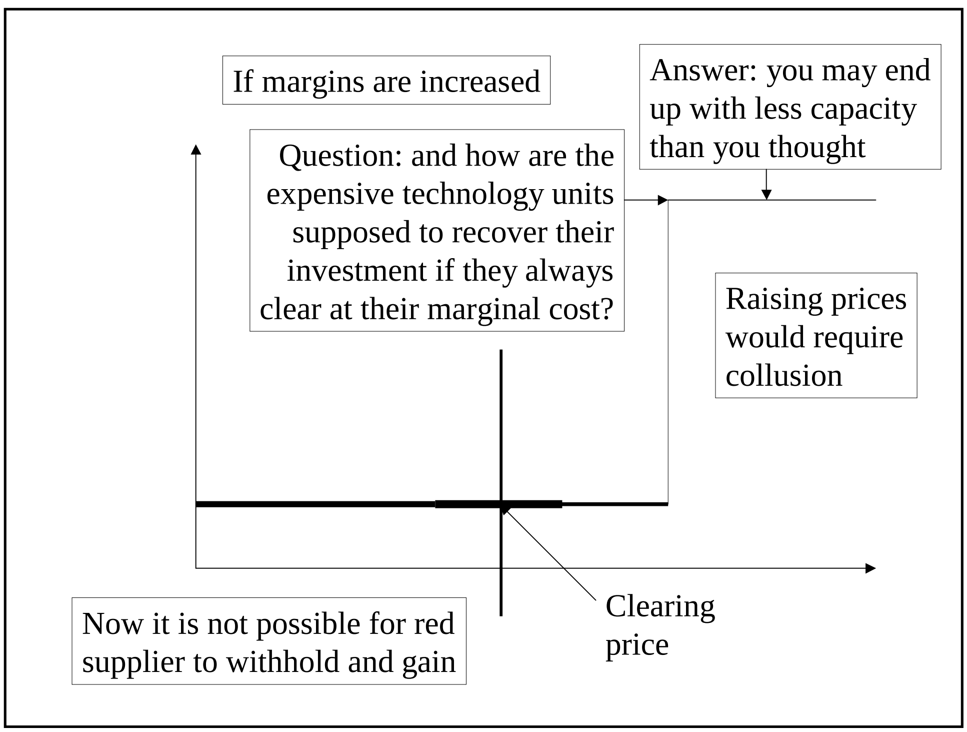
Market Power: Assumptions

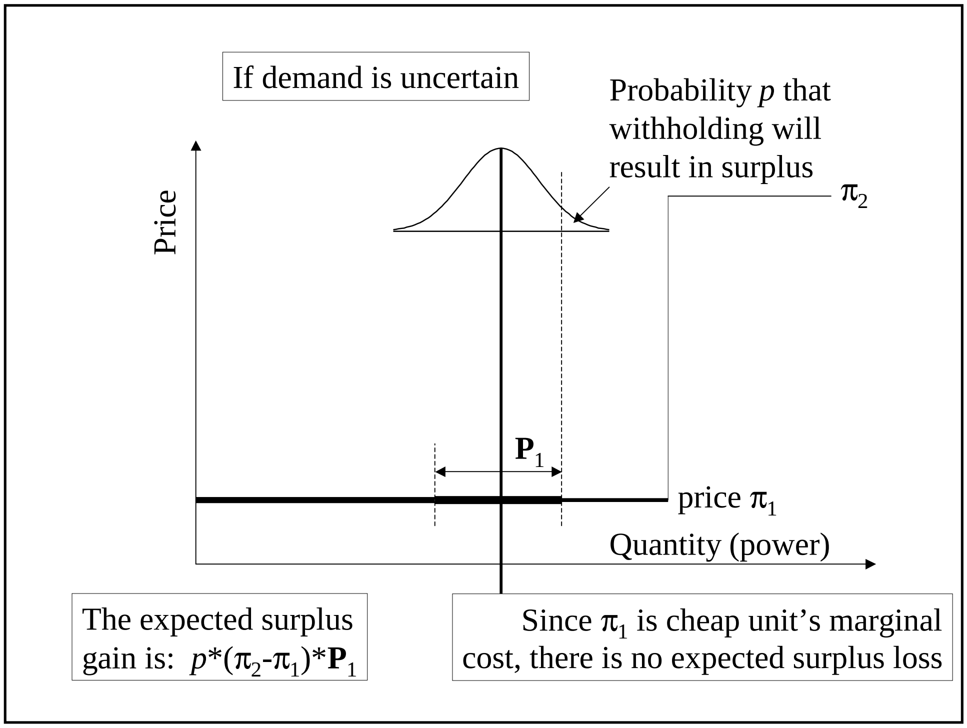
- **There are exactly two technologies**
  - **Each technology has a fixed marginal price**
  - **∞ availability of the expensive technology**
  - **Limited availability of the cheap technology**
  - **Cheap technology has fixed costs (investments) to recover**
- **Demand is inelastic**
- **All suppliers but *a* schedule all their cheap power**
- ***a* owns P MW in $n \geq 1$ equal-sized generators**
  - **Supplier *a* can "withhold" one or more generators**
  - **Bidding above marginal cost is not allowed, withholding is**

The piece-wise nature of the supply curve revisited




Red generator decides to withhold one generator
Clearing price
Surplus for blue supplier
Surplus for red supplier
Withheld generator
Red supplier now has large surplus
Of course blue supplier has even LARGER surplus!


