The Economics of Electric Power Networks

Steven Stoft

March 5 − 16, 2007

Master Erasmus Mundus EMIN, Paris

Four problems

1. Find the best prices for dispatch and consumption
2. Find the best prices for investment (in an ideal world)
3. Can the market solve the reliability problem?
4. Transmission investment: Is the market better than planning?

- These are the 4 main economic problems of electricity markets.
- All problems are part engineering and part economics.
- System security is a fifth problem—but mostly an engineering problem.
- Electricity is the only network with prices that change every 10 minutes.
- Can these same prices work for 30 year investments?

Introduction to Electricity

Abbreviations (reference slide)

CLPs	Competitive locational prices			
CRR	Congestion revenue rights			
FC	Fixed cost			
GT	Gas turbine (~jet engine)			
CC	Combined cycle (GT with steam turbine)			
MC	Marginal cost			
SO	System operator		References	
VOLL	Value of lost load		Available at: `stoft.com/p/erasmus.html`	
⇒	Implies	PSE	*Power System Economics*, Stoft, IEEE press, 2002	
plant	Generating station			
		ICAP	Convergence of Market Designs for Adequate Generating Capacity, Cramton & Stoft, 2006	
		Fewer prices	Fewer Prices than Zones, Electricity Journal, 1998	
		Tx Invest	Transmission Investment, Ch. 2, ***Competitive Electricity Markets & Sustainability**, François Lévêque, Edward Elgar, publisher, 2006*.	

Measuring electric power & energy

- **1 kW** = 1 kilowatt = 1,000 Watts = **Power**

  1 kW will power ten 100-Watt lights.

  1 kW will burn out one 100-Watt light in a flash.

- **1 kWh** = 1 kilowatt-hour = **Energy**

  1 kWh will power ten 100-Watt lights for 1 hour.

  1 kWh will power one 100-Watt light for 10 hours.

- **1 MW** = 1 megawatt = 1,000 kW

- **1 GW** = 1 gigawatt = 1,000 MW

(1 mW = 1 / 1000 Watts)

Types of power plants

2007	Cost € / kW	Size MW	FC/Cap. € / MWh	Output/ Size*	FC/Out € / MWh	MC/Out € / MWh	Total € / MWh
GT	340	160	6	1%	602	68	670
CC	475	250	8	40%	21	42	63
Coal	1030	600	18	90%	20	14	36
Nuclear	1680	1200	30	90%	33	2	36
Wind	965	1.3	17	30%	57	0	57

Gas CC = Combined Cycle = gas turbine + steam turbine.

Cost = Fixed costs as a one-time cost.   Output / Size = Capacity Factor.

FC / Cap = Fixed cost per MWh of capacity

FC / Out = Fixed cost per MWh of output

Plant cost data are from US DOE. Currency conversion = 1.3 dollar / euro.

* Capacity factors can vary widely between plants.

Fixed cost units: € / MWh ?

- All calculations will use **€ / MWh** for both fixed and marginal cost.

- This is unusual, but simple and correct.

- Suppose a 1MW line or generator cost 60,000 €.

- To rent it would cost ~ 8760 € / year.*
  (discount rate, taxes and 20-year payback period)

- There are 8760 hours / year.

- Rental cost = 1 € per hour for each MW.
  $$= 1 \text{ € / hour / MW} = 1 \text{ € / MWh.}$$

* A business calculation, not adjusted for inflation or technical progress.

Introduction to electricity

- Electricity flows from the power plant to the consumer at 200,000 km/second, and cannot be stored.

- Some power plants must constantly change their output.

California ISO Load, Feb. 26

- Coal plants "ramp" up and down slowly, ~3 MW / minute
- Gas turbines (GTs) and hydro ramp up and down quickly.
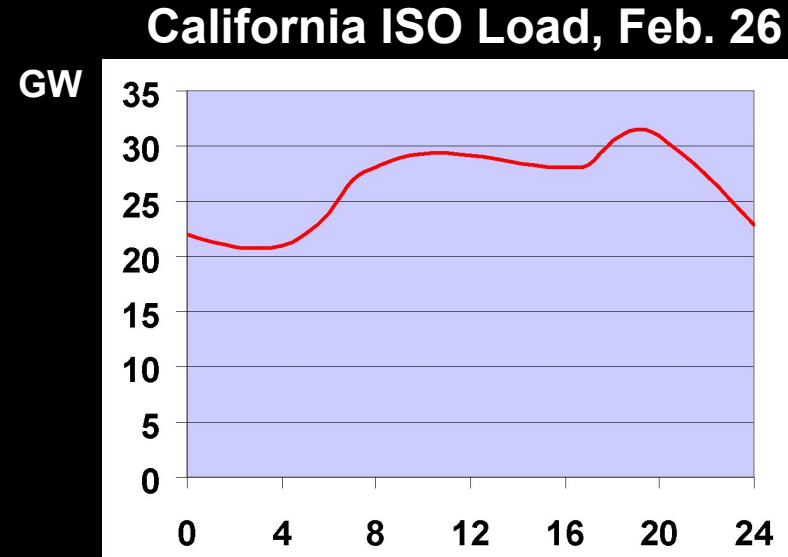
PJM's load duration curve, 2005

GW

For example, PJM's Load was greater than 90 GW 20% of the time during 2005.
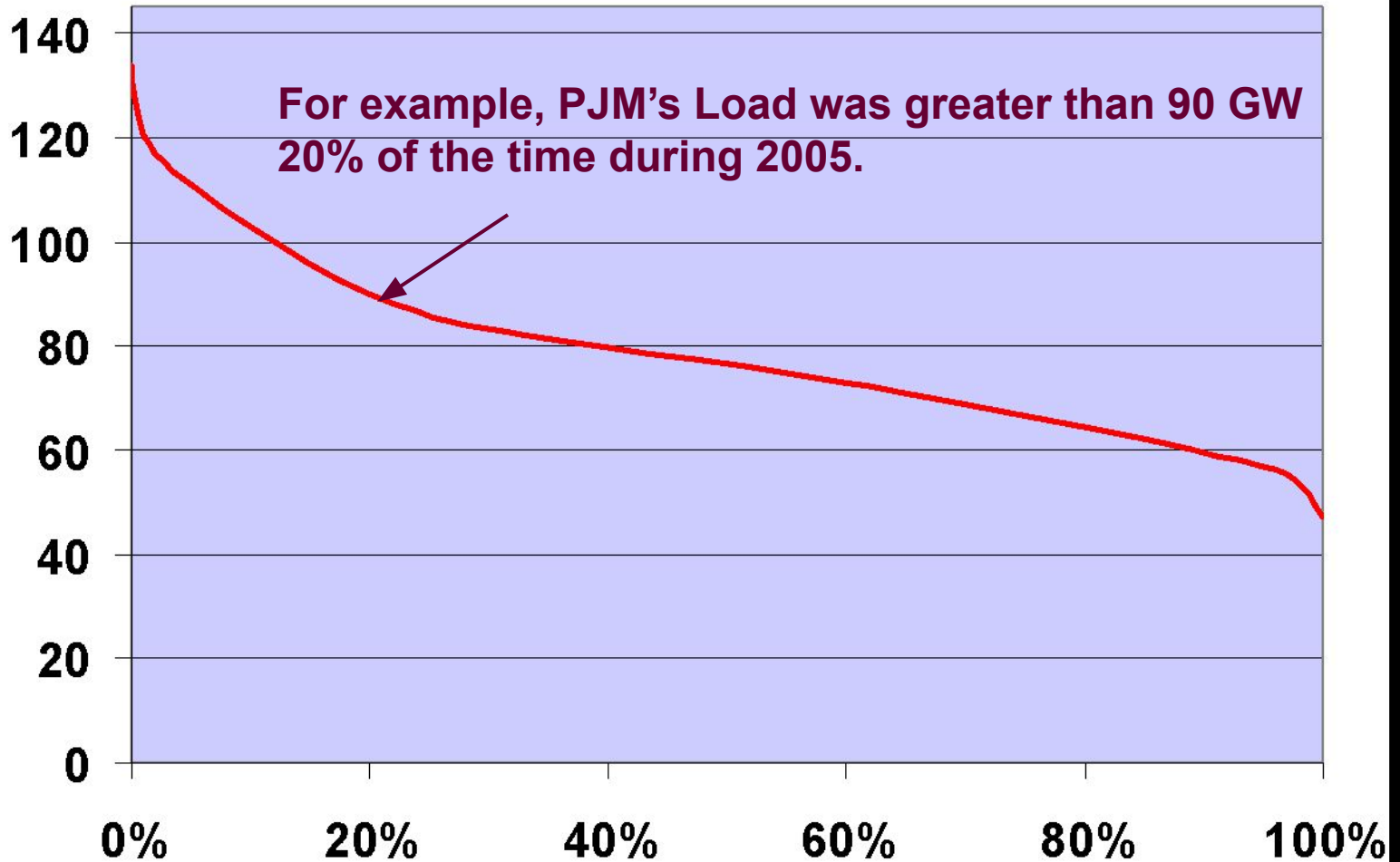
Generating Stations
(power plants) and
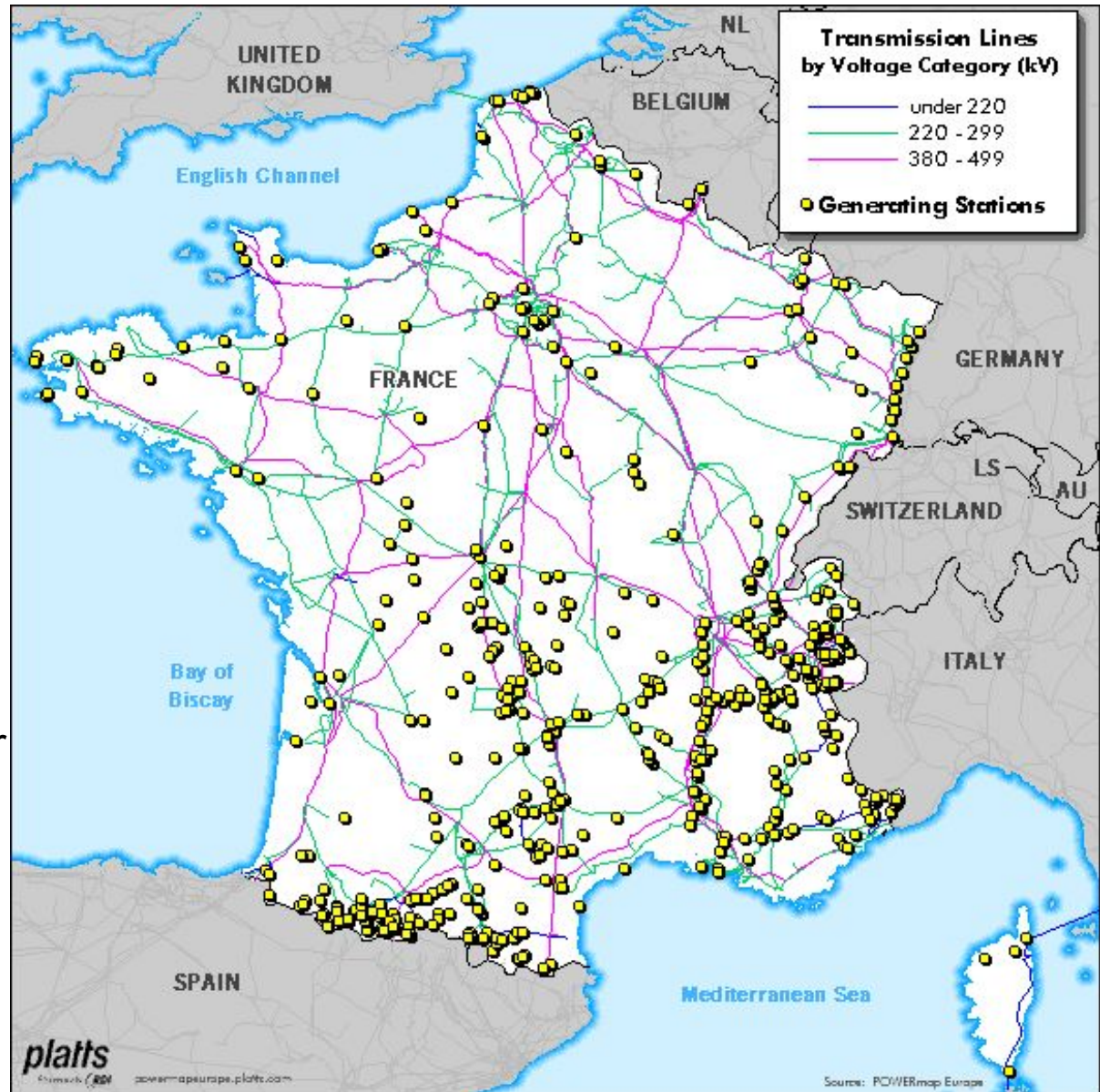
Transmission Lines
(the grid)

Pink lines are 400 kV
(??)

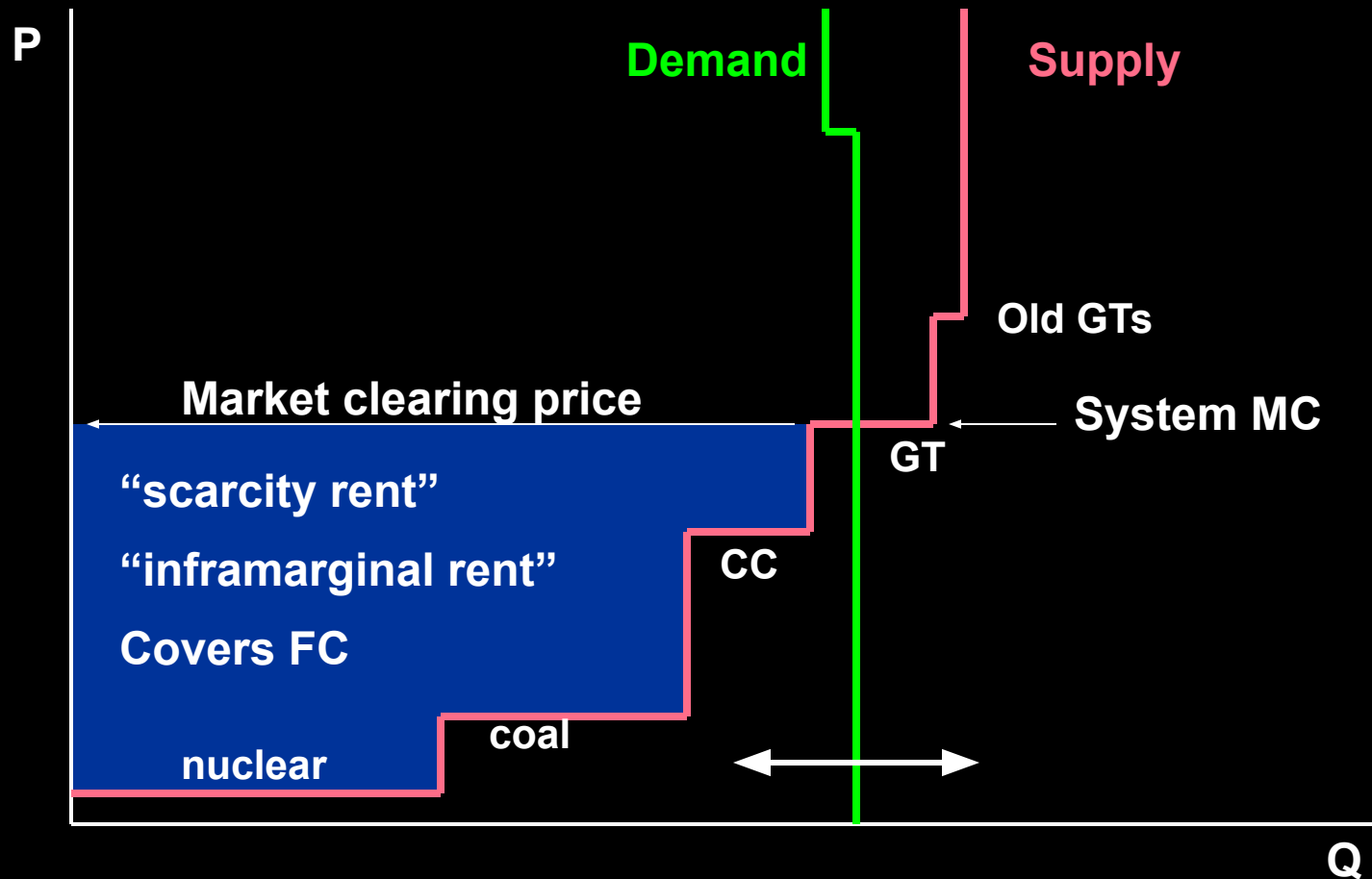Sparks jump 1 cm in dry air for each 10 kV.

But on a 400 kV line maximum voltage difference may be near 800kV

AC power: the ultimate network

- Electric power flows through the space around the power lines in an electromagnetic field.

- This field rotates 60 times per second like the rotating steel shaft which carries power from your car's engine to it's wheels—but it is *much* stronger.

- All generators are connected to this rotating field and rotate exactly together even when 1000's of km apart.

- A connected generator cannot be stopped without breaking it. (To stop, first disconnect.)

- The AC network is one giant machine connecting every power plant to every home.
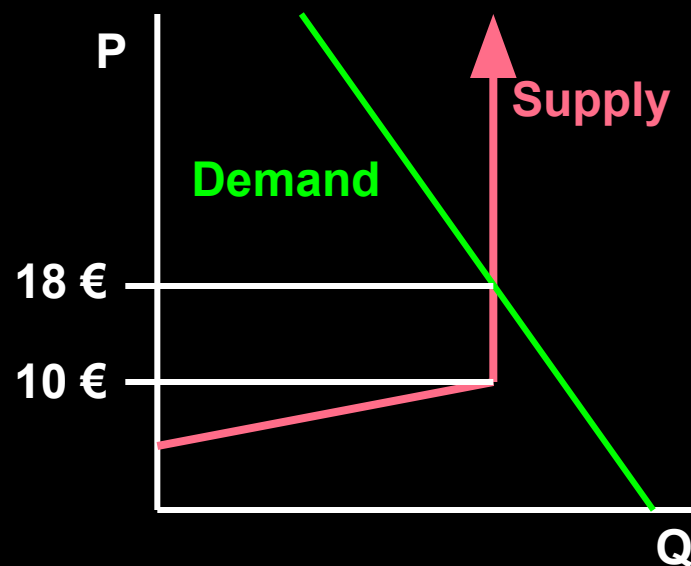
Typical electricity market

P

Demand **Supply**

Old GTs

Market clearing price · · · · · · · · · · · · · · · System MC

GT

"scarcity rent"

"inframarginal rent" CC

Covers FC

coal

nuclear

Q

Some basic economics for electricity

Assume competitive supply and competitive demand curves.

P | Demand | Supply
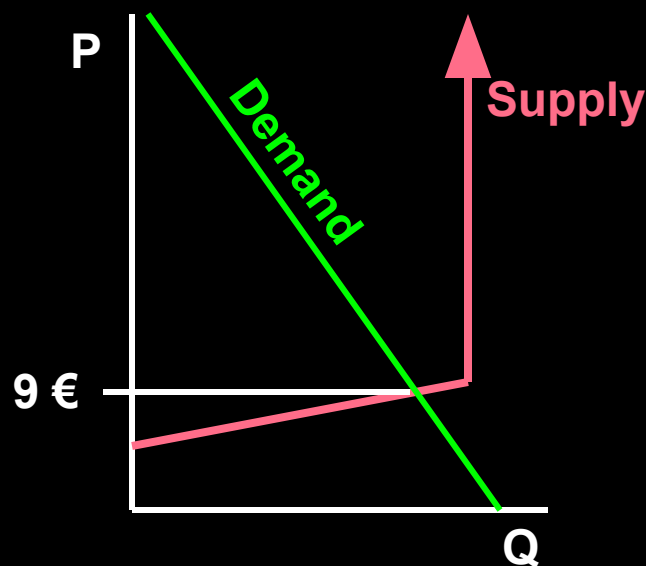
Competitive price = 9 €.
MC = 9 €
MV = 9 €

9 €

Q

P | Demand | Supply

18 €

10 €

Q

Competitive price = 18 €.
Marginal value = 18 €.
The marginal cost is ambiguous,
but: 10 € < MC < infinity.

Many say that competitive price > MC. This is false.

Reality is simpler

It's simple to think the supply curve is absolutely vertical, but this makes the math more difficult because MC goes to infinity with an infinitesimal change of output.

In reality, MC goes from low (~30 €) to infinity with about a 3% change in output.

There is no discontinuity.

The math is simple and ordinary.

High MC = probability of breakdown × the cost of a breakdown.

P

Demand

Supply

Not vertical

18 €

10 €

Q
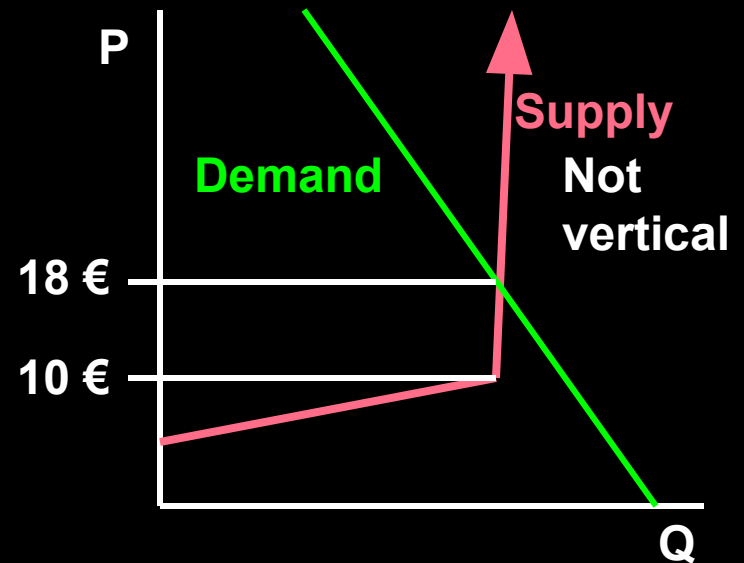
Competitive price = 18 €.
Marginal value = 18 €.
Marginal cost = 18 €.
No ambiguity!

A dangerous confusion

- If there is no market power, P = MC.
- If P = MC, peakers cannot cover FC.
- This proves "We need market power."
- Some market power is good.
- When the price is high, it is impossible to tell if it is from good market power or bad market power.
- To find bad market power, you must watch profits for years.
- It's bad to watch profits—they are private.
- Looking for market power is a bad idea.

The truth about market power

- In a well-designed market
  - No market power is needed (none, zero).
  - Market power is bad.
  - The perfectly competitive price can cover all FC.
- Every market has some market power.
- A little market power does little harm.
- Don't worry about a little, but don't encourage it.
- Monitor the market for significant market power.

(Lecture 3 will cover the problem of "no competitive price," but market power is still not needed.)

Problem #1

Prices for Dispatch and Consumption

The old central dispatch problem

- Some generators cost more to run.
- Some are in the wrong location.
- Minimize the cost of the dispatch.

- **The Old Solution:**
- Collect all the cost and transmission-line data.
- Solve a linear program.
- Tell each power plant when to start and how much to produce.

New central dispatch problem

- Find the prices that will cause
- power plants to produce power a least cost
- and consumers to use power efficiently.

- **The New Solution:**
- Have power plants bid:
  - Marginal cost, Startup cost, … ?
- Collect transmission data.
- Solve for the competitive prices.

The role of central dispatch

- Without central control:
  - (1) consumers could steal electricity.
  - (2) the traders would melt the transmission lines.

- The <u>system operator</u> (SO) controls the system

- With a market, does the SO need to set prices?
  - (1) No. Pravin Varaiya (UC Berkeley) has shown that the SO could just limit bilateral trades to protect the power lines and the market could figure out the prices.
  - (2) This has never been tried.
  - (3) Pure bilateral trading would probably be less efficient.
  - (4) That's why we have stock exchanges.

Competitive locational prices, CLPs

- Prices used for dispatch are called
  - "nodal prices," "locational prices"
- Nodal prices may not be competitive prices.

  CLPs are efficient. ⬜ True.

  Nodal prices are efficient. ⬜ May be false.

- CLP is my term. If I am talking about <u>competitive</u> prices, I will say CLPs, otherwise, I may say, "nodal."

Are CLPs "centralized prices"?

- No.

- The are just ordinary competitive prices.

- They can come from a centralized auction.
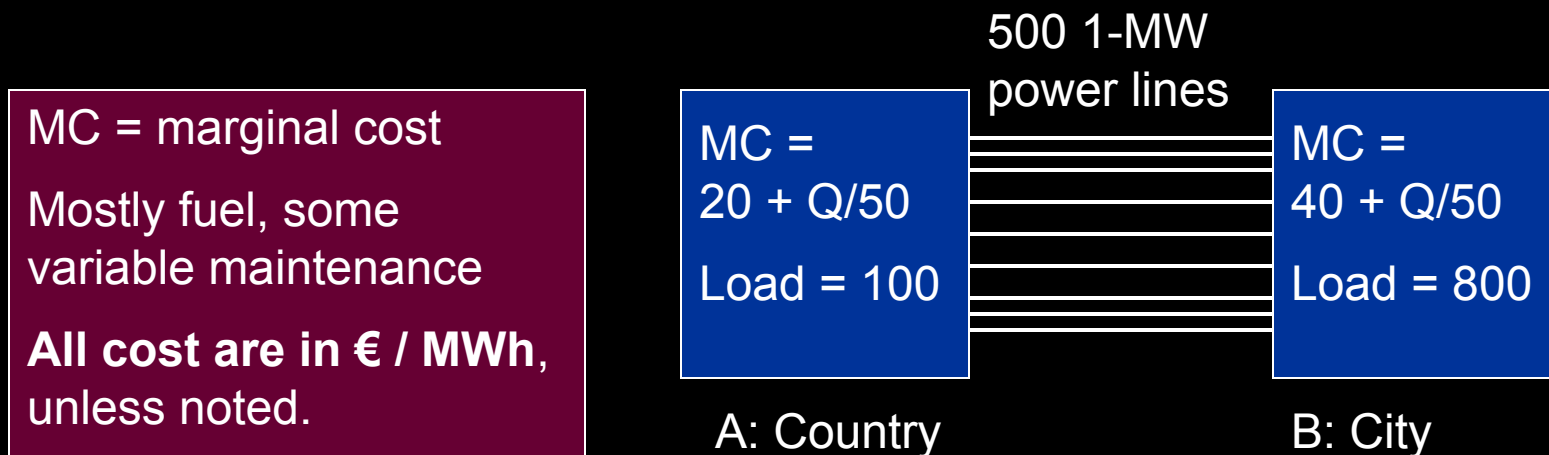
- They can come from bilateral trading.

  (Bilateral trading is trading between two parties rather than trading with an exchange or a central market.)

What are CLPs like?

- They depend on the physics of power flow and transmission limits.

- They seem wrong to most people, and most people don't like them.

- When they are not all the same, a big market may have 2000 different prices.

- They change every 5 or 10 minutes.

- The are the only prices that cause efficient dispatch, investment, and consumption.
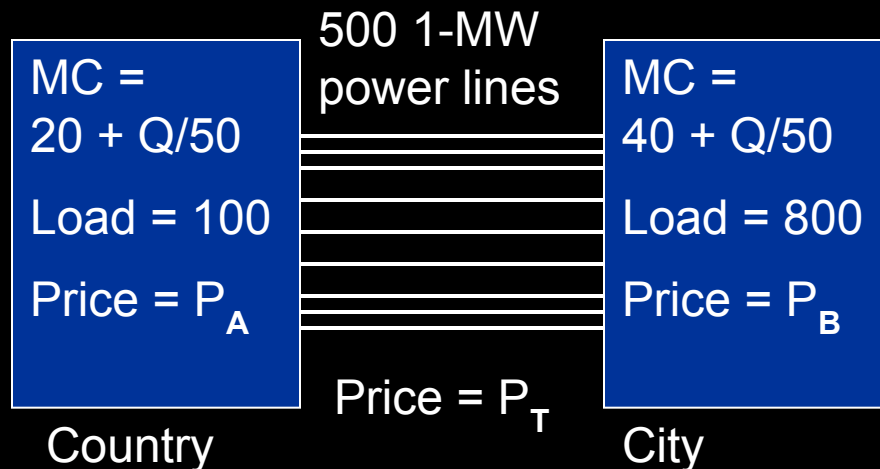
Finding CLPs: an example

- Two regions with many small generators
- Many small connecting lines. Different owners
- What are the competitive prices for
  - Power in the remote location?
  - Power in the city?
  - Use of a power line?

500 1-MW power lines

MC = marginal cost

Mostly fuel, some variable maintenance

All cost are in € / MWh, unless noted.

MC = 20 + Q/50

Load = 100

A: Country

MC = 40 + Q/50

Load = 800

B: City

Finding CLPs: an example

- Power will be more expensive in the city, so city folks will pay to use a line and buy power from the country. They will pay $P_B - P_A$, but no more.

- $P_T = P_B - P_A$

- Does $P_T = 0$, or is $P_T > 0$??

$P_T > 0$ means

the lines are congested.
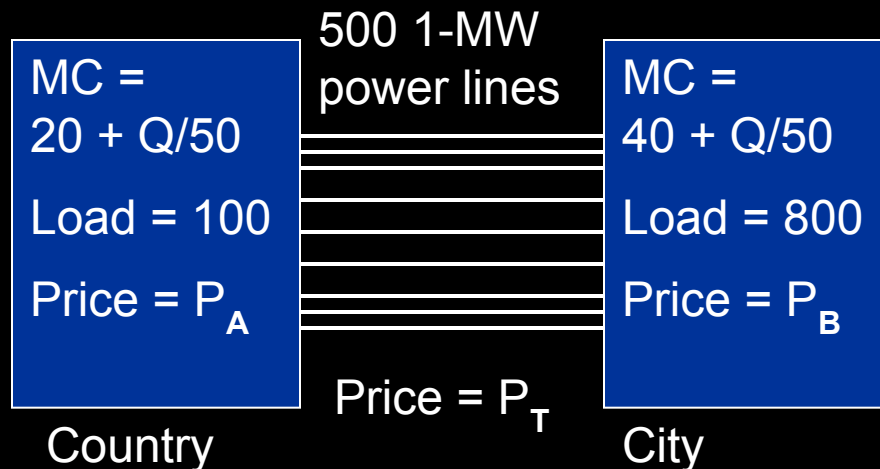
(More transmission would be used if available.)

500 1-MW power lines

MC = 20 + Q/50

Load = 100

Price = P_A

Country

MC = 40 + Q/50

Load = 800

Price = P_B

City

Price = P_T

Finding CLPs: an example

- Assume there is no congestion
- If all 900 MW is bought at "A", the competitive price would be 20 + 900/50 = 38 € / MWh.
- If possible, everyone will buy power from A.
- They would need 800 MW of transmission to the city.

Transmission is scarce.

$P_T > 0$.
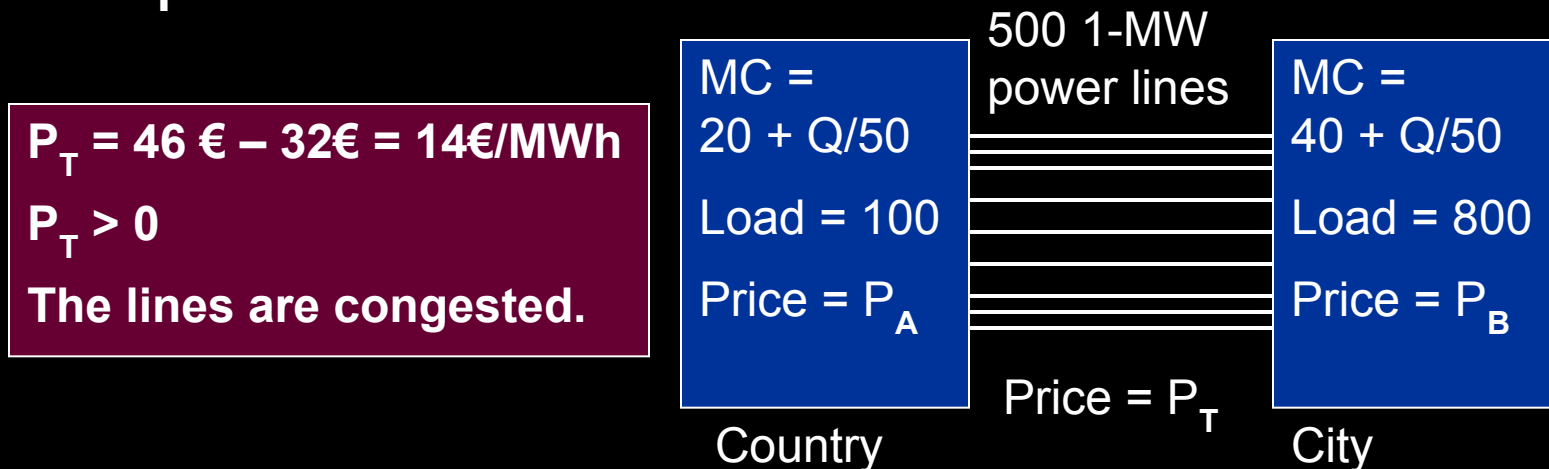
The lines are congested.

500 1-MW power lines

MC = 20 + Q/50	MC = 40 + Q/50
Load = 100	Load = 800
Price = P_A	Price = P_B

Price = P_T

Country   City

Finding CLPs: an example

- The city will buy 500 MW from the country and 300 MW in the City.

- $P_B = 40 + 300/50 = 46$ € / MWh

- Country generators will sell 500 + 100 MW.

- $P_A = 20 + 600/50 = 32$ € / MWh

- $P_T = 14$ € / MWh

$P_T = 46$ € $- 32$€ $= 14$€/MWh

$P_T > 0$

The lines are congested.

500 1-MW power lines

MC = 20 + Q/50		MC = 40 + Q/50
Load = 100		Load = 800
Price = P_A		Price = P_B

Price = P_T

Country   City

CLPs are bilateral prices

- There was no central market in our example.

- Only bilateral traders.

- CLPs are simply competitive market prices.

- They can also be computed from competitive bids in a central market.

Properties of the CLPs

- CLPs give
  - The cheapest dispatch (given consumption).
  - The most valuable consumption (given the dispatch).
- CLP = marginal cost of generators at the location of the price.
- CLPs are just normal competitive market prices.
- If sellers have market power, the locational (nodal) prices will not be CLPs.
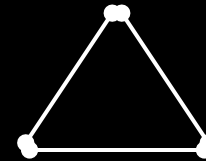
Networks with loops
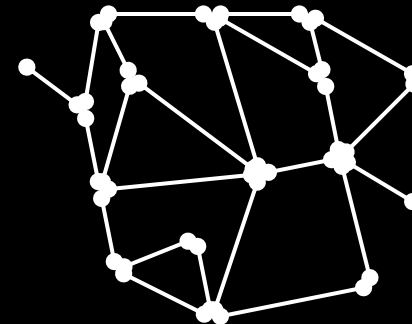
The dots are "nodes" or "buses."

Networks with Loops
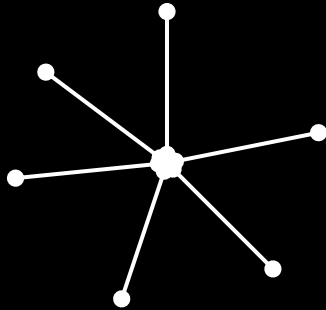
**Radial Networks
(no loops)**
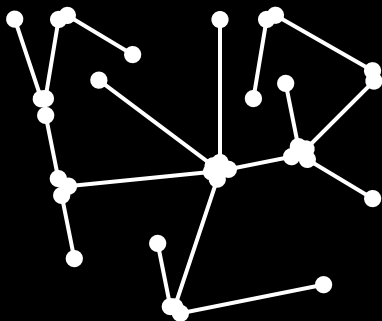
difficult

simple

**A meshed network
(lots of loops)**

Water or DC current

○ = Light, or Water Turbine
1 Ohm of Resistance

+ 5 Volts, or
+ 5 kg/cm^2

5 Amps

5 Amps

10 Amps

+ 10 Volts, or
+ 10 kg/cm^2

0 Volts, or
0 kg/cm^2

+ **10 V Battery, or Water Pump** **–**

15 Amps
15 liters/second
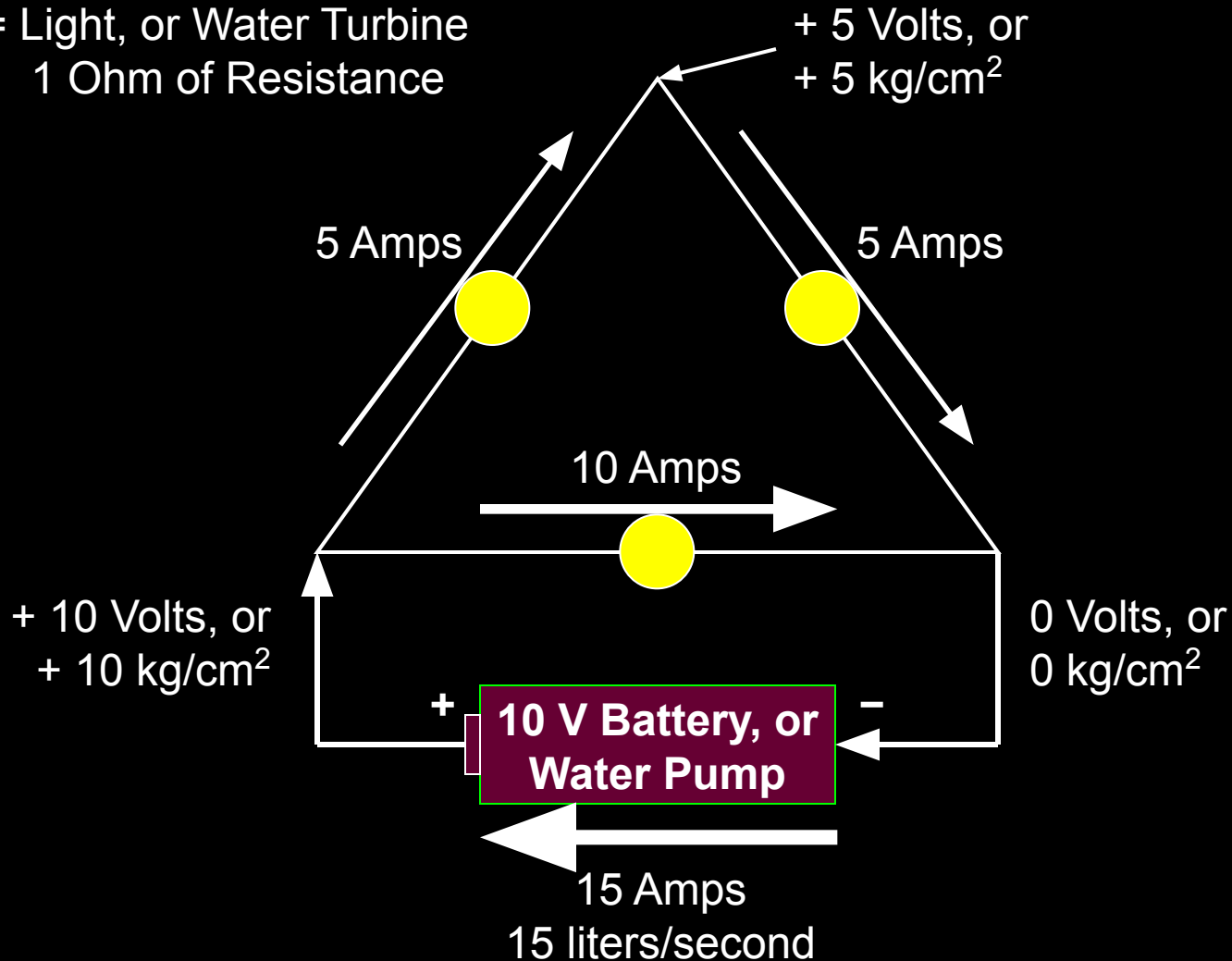
Kirchhoff's laws & Ohm's law

1. The net current flow into a node = 0.

    Example: lower left: 15 – 5 – 10 = 0

2. The net voltage drop around a loop = 0.

    around the triangle: (10–5) + (5–0) + (0–10) = 0

- Ohm's Law: V = I·R

    voltage drop = current × resistance

- These are the laws of current flow in a network
- They are the same for electrons and water.