If margins are increased
Answer: you may end up with less capacity than you thought
Question: and how are the expensive technology units supposed to recover their investment if they always clear at their marginal cost?
Raising prices would require collusion
Now it is not possible for red supplier to withhold and gain
Clearing price



Additional observations

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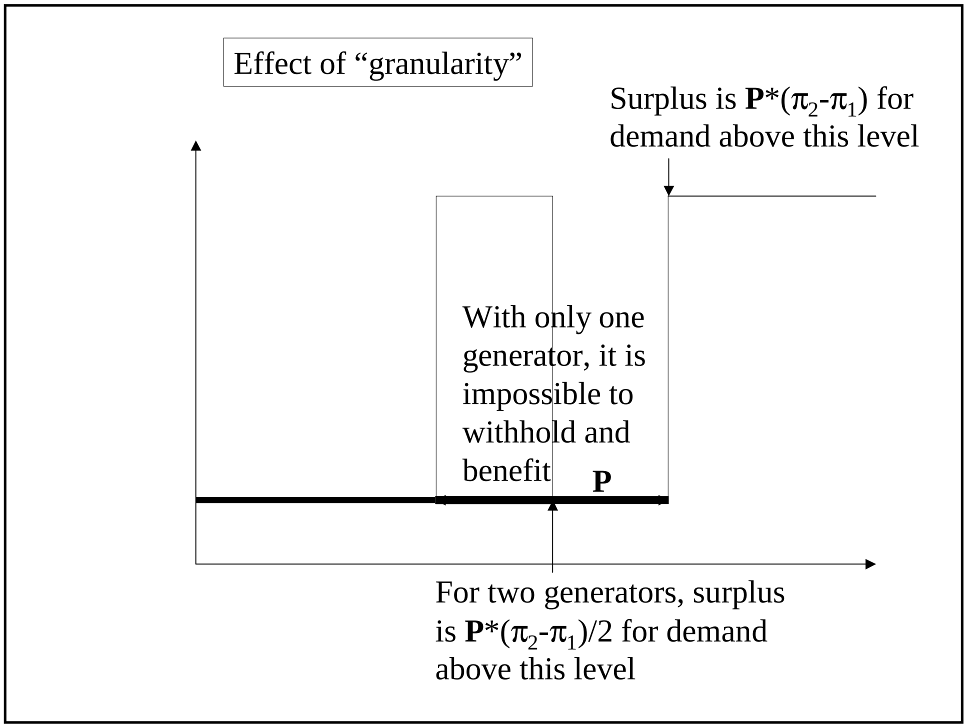
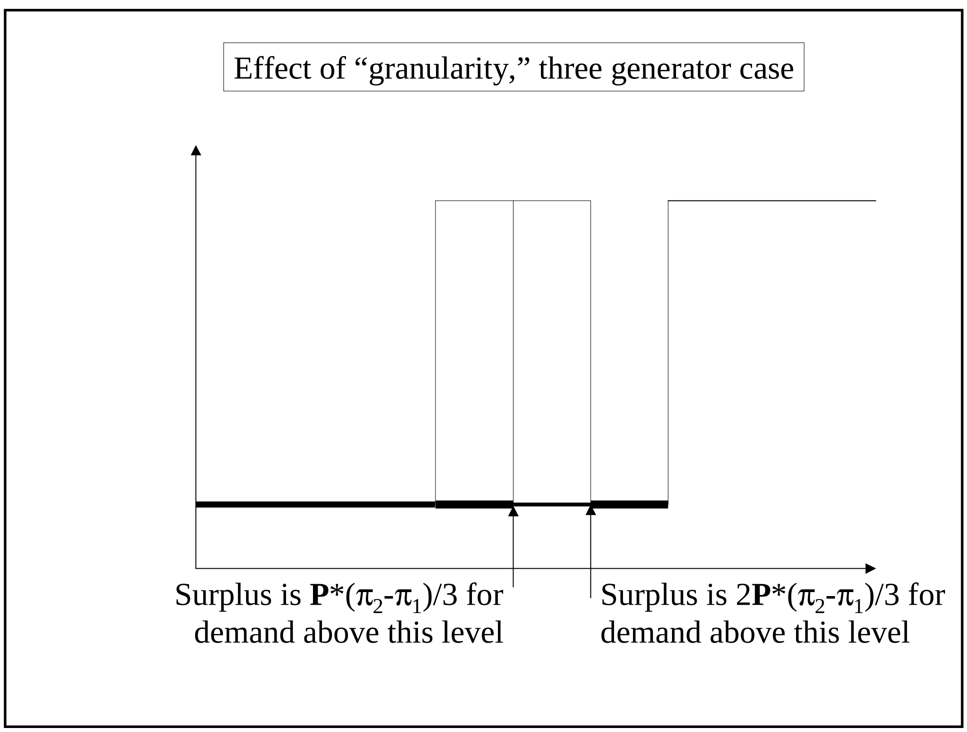
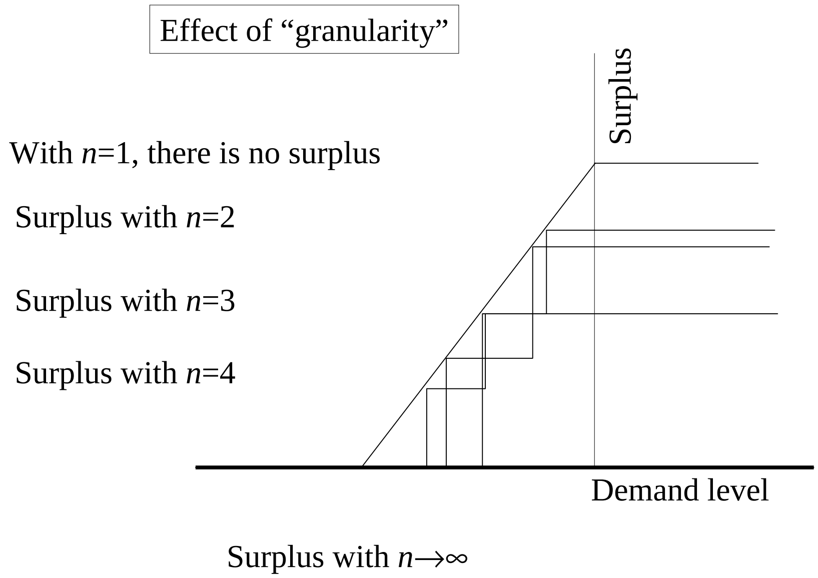
- If the margin to the "knee" is P_m, any supplier with a total ownership above P_m *may* profit from withholding
  - If more than one supplier meets this conditions, chances are that someone will withhold

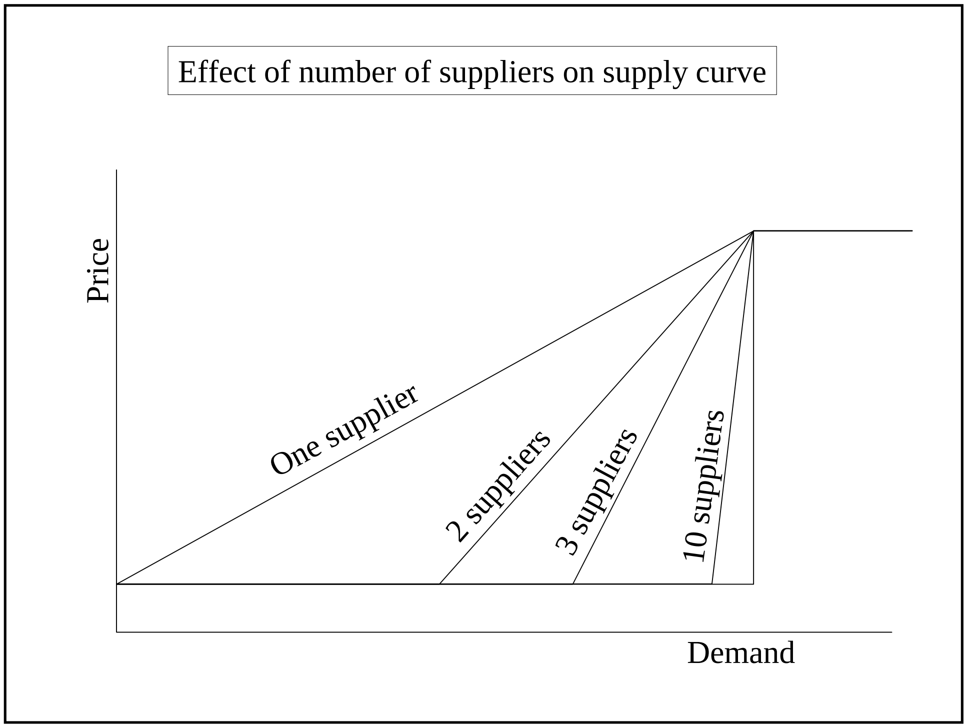

Effect of "granularity"
Surplus is P*(π2-π1) for demand above this level
With only one generator, it is impossible to withhold and benefit
P
For two generators, surplus is P*(π2-π1)/2 for demand above this level