Benjamin Franklin was wrong. Electrons are negative, so they flow in the opposite direction to his electrical "current."
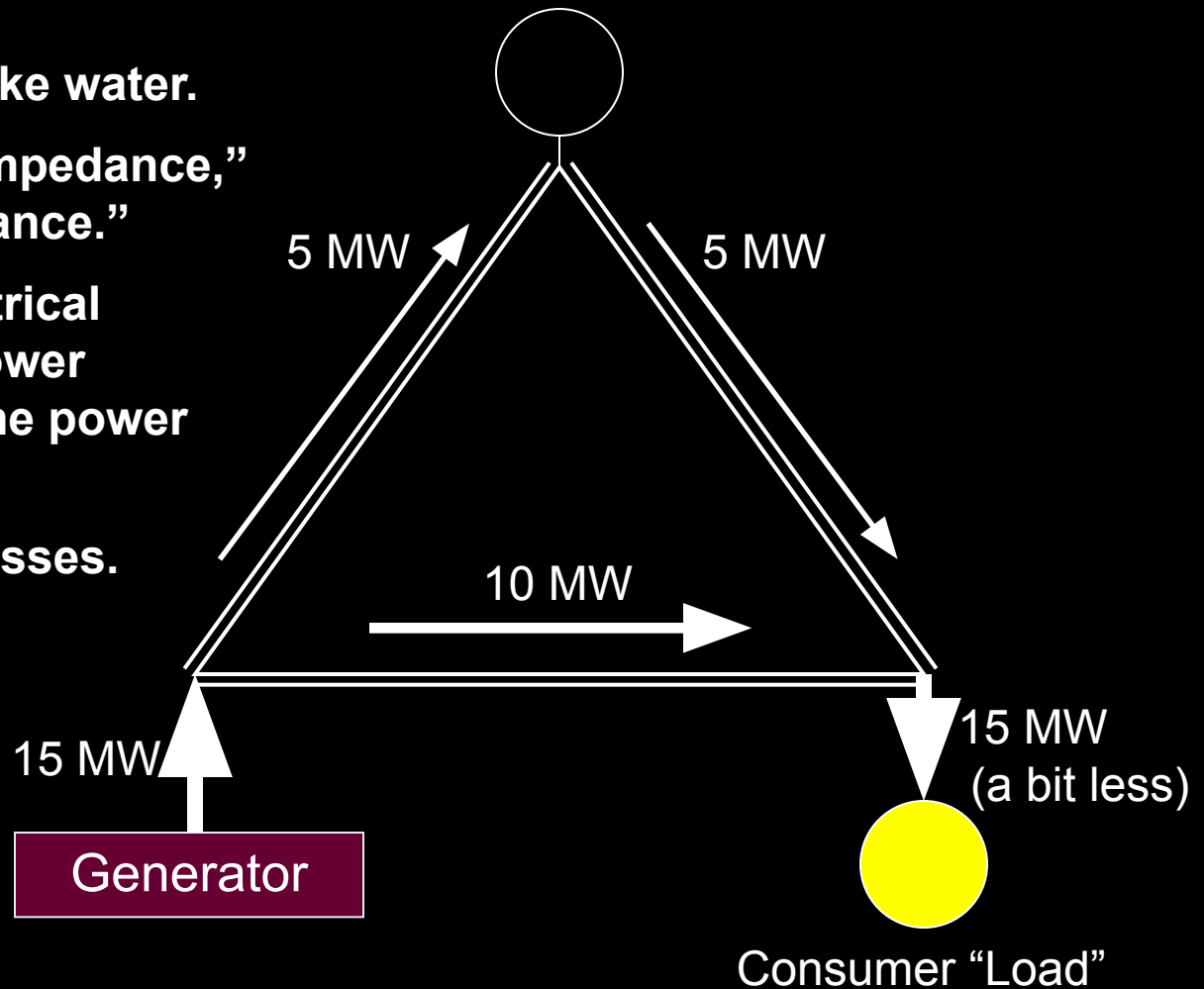
Electrical power flow

Power flows much like water.

Power lines have "impedance," which is like "resistance."

Unlike water or electrical current, there are power "losses." Some of the power heats the wires.

Usually we ignore losses.
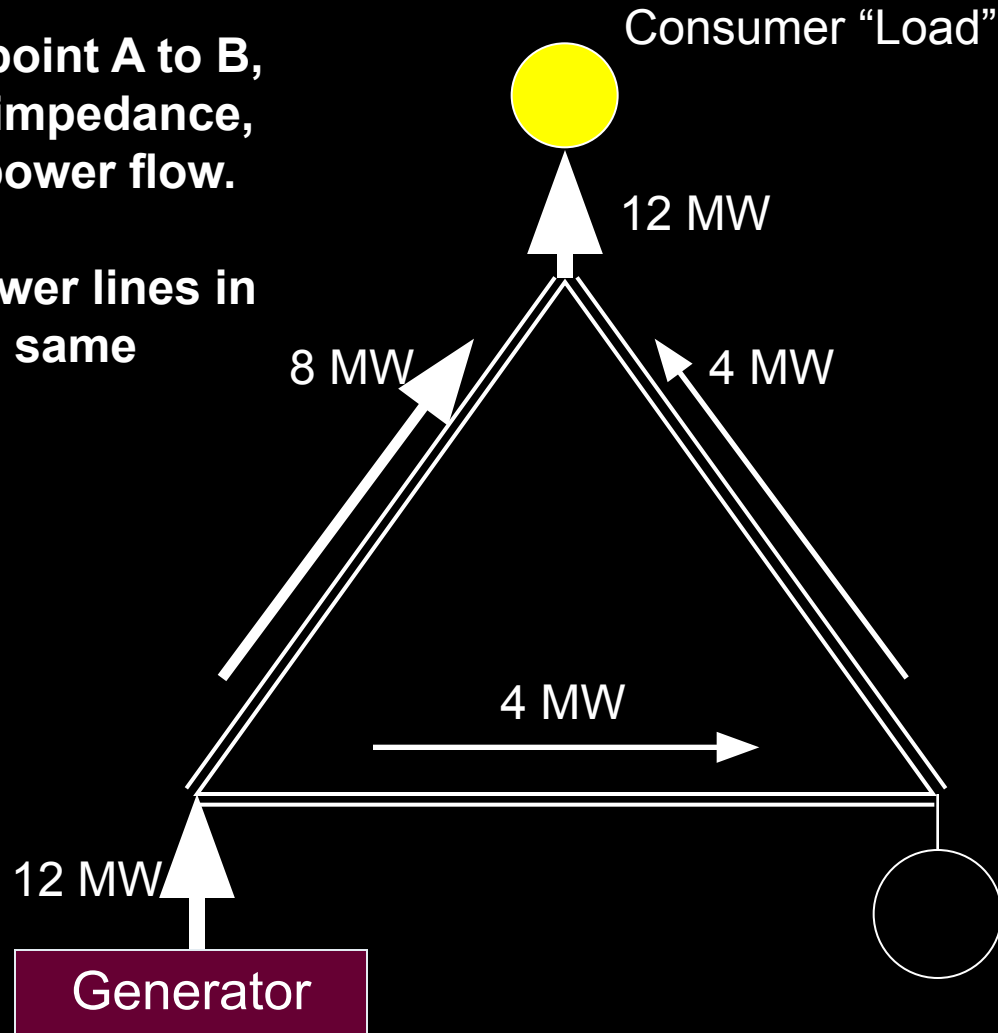
5 MW

5 MW

10 MW

15 MW

15 MW
(a bit less)

Generator

Consumer "Load"

Electrical power flow

For two paths from point A to B, if one has twice the impedance, it will have half the power flow.

Each of the three power lines in this diagram has the same impedance.

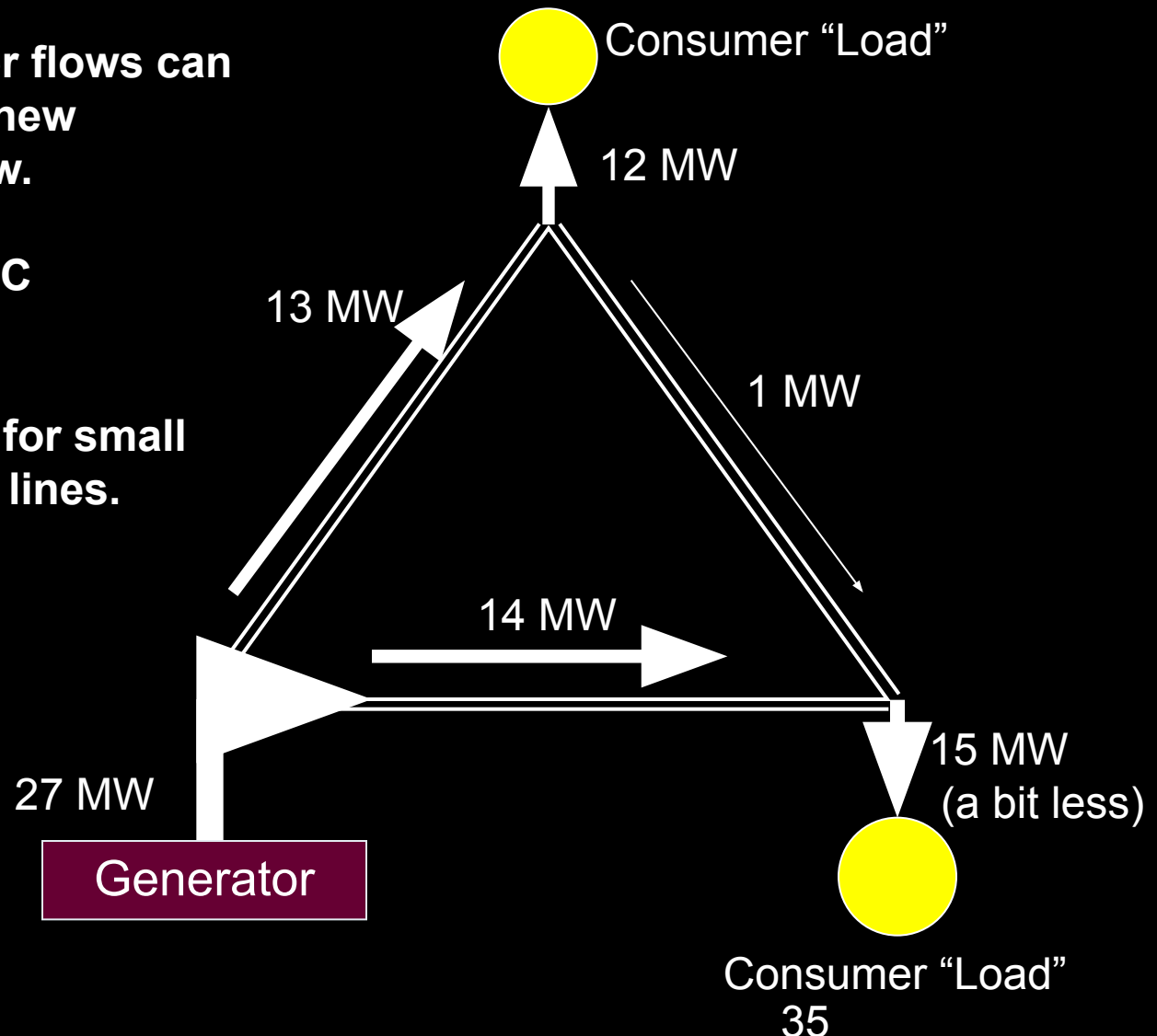Consumer "Load"

12 MW

8 MW

4 MW

4 MW

12 MW

Generator

The "principle of superposition"

Two possible power flows can be added to find a new possible power flow.

This is called the DC approximation.

It is almost perfect for small power flows on AC lines.

Consumer "Load"

12 MW

13 MW

1 MW

14 MW

27 MW

Generator

15 MW
(a bit less)

Consumer "Load"
35

An impossible flow

If the lines have equal impedance this flow is impossible.

Without very expensive "phase shifters," engineers cannot control where the power flows except by turning generators on and off.

Consumer "Load"

12 MW

10 MW

2 MW

17 MW

27 MW

15 MW (a bit less)

Generator

Consumer "Load"

36
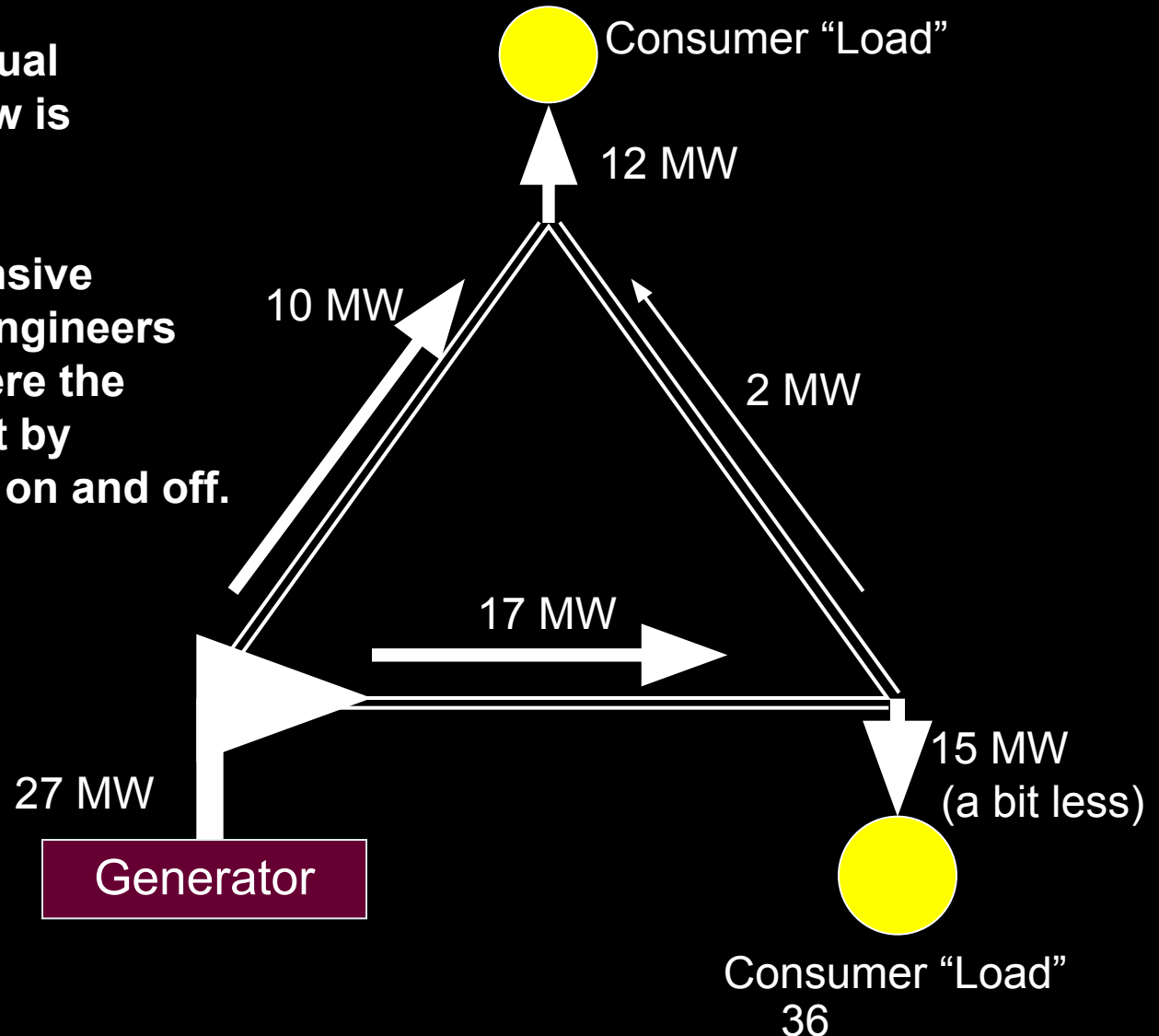
Simplest looped CLP problem

CLP = 30 100 MW load

Problem:
Find the 3 CLPs

B

Solution:

200 MW limit 400 MW load

CLP = 20, A C
Q = 350

CLP = 40,
Q = 150

MC = 20 MC = 40

Looped CLP problem #2

MC = 30 + Q/50

600 MW load

Problem:
Find the 3 CLPs

B

100 MW limit

300 MW load

A

C

600 MW load

MC = 20 + Q/50

MC = 40 + Q/50
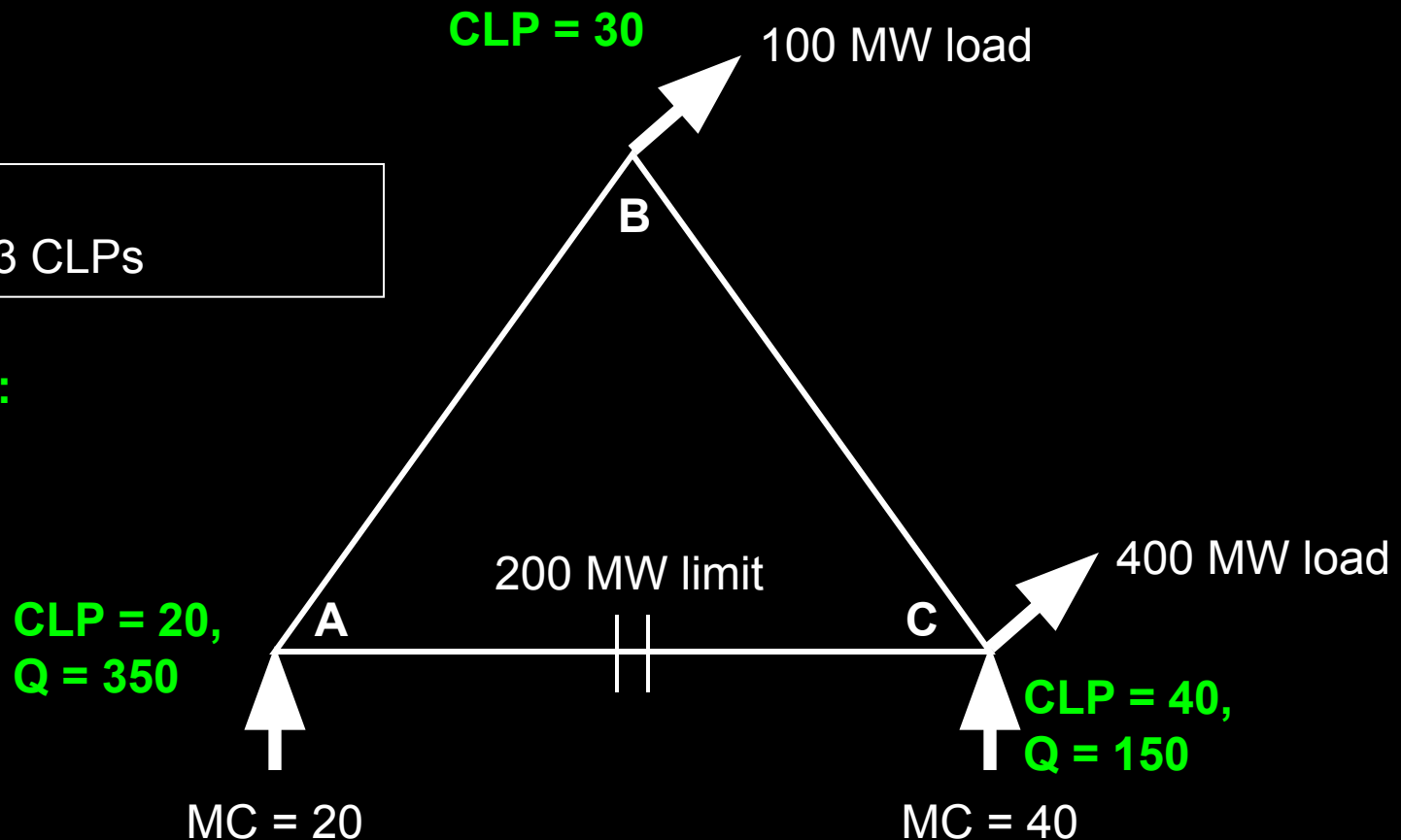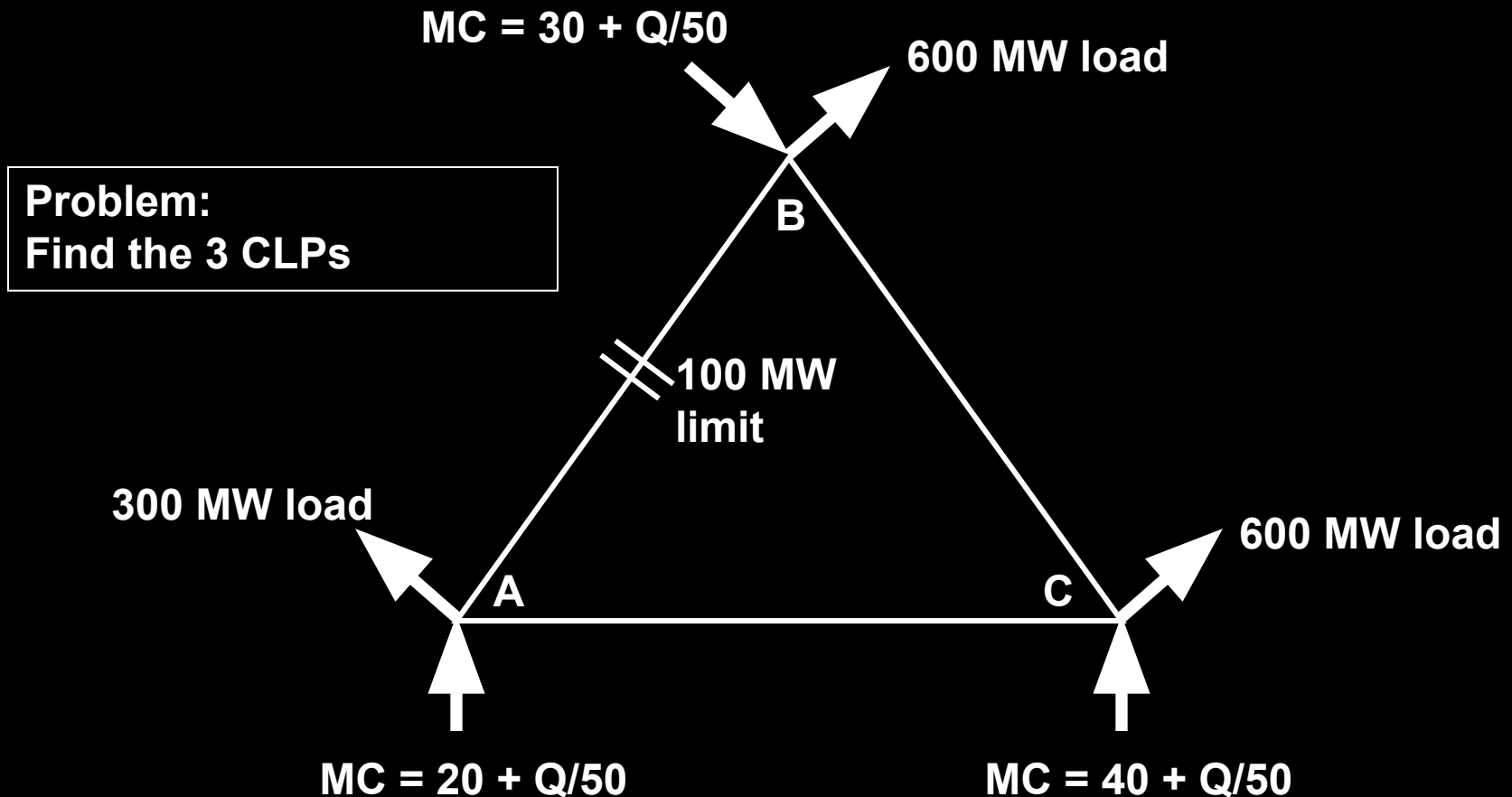
Finding CLPs (simplified)

- CLPs will minimize production costs.

- A good way to find them is to look for the dispatch (generator outputs) that minimize production costs.

- Each output, determines the marginal cost (MC) of a generator. This is the CLP at that generator's node.

Looped CLP problem #2 solution

750 MW, **45 €** /MW

600 MW load

B

100 MW

250 MW

100 MW limit

300 MW load

350 MW

600 MW load

A

C

750 MW, **35 €** /MW

0 MW, **40 €** /MW
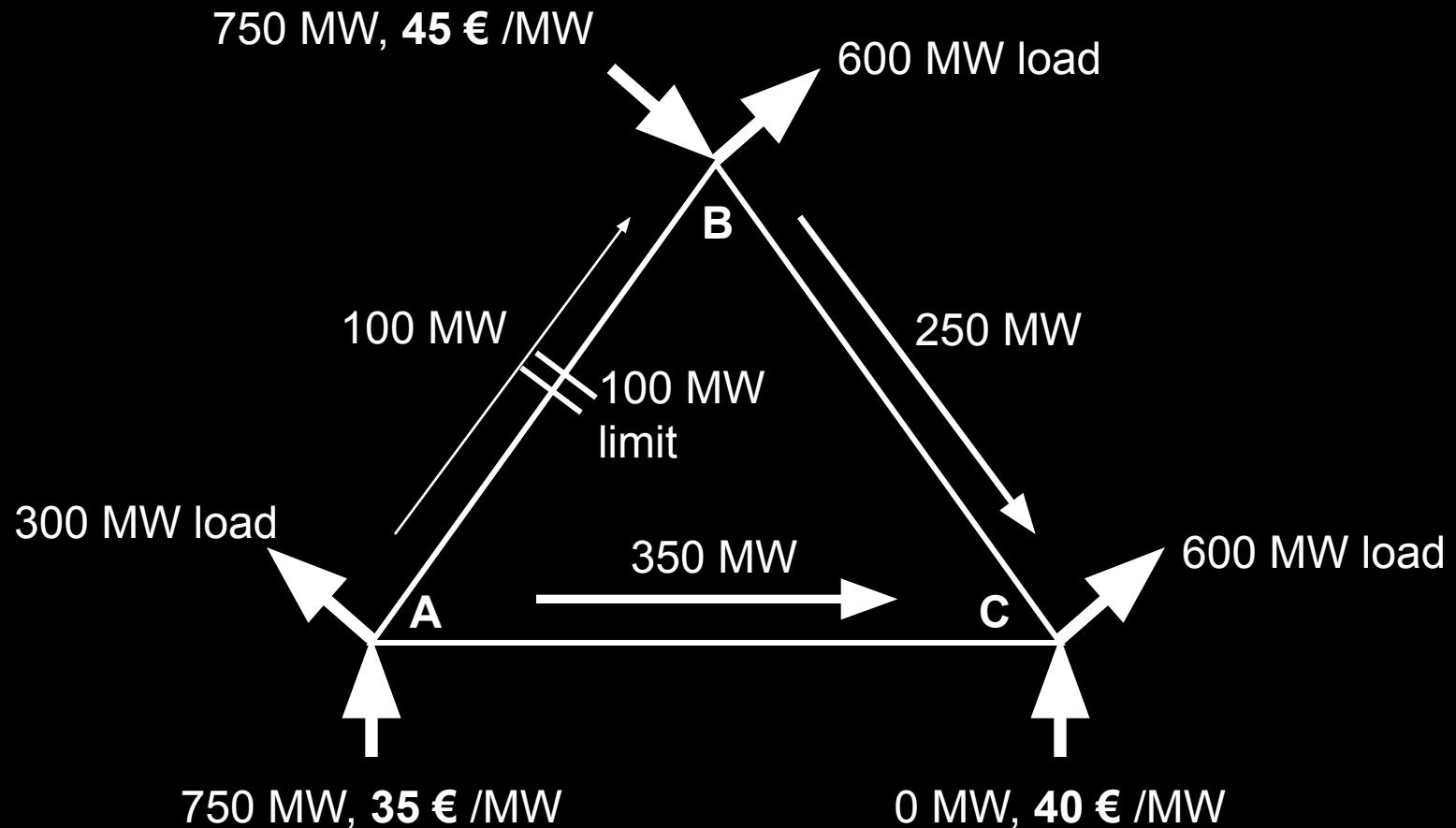
To check the solution (part 1):

- First check the power flow. Is it possible?
- **Step 1:** pick inputs and outputs:
  300: A□A. 450: A□C. 600: B□B. 150: B□C
  Or
  600: A□B. 150: A□C. 300: B□A. 450: B□C
- You can't tell which is right, and it doesn't matter. You can't tell where power goes. It gets all mixed together at the nodes (buses).
- **Step 2:** use the impedances and Ohms law to find all 4 power flows and add them up.

To check the solution (part 2):

- **Is it possible to produce the power more cheaply?**
- Costs are: 35 € at A, 45 € at B, and 40 € at C.

- **Check 1:** produce 1MW more at A, 1 less at B.
  – 2/3 MW more would flow from A to B: not allowed.
- **Check 2:** produce 1MW more at A, 1 less at C.
  – Impossible. C is producing 0.
- **Check 3:** produce 1MW more at C, 1 less at B.
  – 1/3 MW more would flow from A to B: not allowed.
- **Check 4:** 2MW more at C, and 1 less at both A & B.
  – Allowed, but it does not save money.

How to find CLP, given a power flow

- To find the CLP at a node,
  - Find the dispatch and consumption pattern that maximizes consumer value minus production cost.

    (If consumption is fixed, just minimize production cost.)

  - Assume the market is perfectly competitive.

  - Give a trader 1kW of power at the node and see how much money he can make. That is the price per kWh.

    (Sometimes a complex trade is necessary. The trader might need to pay another generator to produce less.)

Problem: Find the CLPs at A, B, & C

Hint: There is an answer, and the math is simple.

Unlimited generation at both A & C.

Load = $(600 - P_B)$ MW

B

100 MW limit

600 MW load

A

C

MC = 20 €

MC = 50 €
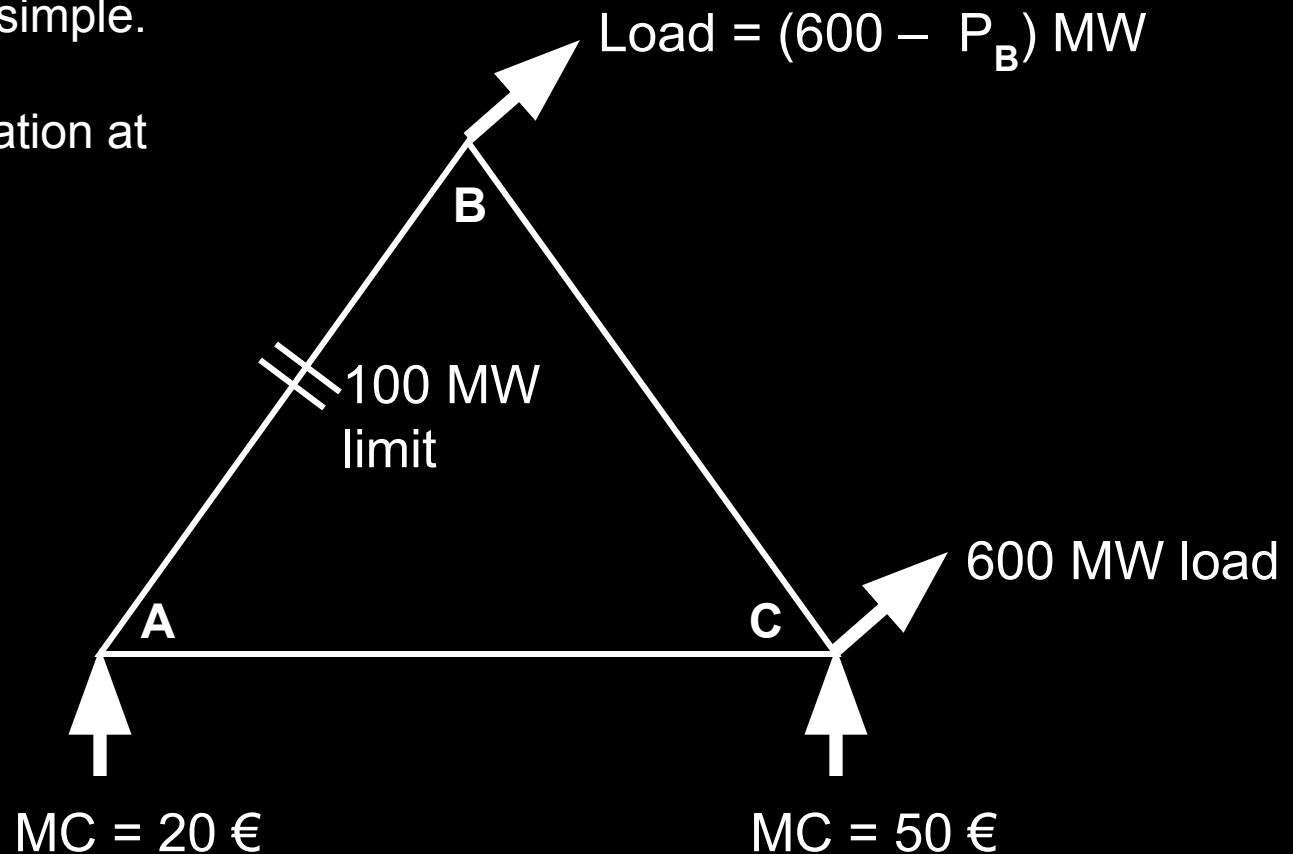
Types of transmission constraints

- **Thermal limit:** A power flow limit to prevent a line from overheating and stretching permanently.

- **Stability limit:** A power flow limit to prevent voltage collapse on a long AC line.

- **Contingency limit:** A power flow limit on one line to prevent a limit-violation on another line if that the first line goes out of service.

- Contingency limits are the cause of congestion.

A contingency constraint
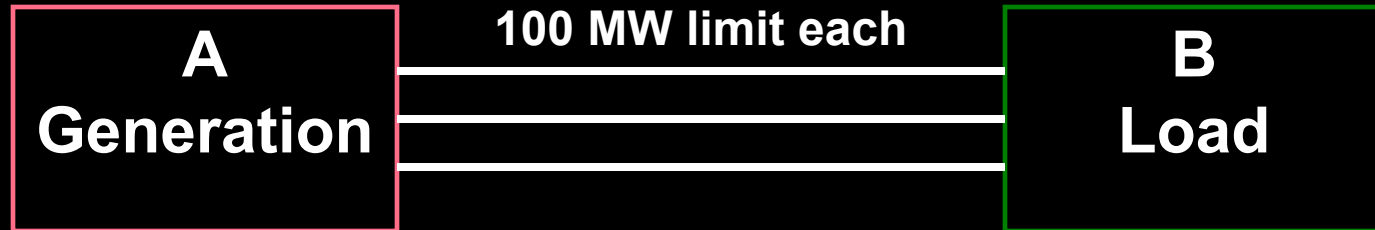

A Generation — 100 MW limit / 200 MW limit — **B Load**

Suppose the large line has **½** the impedance of the small line. When 300 MW flows from A to B, 200 MW will flow on the large line. No problem.

If 101 MW flows from A to B, and the large line breaks, the small line will exceed its limit.

The contingency limit from A to B is 100 MW.

A contingency constraint

| A Generation | 100 MW limit each | B Load |

Now the contingency limit is 200 MW.

Contingency limits are important for engineers.

For economics, remember this:

1. When they are constant, they cause no problem. They are just limits on trade and the reason for the limit does not matter.
   (Possible exception: transmission investment.)

2. They can change from hour to hour.

Locational prices in a meshed network
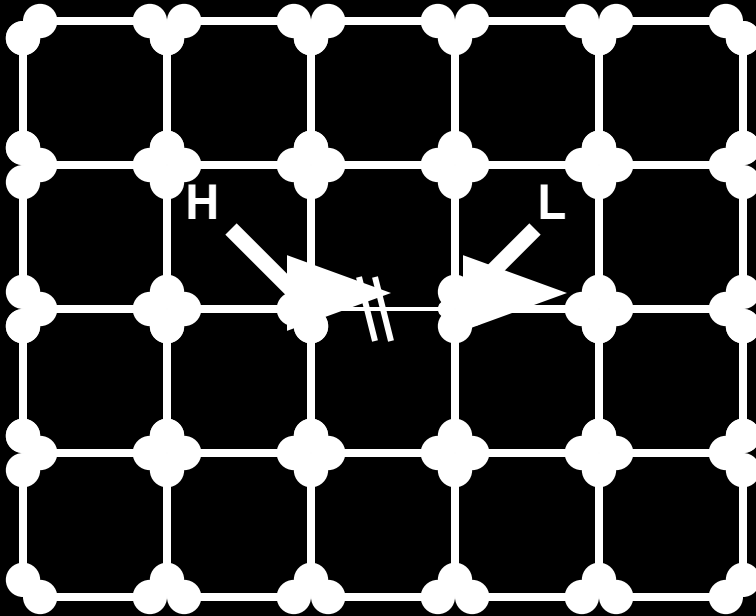
There is 60 € (High priced) generation at H and 20 € (Low price) generation at L.

Some (not all) generators are running at both H and L.

The only congested line is H --- L.

There are many other generators and loads at many locations.

Every line is the same.

Can you find all the CLPs?