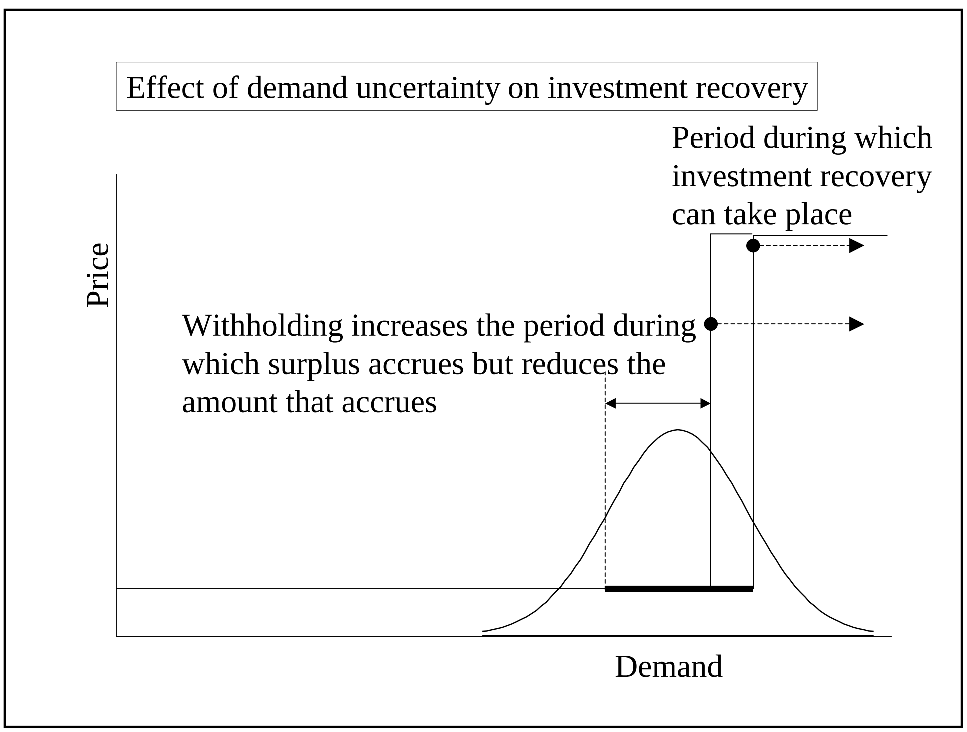

Effect of "granularity," three generator case
Surplus is P*(π2-π1)/3 for demand above this level
Surplus is 2P*(π2-π1)/3 for demand above this level



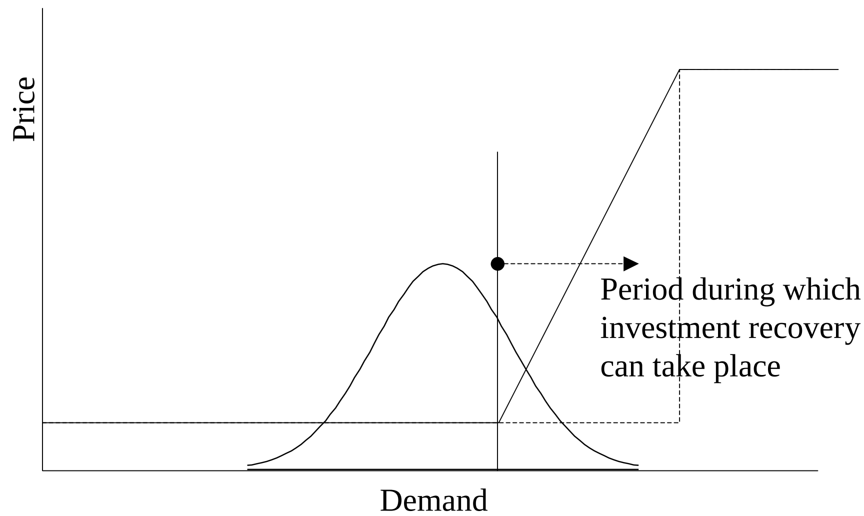
Observations and assumptions

- **For “worst case” effect, assume *n*=∞**
- **Assume withholding *will* occur**
  - **Withholding “softens” the supply curve**
- **High cost periods needed for investment recovery**
- **Demand is probabilistic**
- **Suggestion: market power occurs if expected surplus far exceeds investment recovery**
  - **This is also a signal for system expansion**


Effect of number of suppliers on supply curve
Price
One supplier
2 suppliers
3 suppliers
10 suppliers
Demand


Effect of demand uncertainty on investment recovery
Period during which investment recovery can take place
Price
Withholding increases the period during which surplus accrues but reduces the amount that accrues
Demand

The effect of demand uncertainty on investment recovery



Numerical studies

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- Demand is 60/70/80/90/95% of “knee”
- σ for demand varies from 0 to 20%
- Demand probability function is normal
- Supplier has ∞ equal size units available
- There are 3/6/10/15/∞ suppliers

We illustrate the investments that can be recovered for each of the case combinations above according to our earlier withholding assumptions

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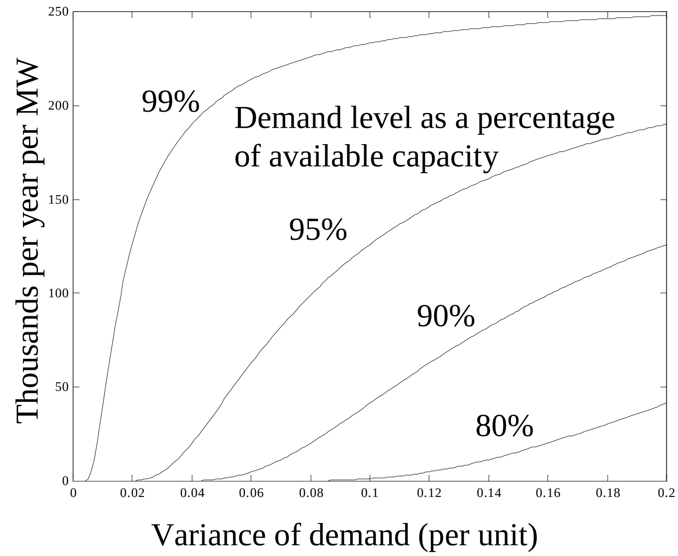
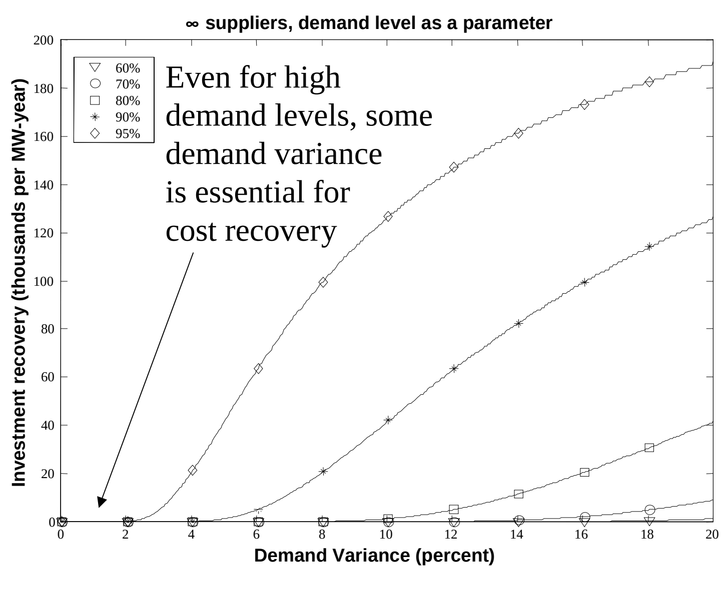
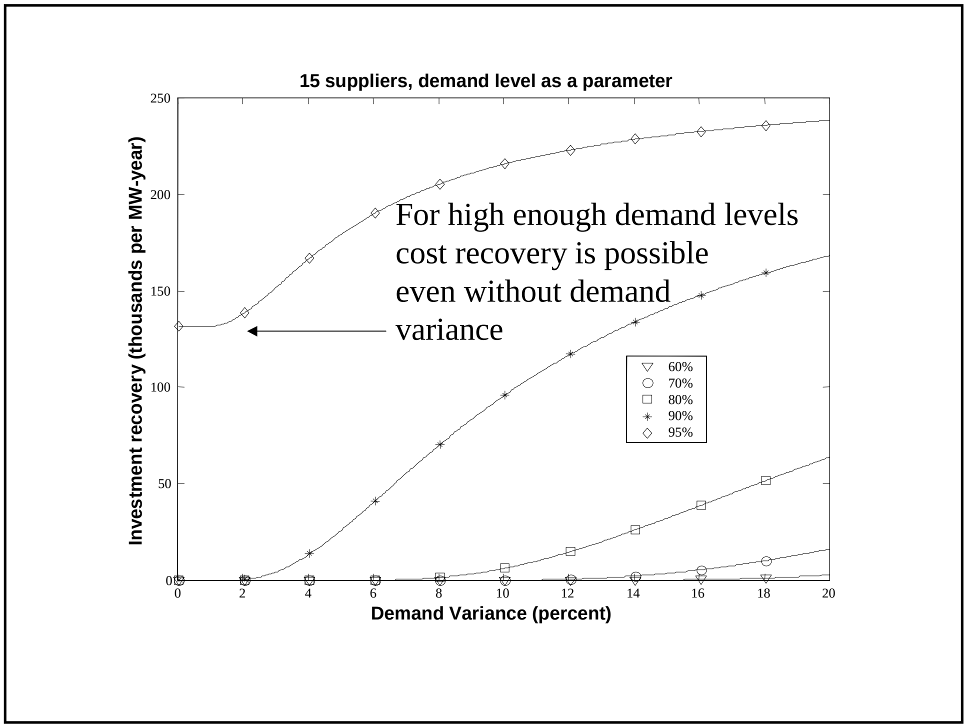