An electric network to calculate prices
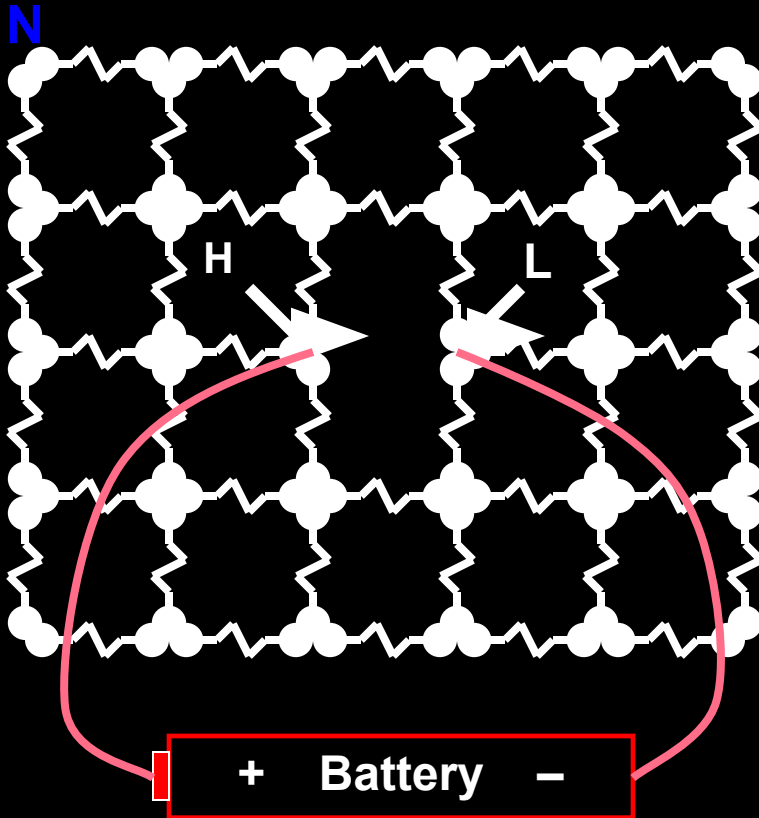
How to Find All the CLPs:

1. Build a network of identical resistors.

2. Attach a battery to H and L.

3. Measure the voltage at every node.

(This is an analog computer.)

An electrical network
can calculate prices!

If voltage (pressure) at H is 12 V, and at L is 0 V, and at node N is 8 V,

then the CLP at node N = 20 € + (8/12) × (60 € – 20 €) = 46.7 € / MWh.

Nodal prices for previous example

46.85 €	45.86 €	43.00 €	37.00 €	34.14 €	33.15 €
47.84 €	47.74 €	46.15 €	33.85 €	32.26 €	32.16 €
48.92 €	51.10 €	60.00 €	20.00 €	28.90 €	31.07 €
47.84 €	47.74 €	46.15 €	33.85 €	32.26 €	32.16 €
46.85 €	45.86 €	43.00 €	37.00 €	34.14 €	33.15 €

- Ohm's law, Kirchhoff's law for currents □
- Each value equals the average of neighbors.
- The H and L nodes are not neighbors.

Fewer Prices

N+1 prices will hedge N constraints
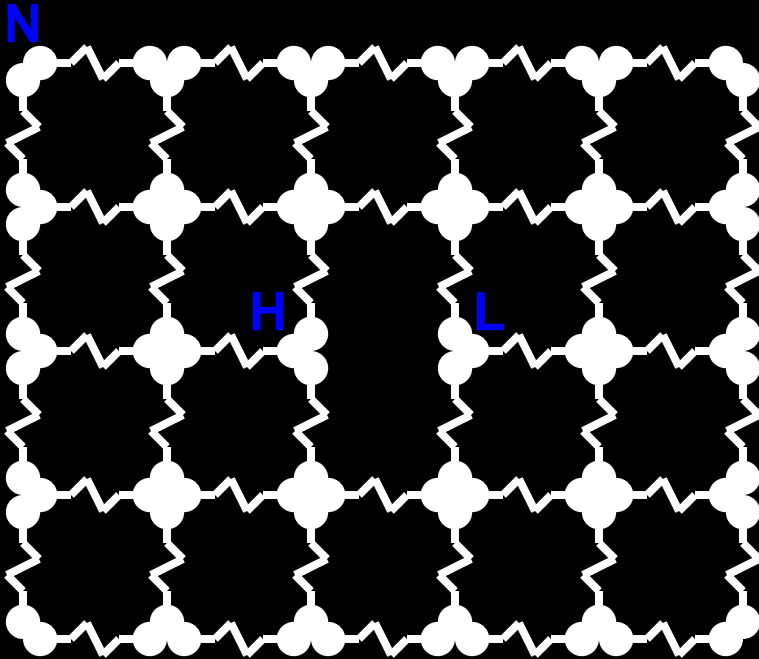
Suppose node N is 1/3 of the electrical distance from H to L.

To hedge prices at N, buy 2/3 of your power **forward** at H and 1/3 of your power **forward** at L.

(A "forward" contract is like a "futures" contract.)

The problem is that constraints can change.

But the major constraints, which cause most of the price changes, stay the same.

1 price is needed for 0 constraints, and each constraint adds a price.

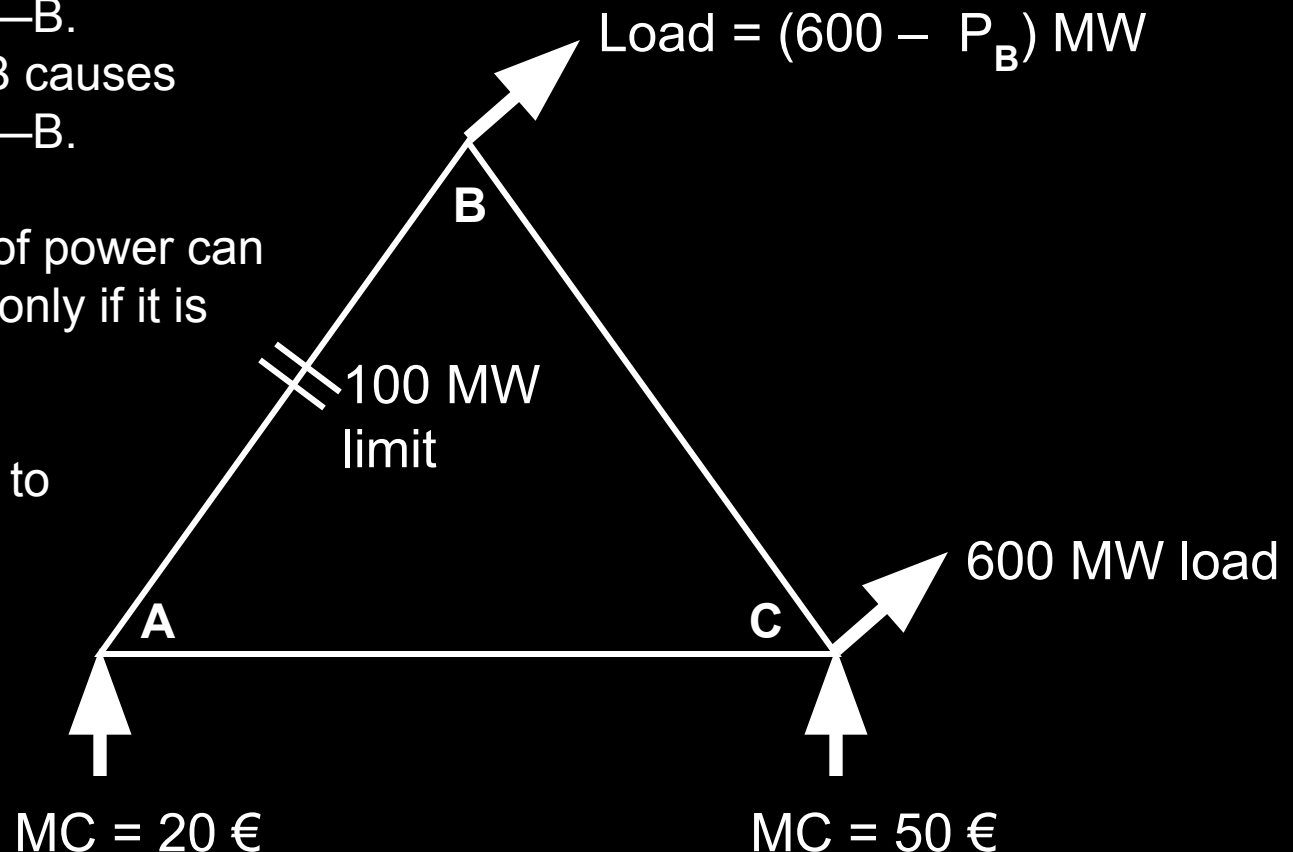# Solution: finding CLPs at A, B, & C

1 MW from A → B causes
2/3 MW on line A—B.
1 MW from C → B causes
1/3 MW on line A—B.

At most 300 MW of power can
be sent to B, and only if it is
sent from C.

P_B must limit load to
300 MW, so
P_B = 300 €.

Load = (600 − P_B) MW

B

100 MW
limit

600 MW load

A

C

MC = 20 €

MC = 50 €

Checking net benefit

- Has net benefit been maximized?

- 2 MW from C could be replaced by 1 MW from A.

- This would save 80 € of production cost, but it would reduce consumer value by ~2×300 €.

- So net benefit has been maximized.

Finding Price

- Give a trader 1kW of power at the node and see how much money he can make.

- If the power has negative value, he must pay to get rid of the power. Then the price is negative.

What is the price at A, P_A?

- What is the value of 1 MWh injected at A?

- **If it flows to B** it uses 2/3 MW capacity on line A—B, and this blocks 2 MW from C.

- Consumers lose (at the margin) 300 € / MWh, but 2 × 50 € is saved in production cost, so the value of this MWh = minus 200 €.

- **If it flows to C**, it uses 1/3 MWh capacity A—B, which blocks 1 MWh of energy from C=>B.

- 300 € of value is lost, but 2 MWh is saved at B for a gain of 100 €. Again P_A = –200 €.

What is P_A ? (#2)

- If **1 MWh is consumed a A**?

- It can be purchased at A for 20 €.

- But traders always look for the best trade. To find the price at A, we must find the cheapest way to buy power at A.

- It can be purchased from C, and this will reduce congestion on A—B by 1/3 MWh, so one more MW can be sent from C to B.

- This is valuable to consumers at B, so the trader can ask a consumer at B to pay.

What is P$_A$? (– 200 € again)

- The trade goes to B and asks how much they will pay for 1 MWh. They bid up to 300 €.

- Then the trader goes to C and buys 2 MWh for 100 €.

1/3

- Then the trader uses 1 MWh at A while 2 MWh are produced at C.

- 1 MWh flows to A and 1 to B, so congestion is not changed.

1/3
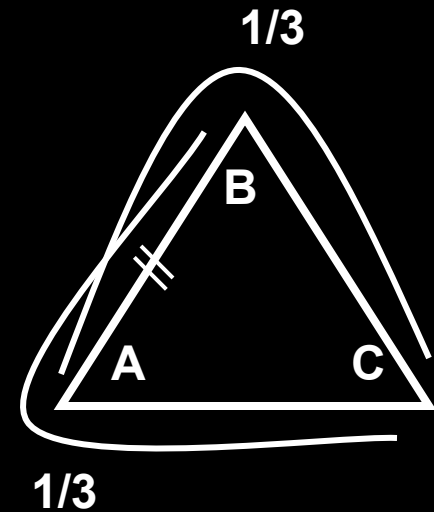
The trader makes 200 € by **_using_** 1 MWh at A.

Properties of the Solution

Notice that the P$_C$ is half way between P$_A$ and P$_B$. This is always true when the line between A and B is congested.

Notice that power flows from C to A, even though it is worth less at A.

Load = (600 − P$_B$) MW

P$_B$ = 300 €

B

100 MW

100 MW limit

200 MW

600 MW load

100 MW

A

C

P$_C$ = 50 €

P$_A$ = −200 €

MC = 20 €
Q = 0 MW

MC = 50 €
Q = 900 MW
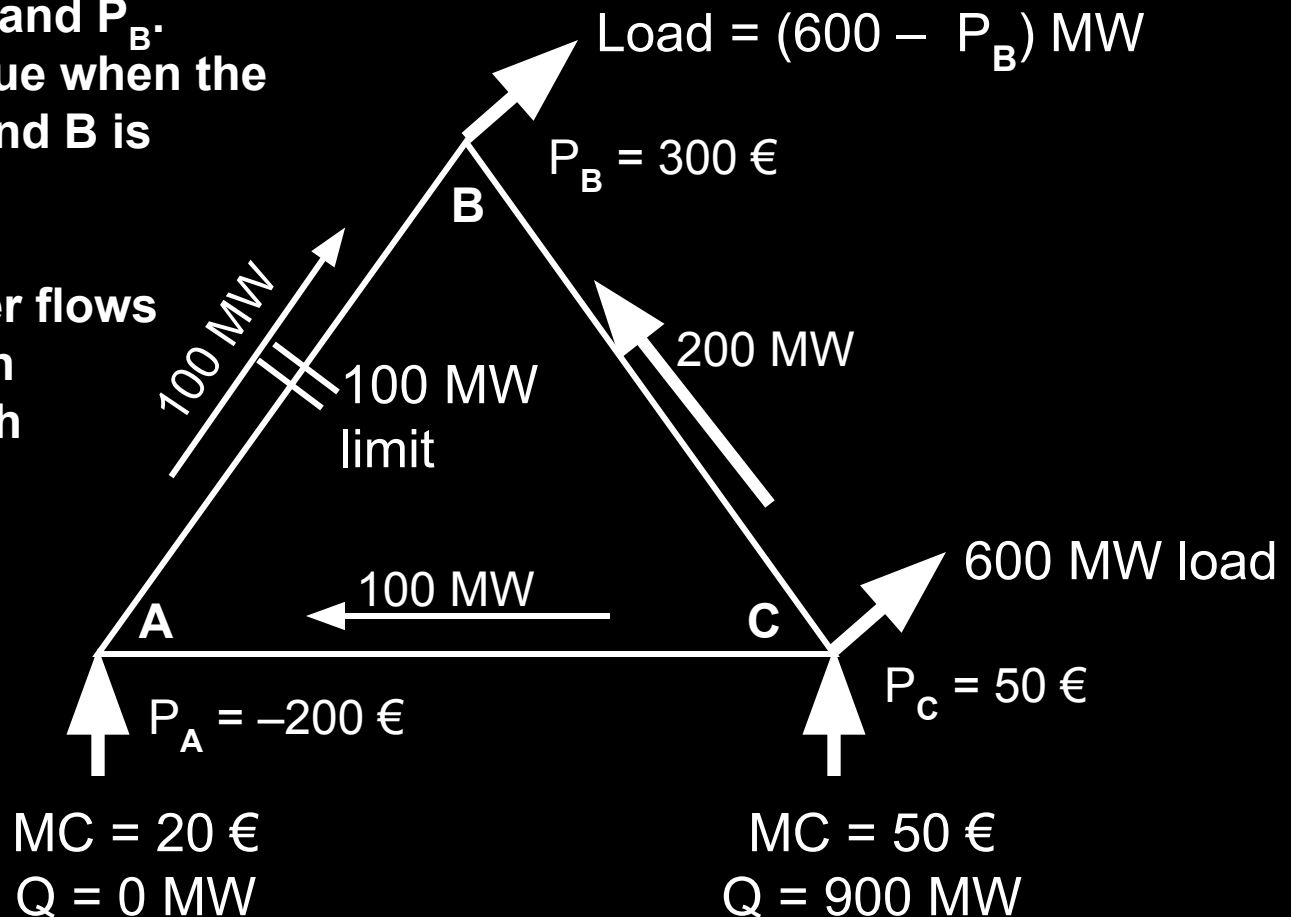
Why is P_C always = $(P_A + P_B)/2$

If A—B is congested towards B, and C needs power, it could buy it all from the high priced node, B. But this is never cheapest.

Instead, buy some from A. But enough must be bought from B to cancel the flow caused by power coming from A.

Suppose 1 MW A→C causes +a MW to flow A→B, and 1 MW B→C causes –b MW A→B.

$$P_C = b\, P_A + a\, P_B$$

100 MW limit

A   B

Low Price   High Price
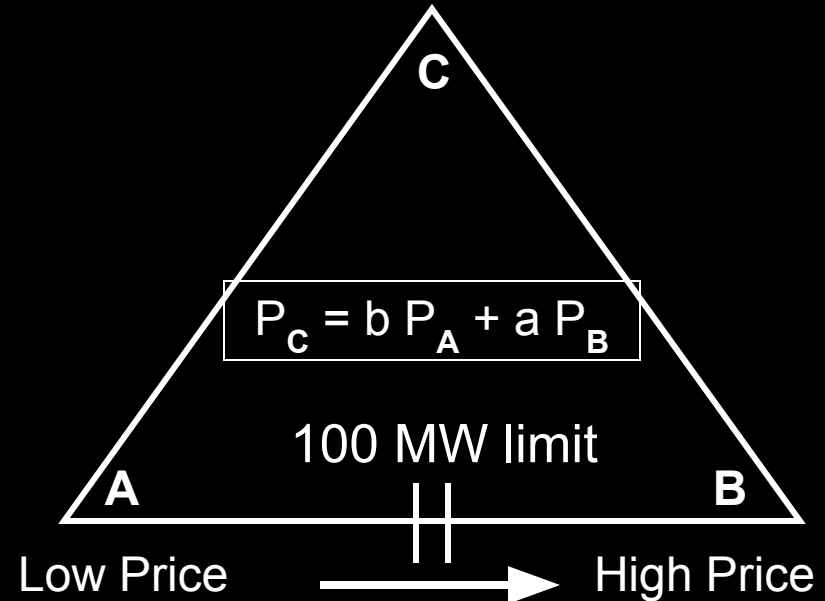
Then the cheapest way to buy 1 MW at C is to buy b/(a+b) from A and a/(a+b) from B. There will be equal and opposite flows of ab/(a+b) on A—B.

Since a = b = 1/3 in this network, the marginal MW at C must be bought half from A and half from B.

58

Can we force: $P_C \neq (P_A + P_B)/2$

If C has unlimited generation at a price ≠ $(P_A + P_B)/2$, what happens?

If A—B is not congested, All prices are 40 €.

If B—A is congested,
(1) Suppose the load is all at **A**.
      A trader at C could offer to sell 1 MW to someone at **B** for 20 €, because then he could sell 1 MW to **A** for 80 €. Revenue = cost = 100 €.

C
50 €

100 MW limit

A
80 €

B
40 €
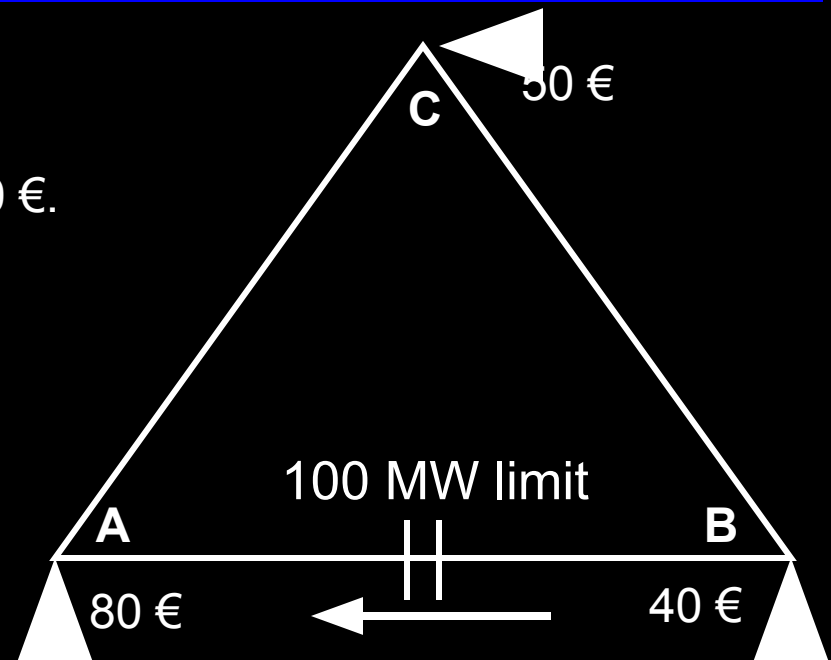
(2) Suppose the load is all at **C**. A Trader at **B** cannot sell power to **C** unless she buys an equal amount of power from **A** to send to **C**. But 1 MW at **A** costs $80 €, so he can only afford to pay 20 € at **B**. Before the line is congested, the price at B is 40 €, but after congestion, it drops to 20 €.