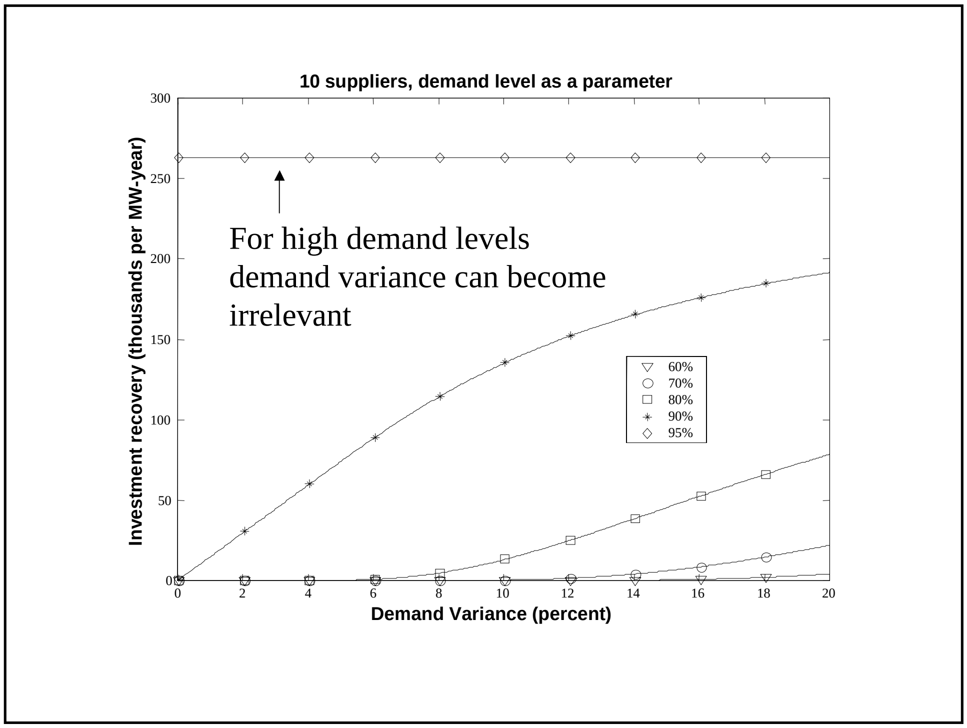
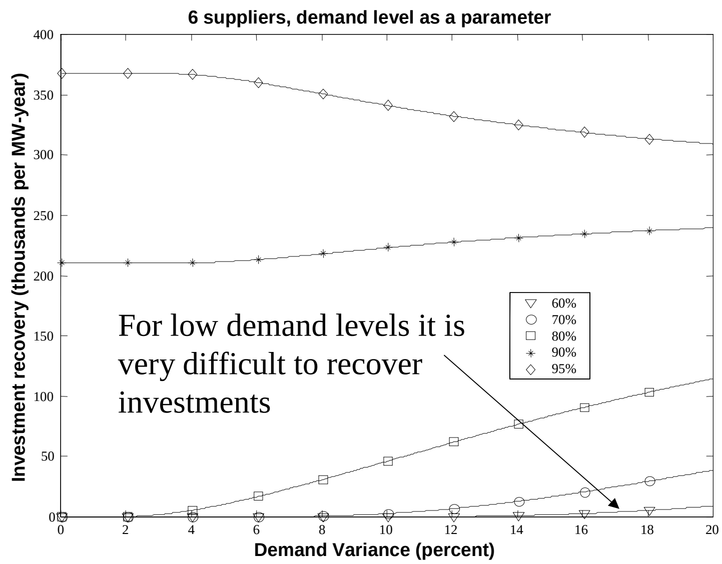
Investment recovery without market power (∞ suppliers)

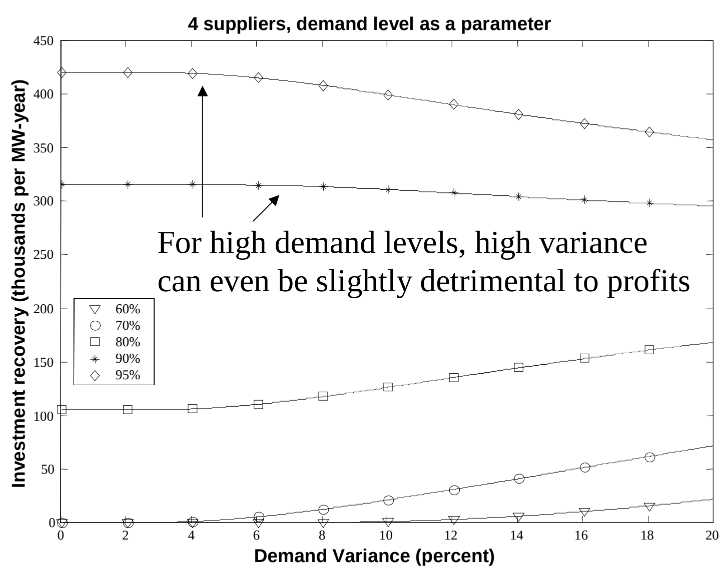


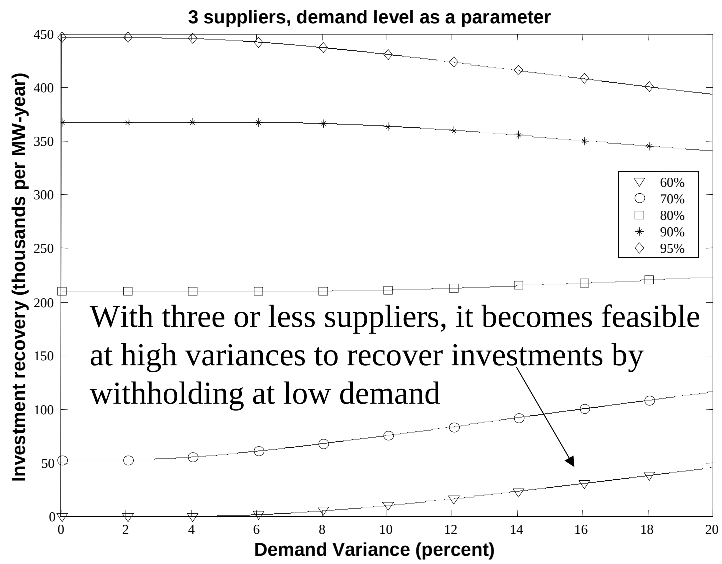


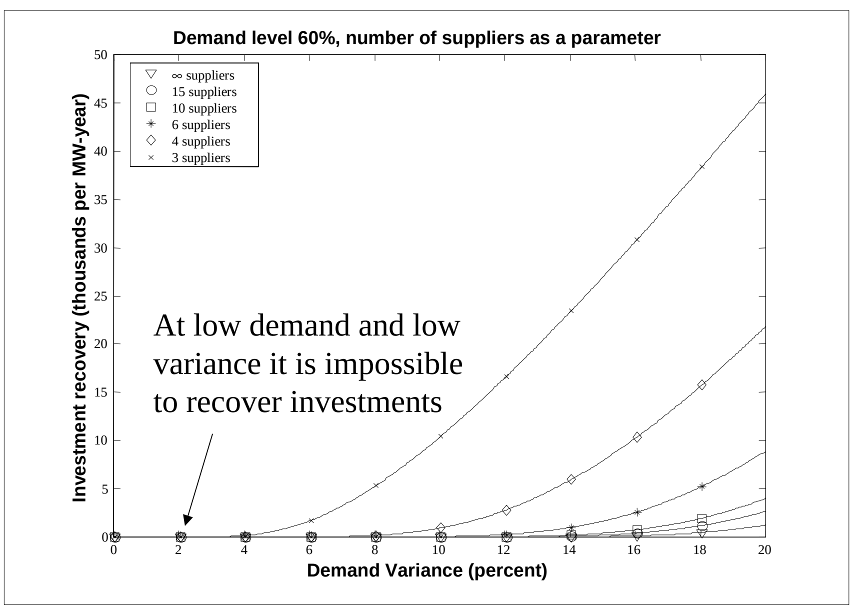

15 suppliers, demand level as a parameter
Investment recovery (thousands per MW-year)
Demand Variance (percent)
For high enough demand levels cost recovery is possible even without demand variance
60%
70%
80%
90%
95%

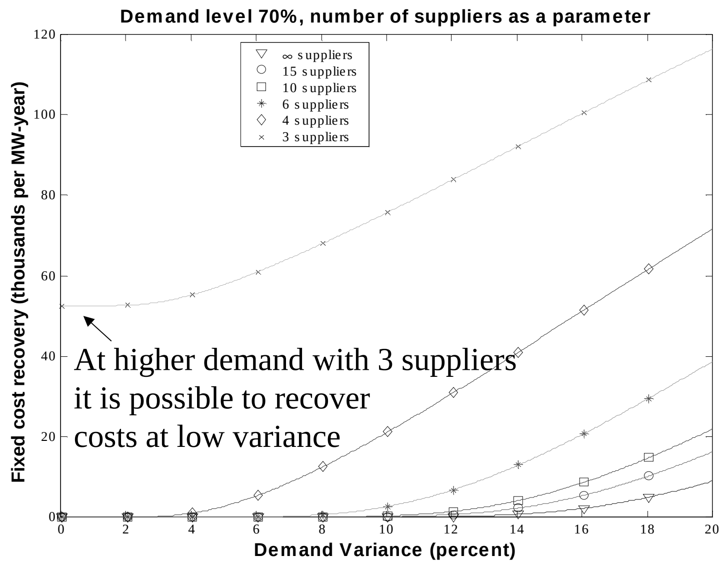

10 suppliers, demand level as a parameter
Investment recovery (thousands per MW-year)
Demand Variance (percent)
For high demand levels demand variance can become irrelevant
60%
70%
80%
90%
95%