Either way the price at B, with B→A congested, is 20 €, not 40 €.

59

Another way to understand CLPs

If line A—B were expanded by 1 MW,
1.5 more MW could flow from B to A,
1 through A—B and one through node C.

So the "expansion value" (EV) of the line
is 60 € / MWh.
That is the price difference times
the total extra power flow.

The nodal price at any node C,
can be found from the price at B,
and the fraction of power that flows
on B→A when power is sent from B to C.
That fraction is called a "distribution factor," DF_C.

$P_C = P_A + EV_{BA} * DF_C$

In this case $P_C = 40 + 60 × (1/3) = 60$

C

100 MW limit

A
80 €

B
40 €

$$EV_{BA} = (P_A - P_B) / DF_A$$
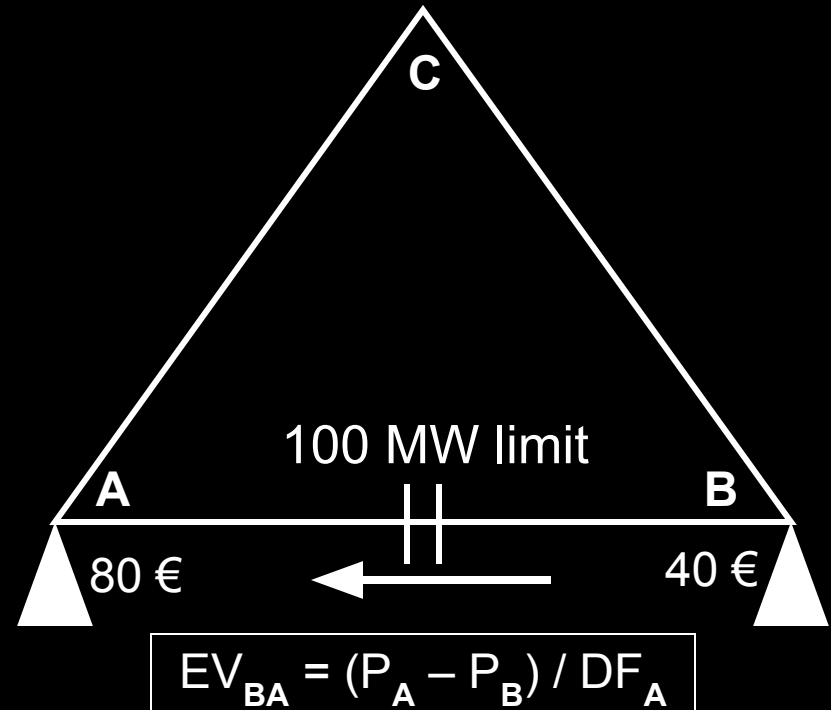
Distribution factors are constant

- Because distribution factors are constant, the expansion value can be found from the price difference $P_A - P_B$.

- Knowing this EV_{BA} and the price at B, and all the other power factors, every nodal price can be found.

- If there are N congested lines then all nodal prices can be found from P_B and the EVs of the N congested lines, and the distribution factors.

- No other economic information is needed.

Distribution factor simplification

- Distribution factors and "expansion values" and one nodal price make it easy to find all the other nodal prices.

- But it is still just as hard to find all the "expansion values."

- So this method helps us understand nodal prices, but it is not a shortcut for central computation.

Conclusion

- CLP = marginal cost of power at each location

Problem #2

Prices For Investment
in an Ideal World

Nodal Prices (CLP) Are Much Criticized

- Most critics have not read an economics book.

- They notice that sometimes there is a shortage, and prices go up above some marginal costs.

- They believe this is unfair.

- They do not consider fixed costs or investment.

- Some examples assume (accidentally) that stupid investments have been made in the past. CLPs provide excess profits when there is a shortage of capacity.

CLPs Are Not the Complete Answer

- While most criticisms of CLPs are confused, you should not assume CLPs can solve all problems.

- But, the problems with CLPs can be understood with careful economic analysis.

- There is no need to invent Electricity Economics.

- Here is an example of a criticism published in "the Electricity Journal." It is understandable, but still quite silly.

Locational profits

A: <u>Remote Generation</u>	50 MW limit	B: <u>City Generation</u>
200 MW @ 24€/MWh		100 MW @ 50€/MWh 150 MW @ 25€/MWh

100 MW Load

199 MW Load, or
201 MW Load.
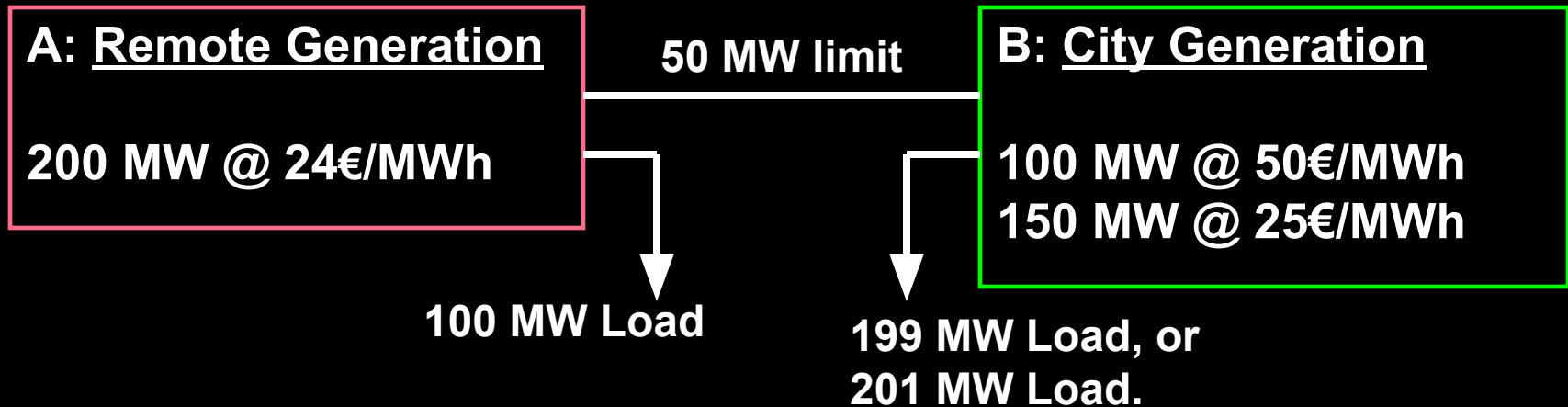
199 MW City Load $\Rightarrow$ P_A = 24 €, P_B = 25 € / MWh.

200 MW City Load $\Rightarrow$ P_A = 24 €, P_B = 50 € / MWh.

So the City needs 2 more MWh, and these cost 25 + 50 = 75 €. But, the city must pay (201 × 50) – (199 × 25) = 5075 € more. Why should they pay 5000 € extra?

Locational profits

- Anti-CLP Complaints:
  - Consumers should only have to pay production costs.
  - Nodal prices are monopoly prices
  - Nodal prices make no sense!
  - They are just prices made up by Bill Hogan.

- Anti-CLP mistakes:
  - The computed prices assume no market power.
  - They were not invented by Bill Hogan.
  - Generation costs are not only fuel costs.
  - Prices are for not only for dispatch. But, also investment.

What is the investment signal?

- The remote generators are paid €24/MWh

- 50 MW of remote generation is not used.

- ⮕ Do not build any remote generation.

- ⮕ Retire some remote generators.

- Given the transmission system and the load, this is the correct signal.

Investment in the city

- Sometimes the 25 € generators make no profit.

- Sometimes they make 25 € / MWh profit.

- Would this cover the fixed cost of a new generator?

- I depends on the % of time making 25 €.

- If the price is 50 € for half the time, and Type D generator can be build for less than ½ × 25 € × 8760 = 109,500 € / MW, then investors will build more Type D generators.

The same example without transmission

Same* "crazy prices."

No transmission lines.

The CLPs are just normal competitive prices.

City Generation
   50 MW @ 24 € /MWh
   100 MW @ 50 € /MWh
   150 MW @ 25 € /MWh

**199 MW Load, or
201 MW Load.**
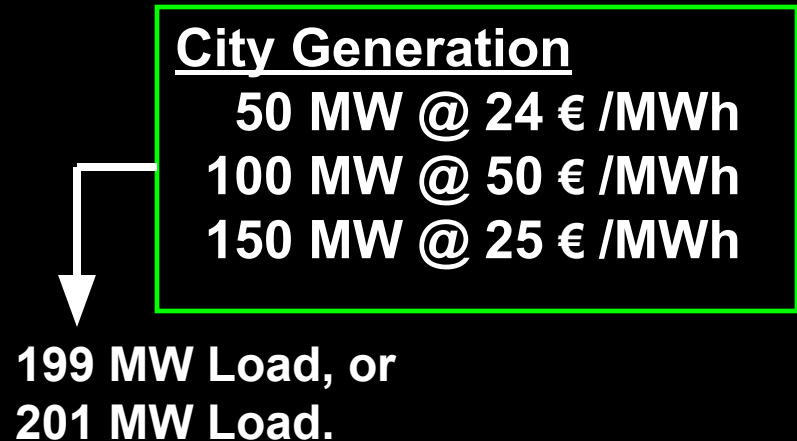
Complaints about CLPs (nodal prices) are

complaints about standard competitive prices.

* There is one difference, when the price is 50 €, the 24-€ generation makes all the profit that was paid to the transmission line in the previous example.

"The Complete Market Example"

Remote Generation $Q_R = ?$	$Q_T = ?$	City Generation $Q_C = ?$

Load   Load
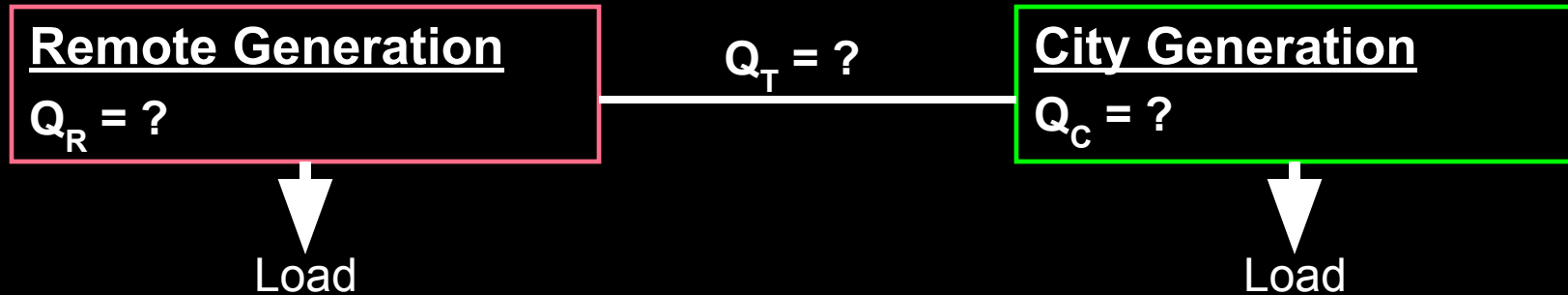
- Peaker generation cost: $FC_P = 10$ €, $MC_P = 60$ €
- Baseload generation cost: $FC_B = 30$ €, $MC_B = 20$ €
- Baseload generation can not be built in the city.
- Transmission cost: $FC_T = 10$ €
- Q is capacity in MW.
- FC = fixed cost = **€ / MWh** of capacity (rental).
- MC = marginal cost = **€ / MWh** of energy.
- Load varies linearly from 400 MW to 800 MW at each location.

71

Problem: Find prices and quantities

- Find the competitive equilibrium prices and quantities for both locations, Remote and City, for every minute of each day.

- Check that competitive prices induce:
  - Optimal investment in generation
  - Optimal investment in transmission
  - Least-cost dispatch (given consumption).
  - Maximum-benefit consumption (given the dispatch).

Congestion Rent

- Generators are paid CLP at injection node.

- Loads are charged CLP at withdrawal node.

- A line is like both at once.

Line = Load	Line = Gen

Remote ➡️——————————➡️ **City**

- If W_{RC} is the power flow from R to C, the line owner is paid "**congestion rent**" =

$$W_{RC} \times P_C \ - \ W_{RC} \times P_{RC}.$$

Line = Gen   Line = Load

Complete Problem with Demand(P)

Remote Generation
Base, Peak? Q_R = ?

Q_T = ?

City Generation
Peak Q_C = ?

Load

FC_B = 30 €, MC_B = 20 €
No baseload in City.
FC_P = 10 €, MC_P = 60 €
FC_T = 10 €

Load

P=100 €

The demand
curve (load)
shifts back
and forth
every day.

midnight

noon

midnight

400 MW

800 MW
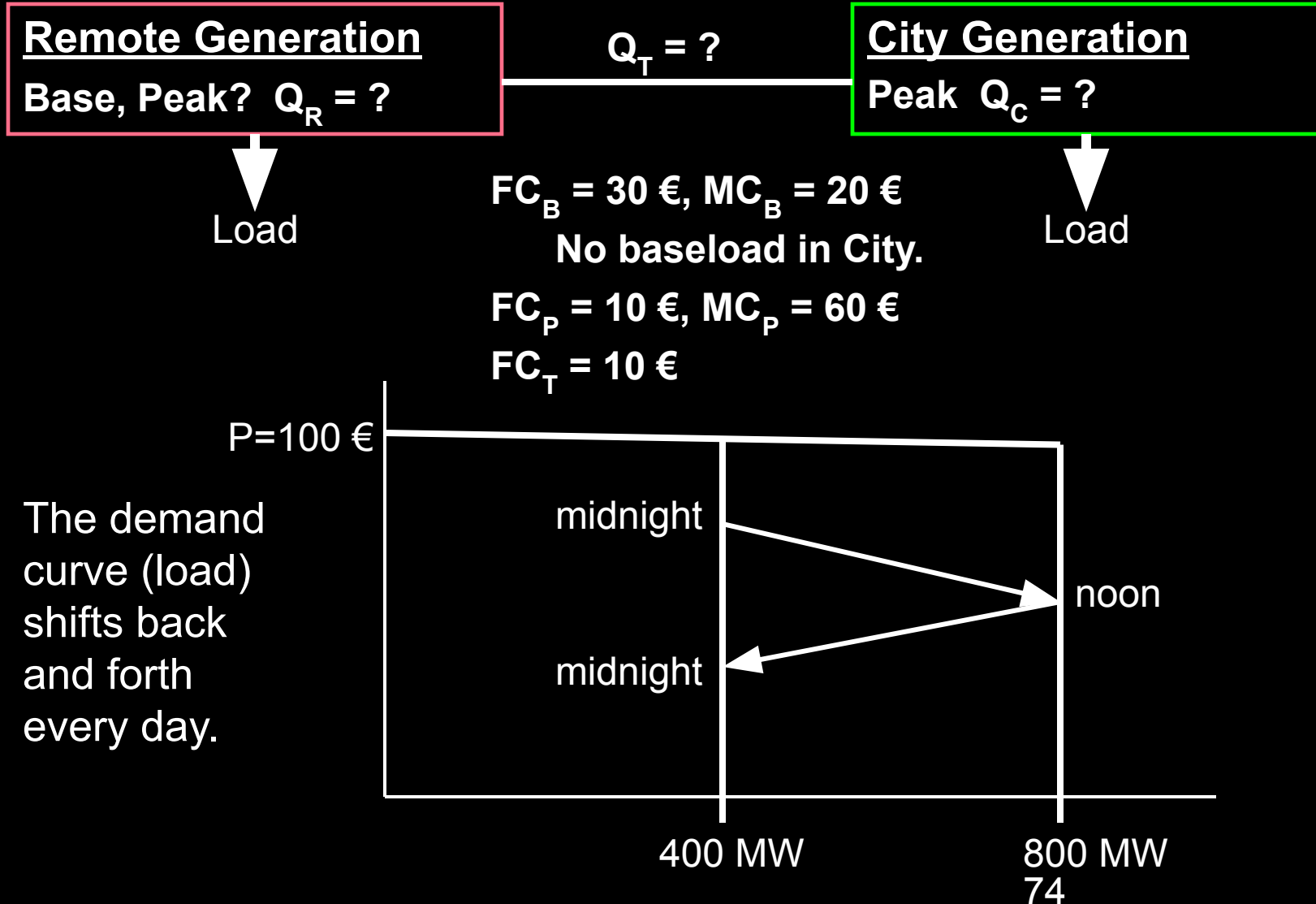
Four demand conditions (at each Location)
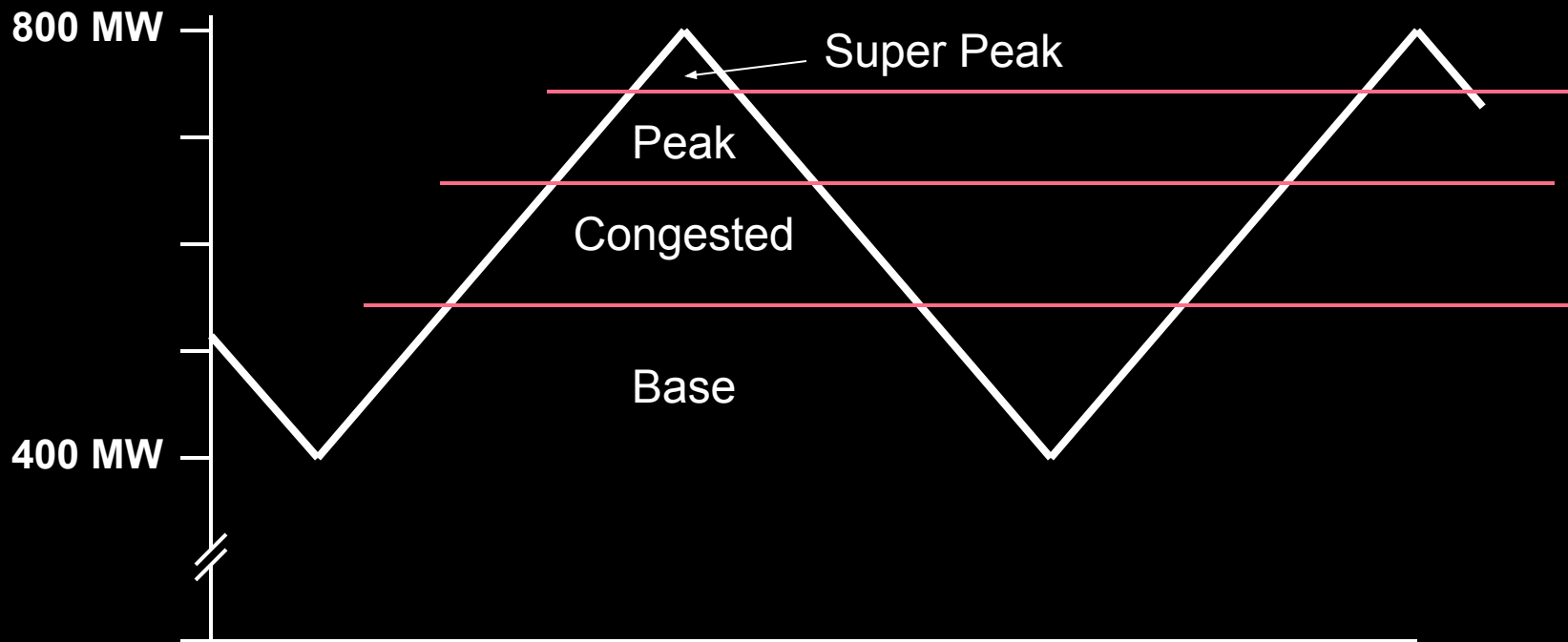
The system will experience 4 qualitatively different demand conditions.

Supper peak ☐ All capacity in use.

Peak ☐ peakers set the price in both locations.

Congestion ☐ different prices in different locations.

Base ☐ Only base load capacity in use. A low price everywhere.

A Qualitative Solution (part 1)

Super peak (high load) hours

Max Gen

R: P = 100 €   → Some Flow →   **C:** P = 100 €

Max Gen*

Price elastic demand   Price elastic demand

Peak hours

Max Gen

R: P = MC$_P$ → Some Flow →   **C:** P = MC$_P$

Some Gen

High Load   High Load
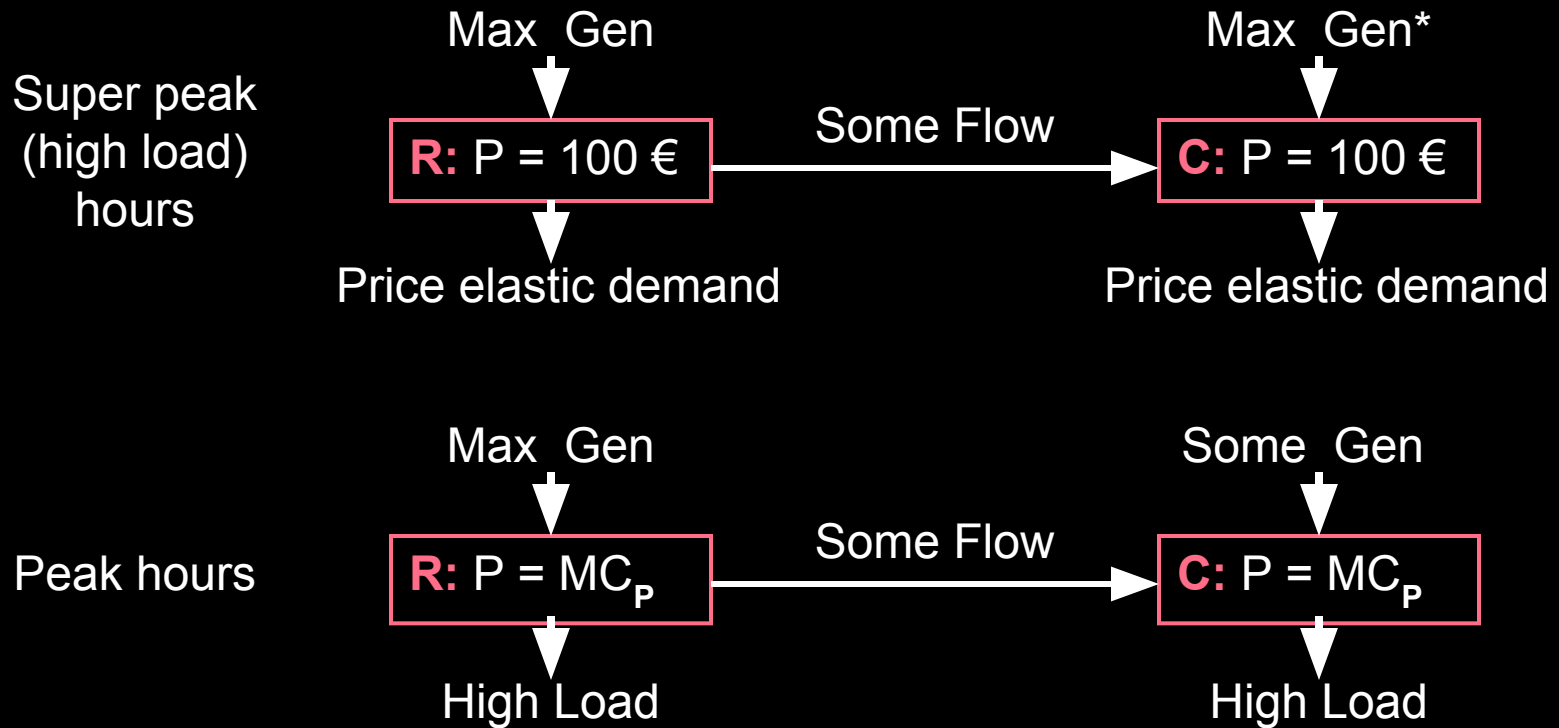
*Max Gen in the city will be less than Max Gen in the remote location.

A Qualitative Solution (part 2)

Mixed hours
(**Congestion**)

Some Gen
↓

| **R:** $P = MC_B$ | → Max Flow → | **C:** $P = MC_P$ |

↓
Medium Load

Some Gen
↓

↓
Medium Load

Base hours

Some Gen
↓

| **R:** $P = MC_B$ | → Some Flow → | **C:** $P = MC_B$ |

↓
Low Load

No Gen
↓

↓
Low Load

Demand Boundaries (at 1 Location)

800 MW —

$(Q_R + Q_C) / 2$ ————— Super Peak

Peak

$Q_R - Q_T$ —————

Congested

Q_T —————

Base

400 MW —
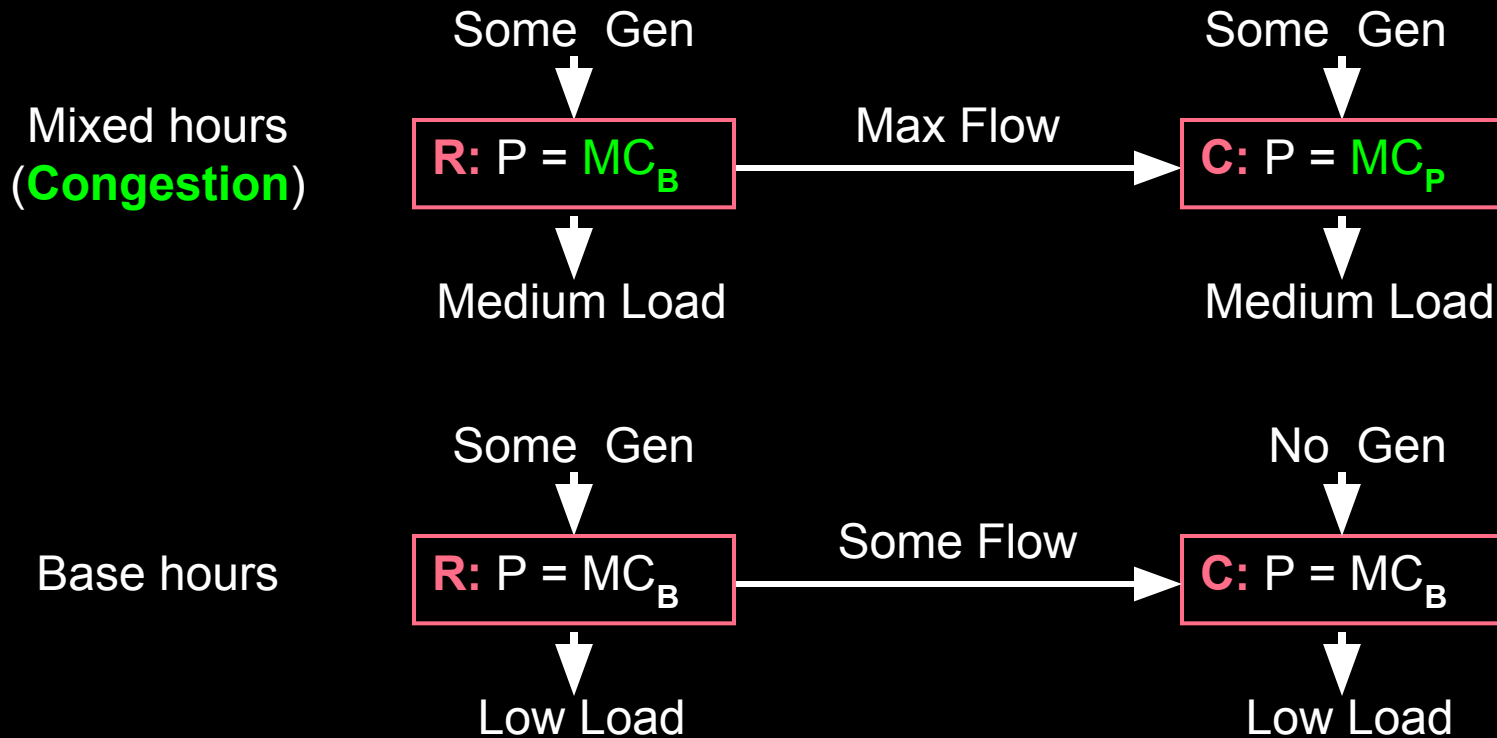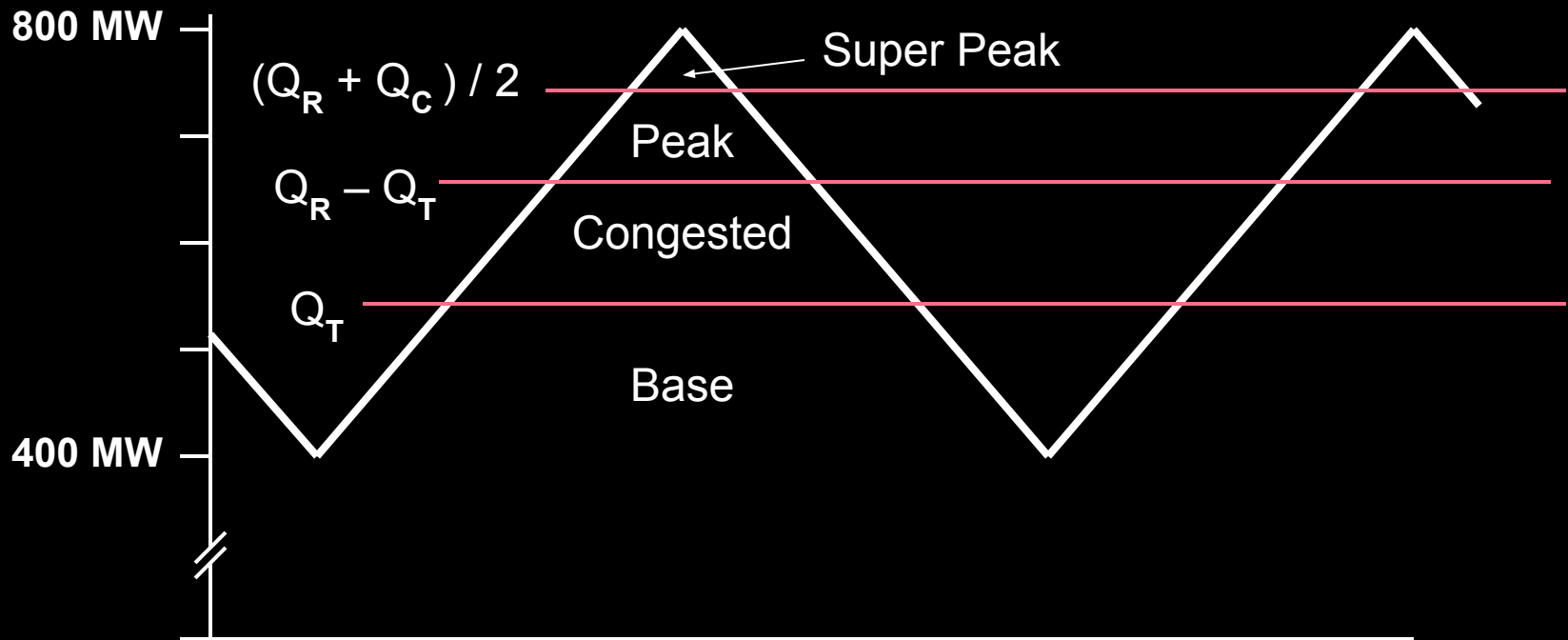
Max total generation = $(Q_R + Q_C)$. Max load per location = **$(Q_R + Q_C) / 2$**.

When City Load < Line Limit, **Q_T**, then all City power can be imported.

The line can only be congested when the remote location has enough surplus capacity to congest the line: $(Q_R - L) > Q_T$, which □ L < (**$Q_R - Q_T$**).

Three Zero-Profit Conditions

- As investors build more generation and more transmission line, their profits decrease. When profits go negative they stop investing.

$$T \times (P - MC) - FC = 0. \quad (\text{Zero Profit})$$

where T = the % of time with price P.

- Short-run production profits pay for investment.

- One condition for each type of investment:

  (1) City Gen, (2) Remote Gen, (3) Transmission line.

1. City Generation (Peakers)

- City generators (peakers) only make short-run profit when $P > MC_P$ □ during super-peak hours.

- $T_{SP} \times (100 - MC_P) - FC_P = 0$.
  Where T_{SP} = percent of super-peak time

- $T_{SP} = FC_P / (100 - MC_P)$
  $T_{SP} = 10 / (100 - 60) = 25\%$.

- $T_{SP} = 25\%$ □ $(Q_R + Q_C) / 2 = 700$ MW, because Load > 700 MW 25% of the time. (See demand graph.)

$$Q_R + Q_C = 1400 \text{ MW}$$

2. Remote Generation (Baseload)

- Remote (baseload) generators make the same short-run profit as peakers (FC_P) during super-peak hours plus this much more: $T_{SP} \times (MC_P - MC_B)$.

- During peak hours they make: $T_P \times (MC_P - MC_B)$.

- Setting their net revenue = to their fixed costs:

  $(T_{SP} + T_P) \times (MC_P - MC_B) + FC_P = FC_B$

- $(T_{SP} + T_P) = 20 / (60 - 20) = 50\%$.

- $T_P + T_{SP} = 50\%$ ☐ **($Q_R - Q_T$) = 600 MW**, because Load > 600 MW 50% of the time. (Also see the Demand-Boundary slide.)
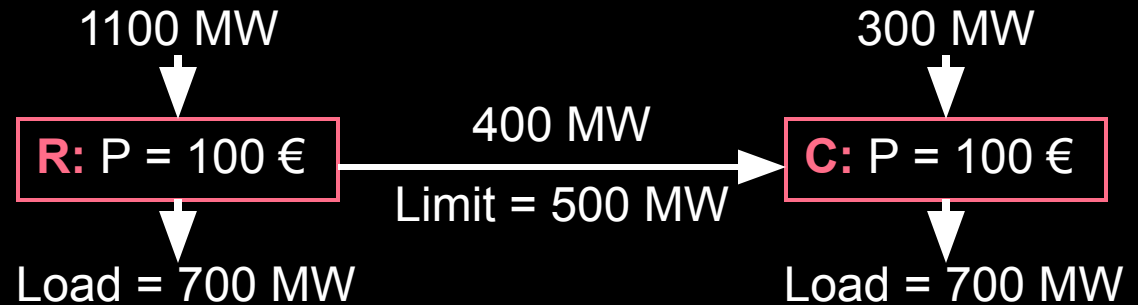
3. Transmission Investment

- A transmission line investors makes profit only when the line is congested (in an ideal world with no market power etc. and line owners are paid the congestion rent).

- Transmission rent = City Price – Remote Price

- $T_M \times (MC_P - MC_B) - FC_T = 0$.
  Where T_M = percent of mixed time (with congestion)

- $T_M = 10 / (60 - 20) = 25\%$.

- $T_M = 25\%$ □ **Q_T = 500 MW**, because
  600 MW > Load > 500 MW only 25% of the time.
  (Also see the Demand-Boundary slide.)

Solving for all investment quantities

- Q_T = 500 MW
- $(Q_R - Q_T)$ = 600 MW ☐ Q_R = 1100 MW
- $Q_R + Q_C$ = 1400 MW ☐ Q_C = 300 MW
- The values for T_{SP}, T_P, and T_M, tells us when the four different load conditions occur.
- We know the CLPs are equal to marginal cost.
- This is the complete solution.

A Quantitative Solution (part 1)

Super peak hours
Load = 750 MW
Before price elasticity

1100 MW

R: P = 100 €   400 MW   C: P = 100 €
Limit = 500 MW

Load = 700 MW

300 MW

Load = 700 MW

Peak hours
Load = 650 MW

1100 MW

R: P = 60 €   450 MW   C: P = 60 €
Limit = 500 MW

Load = 650 MW

200 MW

Load = 650 MW

A Quantitative Solution (part 2)

Mixed hours
(**Congestion**)
Load = 550 MW

1050 MW

R: P = **20 €** → 500 MW / Limit = 500 MW → **C:** P = **60 €**

50 MW

550 MW

550 MW

Base hours
Load = 450 MW

900 MW

R: P = 20 € → 450 MW / Limit = 500 MW → **C:** P = 20 €

0 MW

450 MW

450 MW

Demand Boundaries (at 1 Location)