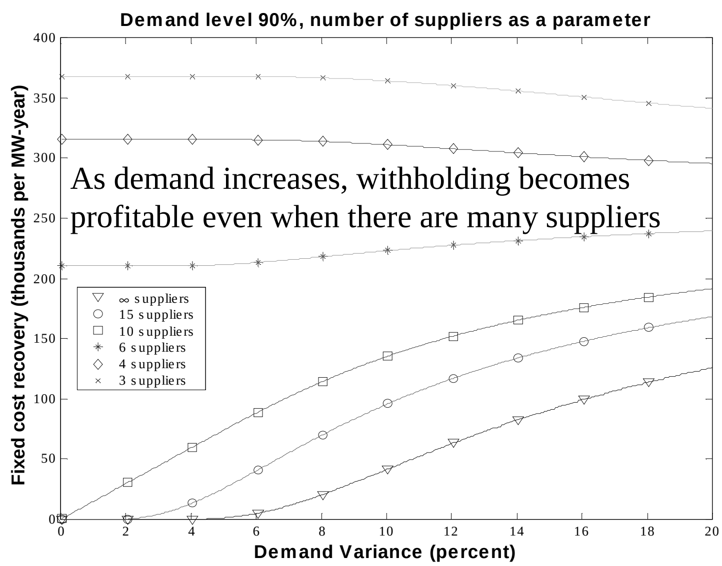

6 suppliers, demand level as a parameter
Investment recovery (thousands per MW-year)
Demand Variance (percent)
60%
70%
80%
90%
95%
For low demand levels it is very difficult to recover investments

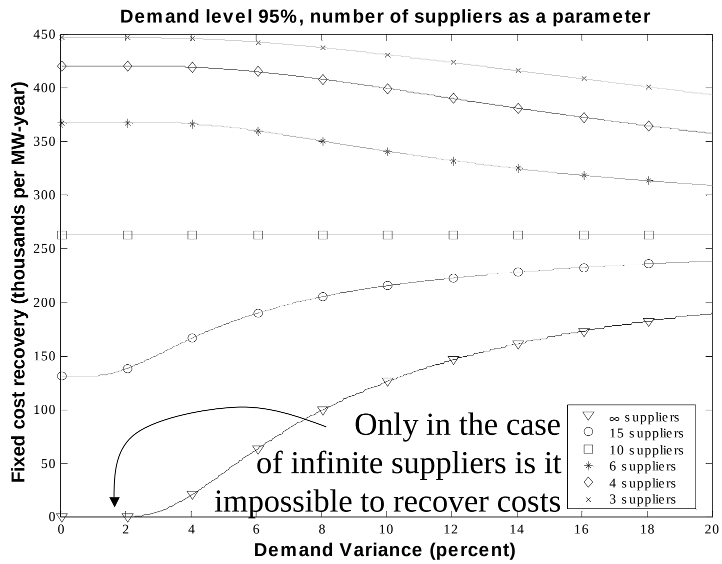

4 suppliers, demand level as a parameter
Investment recovery (thousands per MW-year)
Demand Variance (percent)
60%
70%
80%
90%
95%
For high demand levels, high variance can even be slightly detrimental to profits


3 suppliers, demand level as a parameter
Investment recovery (thousands per MW-year)
Demand Variance (percent)
60%
70%
80%
90%
95%
With three or less suppliers, it becomes feasible at high variances to recover investments by withholding at low demand


Demand level 60%, number of suppliers as a parameter
Investment recovery (thousands per MW-year)
Demand Variance (percent)
∞ suppliers
15 suppliers
10 suppliers
6 suppliers
4 suppliers
3 suppliers
At low demand and low variance it is impossible to recover investments


Demand level 70%, number of suppliers as a parameter
Fixed cost recovery (thousands per MW-year)
Demand Variance (percent)
∞ suppliers
15 suppliers
10 suppliers
6 suppliers
4 suppliers
3 suppliers
At higher demand with 3 suppliers
it is possible to recover
costs at low variance


Demand level 90%, number of suppliers as a parameter
Fixed cost recovery (thousands per MW-year)
Demand Variance (percent)
As demand increases, withholding becomes
profitable even when there are many suppliers
∞ suppliers
15 suppliers
10 suppliers
6 suppliers
4 suppliers
3 suppliers



Comments on numerical results

- **The number of suppliers has a strong influence on investment recovery**
  - **Below a certain number of suppliers, investment recovery by withholding becomes easier**
- **There are demand thresholds beyond which there is a jump in the ability to recover investments**
- **All studies have assumed that supplier adjusts withholding *after* learning the demand**
- **Demand variance affects reliability**
  - **It also influences the ability to recover investments**

Final remarks

PSERC

- Reliability not decoupled from economics
  - Tight reliability precursor to price spikes
- The structure of two-technology suppliers can lead to higher prices as the “knee” of the supply curve is approached
  - More suppliers reduce this effect
- Market power studies should consider investment recovery, locational effects
- Congestion, loop flows, voltage, frequency are also important

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