800 MW

Super Peak

700 MW

Peak

600 MW

Congested

500 MW

Base Load
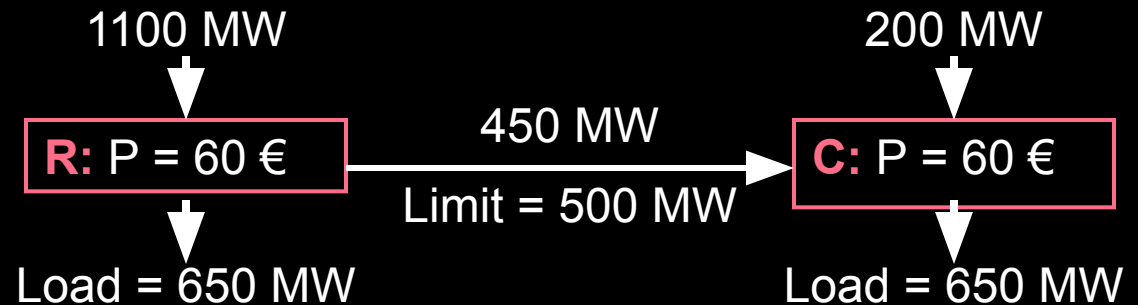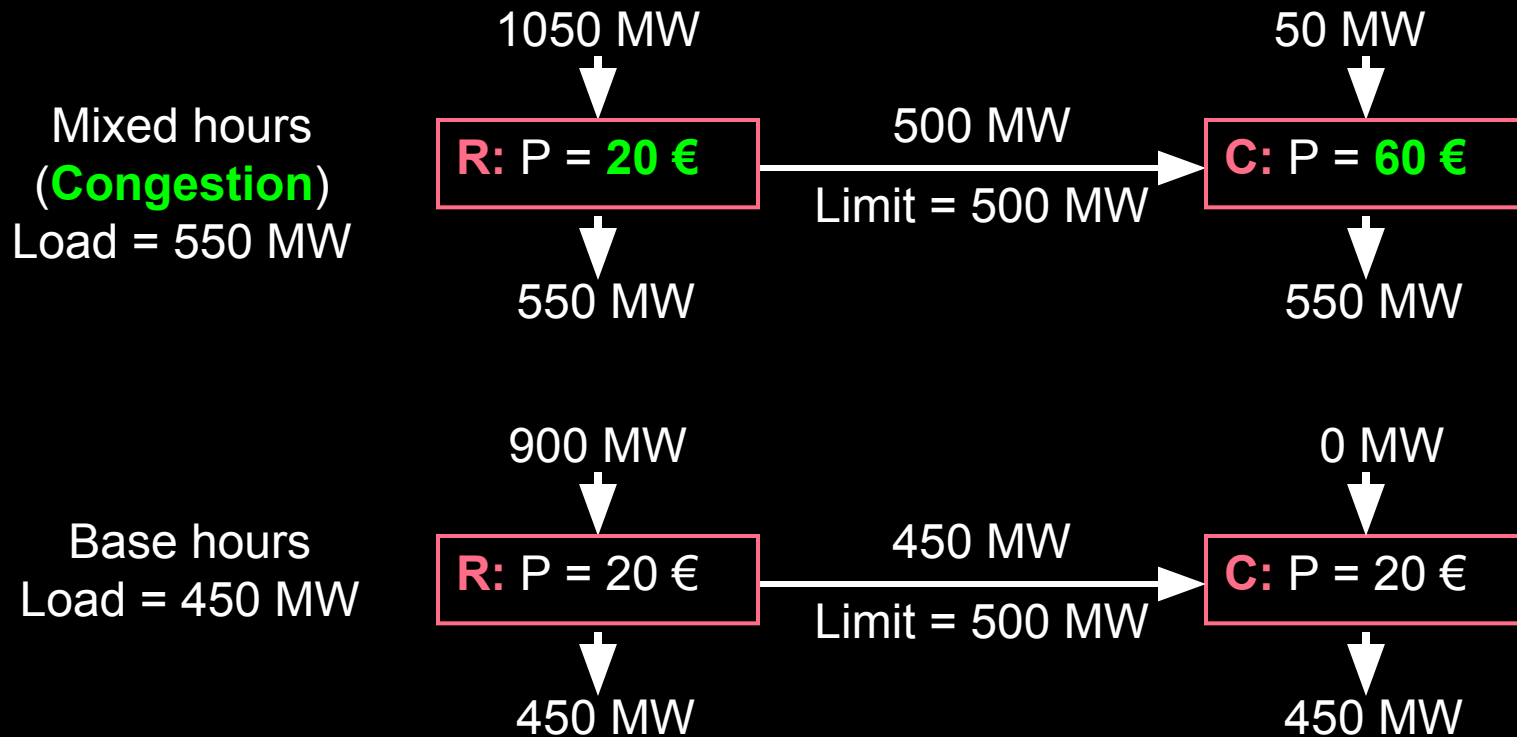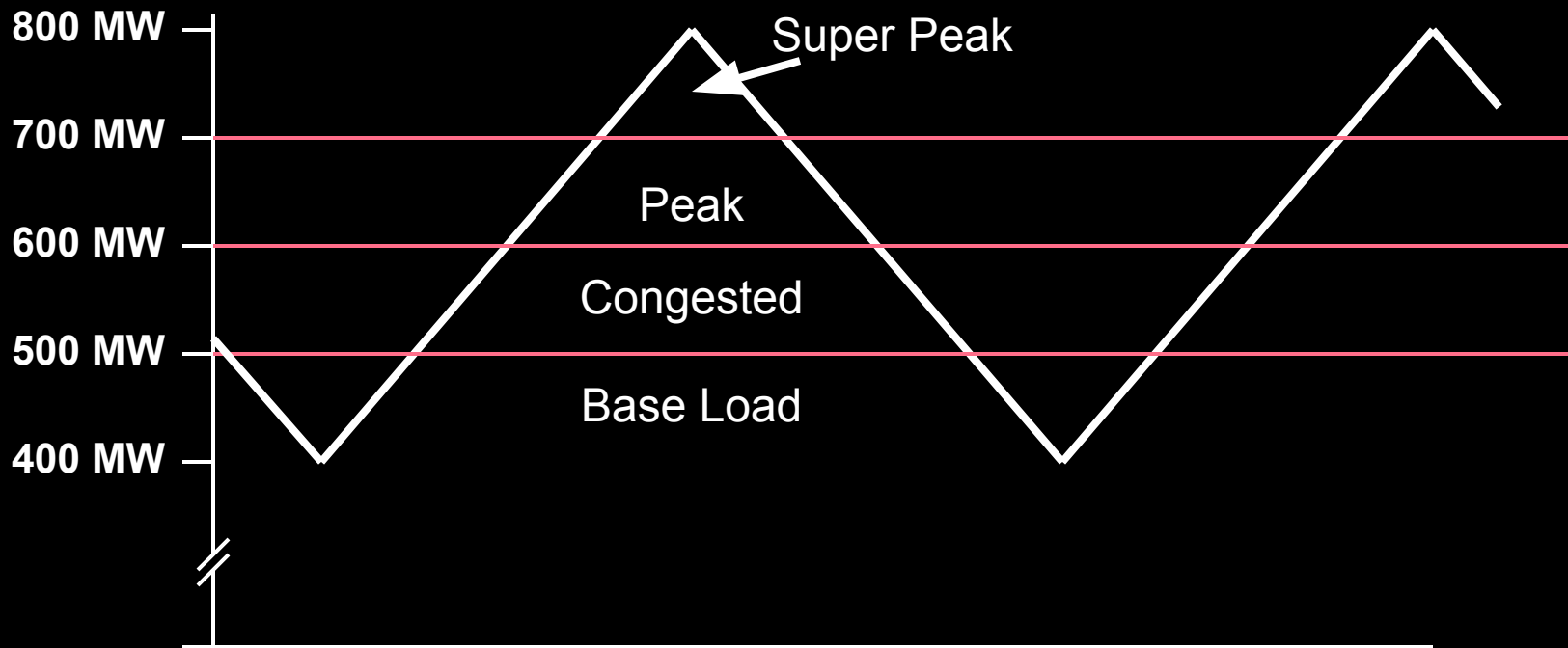
400 MW

Max total generation = 1400 MW ☐ Max load per location = 700 MW.

When City Load < Line Limit, Q_T, (500 MW) all City power is imported.

The line can only be congested when the remote location has enough surplus capacity to congest the line: $(1100 – L) > Q_T$, which ☐ $L < (1100 – 500)$.

Things to Note (1)

- Everything works perfectly.

- Consumers get their electricity at long-run average cost and at short-run marginal cost.

- Investors cover cost including a risk adjusted rate of return—but no more.

- When the City needs 1 MW of City generation, all consumers must pay 60 €/MWh even though the other 1001 MW is produced for 20 €/MWh.

- If these CLPs are "improved" electricity will cost consumers more in the long run.

Things to Note (2)

- In the real world, things do not work so well.
- Some Problems:
  - Consumers don't see the price,
  - Transmission and generation costs are more complex and violate the assumptions of a competitive market.
  - There is market power, mainly in the supper peak hours, and in the transmission markets.
- Competitive Locational Prices (CLPs) are not the problem.
- Non-existent CLPs and nodal prices != CLPs are the problems.

Things to Note (3)

- Congestion (maximum line use) does not happen during the super peak or the peak hours.

- Very often this is the case in the real world.

- The super peak hours last much too long in the model, but the amount of profit generated during those hours is about right.

- Super-peak hours pay all generators enough to cover the fixed costs of a peaker. That's about 1/3 of all short-run profits.

Problems:

1. How much lower would profits of City capacity be, per MWh of capacity, if investors built 350 MW of capacity instead of 300?

2. How much lower would profits of transmission be, per MWh of capacity, if investors built 550 MW of transmission instead of 500?

3. If the transmission owner were a monopolist, and generation investors still built 1100 MW and 300 MW, how much transmission would be built?

Solution #1:

Profits of City capacity if investors built 350 MW of capacity instead of 300?

The extra 50 MW will allow load to increase 25 MW in each location before the super peak begins.

This reduces the duration of the super-peak by 25%, so the short-run profits of peakers is reduced 25%.

Short-run profit in equilibrium = FC = 10 € / MWh, which is 10 × 300 = 3000 € / h.

This is reduced to 2250 € / h, and capacity is increased to 350, so the short run profit per MWh of capacity falls to 6.43 € / MWh, for a reduction of 3.57 € / MWh.

Consequently, total profit is – 3.57 € / MWh.

Solution #2:

What would profits of transmission be if investors built 550 MW of transmission instead of 500?

In equilibrium, congestion begins when load increases from 500.01, so that the city is importing as much as the line can carry.

Congestion ends when remote load reaches 600.01 because at that time, the 1100 MW of country capacity is only enough to export 1100 – 600.01 = 499.99 MW.

With 550 MW of transmission, congestion begins when the load reaches 550, and ends when the power available for export from the remote region drops to 550 = 1100 – L. So it ends when L is 550.

So with a line capacity of 550, the transmission investor makes no profit.

Solution #3:

If the transmission owner were a monopolist, how much transmission would be built?

If the transmission line were only 400 MW it would be congested down to minimum city load of 400 MW, and up to a load of 700 MW because remote export = 1100 – 700 = 400 MW at that load.

With a 399 MW line, the city will run out of capacity at 399+300 MW of load, which is 1 MW sooner than in equilibrium (at 700 MW).

Guess that capacity will be less than 400 and test that guess.

SR profit / MW = T_1 (60 – 20) + T_2 (100 – 20),

where T_1 = the time before L = 300 + Q_T

and T_2 = the time after T_1 and before L = 1100 - Q_T .

(at this point, the remote location runs out of capacity)

Solution #3 continued:

$T_1 = (300 + Q_T - 400) / 400$

$T_2 = \min(1, (1100 - Q_T - 400) / 400) - T_1$

Profit $= [T_1 (60 - 20) + T_2 (100 - 20)] \times Q_T - 10 \times Q_T$

This is easier solved numerically.

$Q_T = 300$ MW,

$T_1 = 50\%$

$T_2 = 50\%$

Profit = 15,000/h = 50 € / MWh

Of course this would not last, as more generation would be built in the city.

Problem #3

Can the Market Solve the Reliability Investment Problem?

Theory versus reality

- This lecture discusses present reality.

- The present market has limitations that would take several years to remove.

- Removing them may not be worth the cost.

- For many consumers, demand is not based on the competitive price.

- This violates an assumption of "perfect competition."

- Standard economic theorems do not apply.

Two Types of Blackouts

- Reliability = There is no "loss of load," "load shedding," or "blackouts."

- **Type 1:** "Controlled rotating power outages," ISO-CA term. Also called "rolling blackouts."

- **Type 2:** "Uncontrolled or cascading power outages," ISO-CA term. Also called "system collapse."

- "Rolling (rotating) blackouts" = Load areas take turns being blacked out.

- Controlled is better than uncontrolled.

Two Types of Reliability

- Reliability = Security + Adequacy

- **Security** = No blackout if (1) a line breaks, or (2) a generator brakes.

- **Adequacy** = Having enough generators for all but "1 day in 10 years." (one definition)

- "1 day" means "1 blackout" = 3 hours on average. This is probably too much reliability.

- Adequacy must take account of the fact that there are always some broken generators ("outages").

Two Ways to Provide Reliability

- **For Security:** Keep extra generators running (spinning reserve). Have quick-start generators in reserve. Respect contingency limits for transmission.

- **For Adequacy:** Build enough (an adequate number of) generators.

- **For Security:** System operator must buy reserves and ancillary services. "The market" will not do this. Everyone agrees.

- **Q:** Will the market buy an adequate number of generators?

Adequacy: The Biggest Controversy

- **The pure-market view:** The market will build enough generation if the system operator does not interfere. It's just normal economics like in "The Complete Market Example."

- **The public-good view:** Individual reliability cannot be purchased. So consumers do not tell "the market" how much reliability they want. Adequacy is an externality (outside the market) like security.
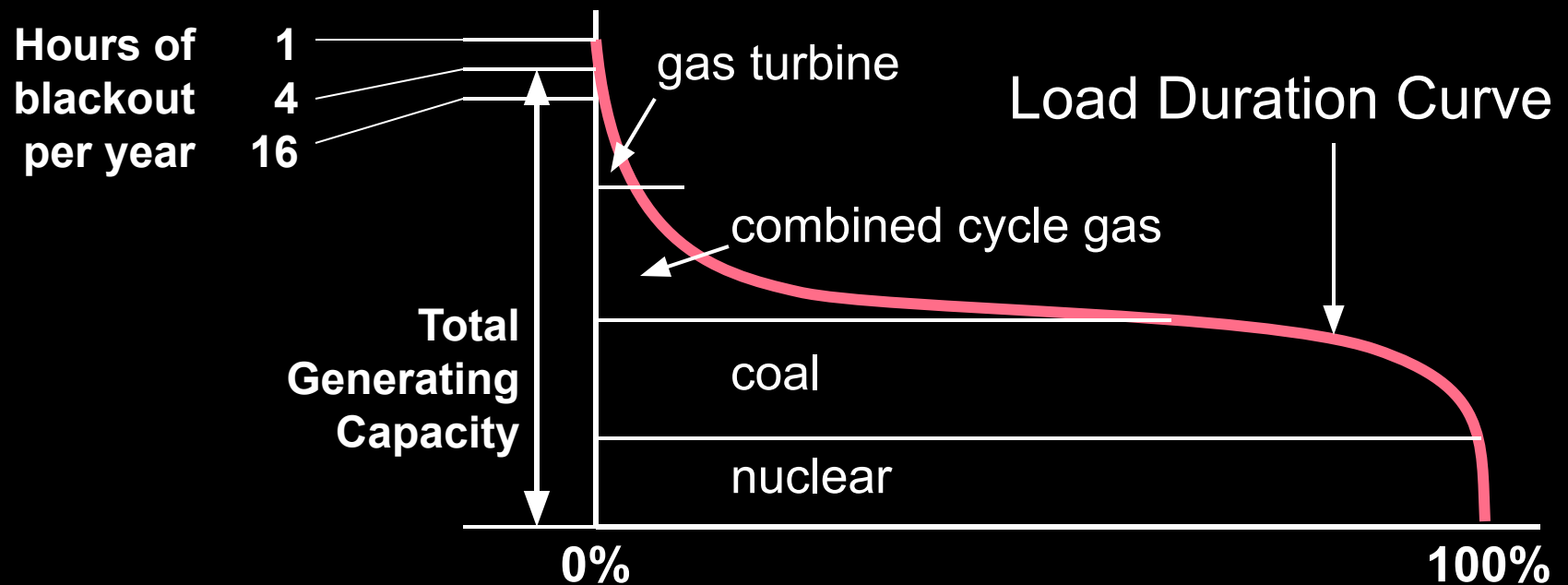
Argument for the Pure-Market View

1. Economic theorem: competitive short-run prices induce optimal investment without regulation.

2. **There is too much reliability** because engineers and regulators are too cautious.

3. Optimal (less) reliability would save money, because fewer generators are needed.

   Step 1 □ A Pure-Market approach will work.

   Step 2 & 3 □ It is important.

What Type of Generator to Buy?

Hours of blackout per year   1   4   16

gas turbine

Load Duration Curve

combined cycle gas

Total Generating Capacity

coal

nuclear

0%   100%

Generators purchased for adequacy will make significant profits for less than 24 hours per year.

The system should have the same number of coal and nuclear plants, for any adequacy level.

For Adequacy: Minimize Fixed Cost

- For a generator that runs only 1-day per year, fuel cost (marginal cost) does not matter.

- Buy the cheapest generator to build.

- For all generators built by the market

  Less Fixed Cost ⟷ More Marginal Cost

- The cheapest plant to build has

  the highest marginal cost

  (a cheap gas turbine, a **GT**)

How Does a GT Make a Profit?

- A GT has the highest marginal cost, MC_{GT}.

- Short run profit > 0 **only** when $P > MC_{GT}$

- When $P > MC_{GT}$ every other plant is running.

- Many GTs will run when $P = MC_{GT}$, but they will make very little profit.

- **An investor in a GT must cover fixed costs during a few super-peak hours when all generators are running at full capacity and $P > MC$ of all generators.**

Restatement of Controversy

- **The Pure-Market View**: The market
  - will send optimal signals (prices) for reliability
  - to investor in GTs
  - during the super-peak hours
  - when P > all MC, and
  - all generators are running.

- **The Public-Good View**: The market
  - Cannot find the competitive price in or near super-peak hours.
  - At these times, price is controlled by regulators and market power, not by competition

The Argument that Pure-Markets Works

1. Economic theorem: competitive short-run prices induce optimal investment without regulation.

   This is the only "proof" that a pure-market approach could work.

   Let us take a closer look.

The argument in more detail

1. The competitive locational (market) price is efficient and induces optimal generation investment, just like in "The Complete Market Example."

2. Optimal generation investment must be "adequate" generation investment.

3. So the "The Complete Market Example" proves that market prices can solve the reliability/adequacy problem.

- **This is wrong.**

Standard Economics Assumes Reliability

- In economics and in The Complete Market Example, 100% reliability is assumed, so

- there is no adequacy problem.

- In standard economics, "Optimal investment" **is not about optimal adequacy**.

- Optimal investment means: enough investment to bring average price down to minimum long-run average cost.

- The concept of "adequate investment" is not in any economics textbook.

Does Economics Assume Reliability?

- It never mentions reliability ???

- It assumes the supply and demand curves always intersect. That means perfect reliability.

- If supply and demand intersect, then **everyone** who wants electricity at the market price will get it. Supply will equal demand. There will never be a rolling blackout (like we had in California).

Conclusion

- The argument for a pure-market approach to investment for reliability is based on a fundamental misunderstanding of economics.

- Standard economics does not support this claim.

- However, standard economics has been extended to cover the reliability/adequacy problem. What does this extension tell us?

Putting Un-Reliability into Economics

Load is shed (lost) when demand is greater than supply.

There is no market-clearing price, where supply = demand.

There is no short-run optimal price, no CLPs.

P

Supply **Demand**

Q
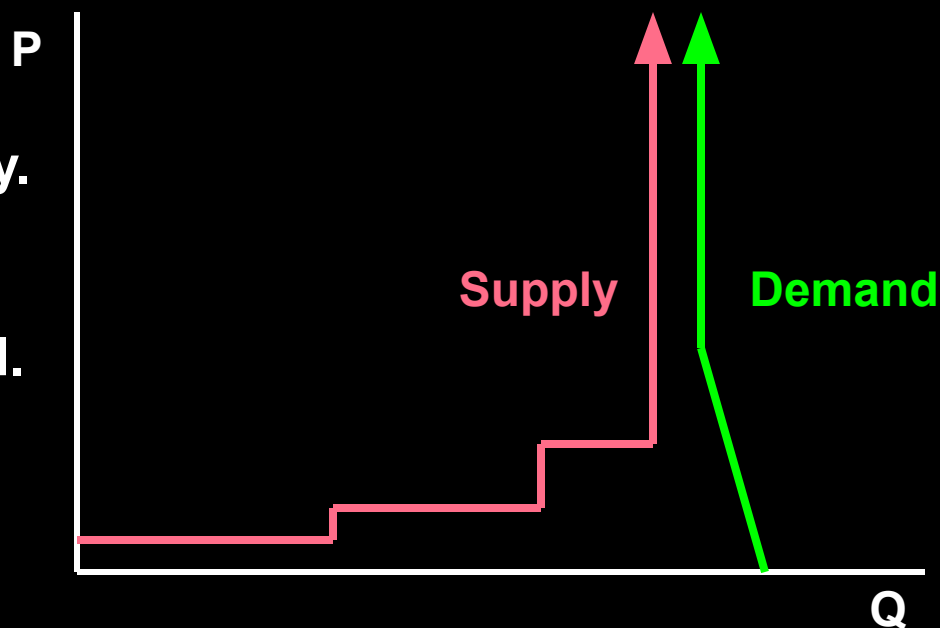
The economics of reliability and adequate investment:

**When there is no competitive price (CLP),
it is best to set P = VOLL, the value of lost load.**

The Economics of VOLL

- P = VOLL is the optimal short-run price.

- P = VOLL is the optimal long-run price.

- Just like CLPs are short and long-run optimal.

- VOLL is the <u>average</u> value lost per MWh for customers who have their power cut off in a blackout. (Customers not assumed identical.)

- We don't know what it is.

- Perhaps 1,000 € < VOLL < 100,000 € / MWh.

Is VOLL Real?

- Many think that because it cannot be measured with reasonable accuracy, that VOLL does not exist or is meaningless.

- Actually, VOLL could be measured with experiments and a market for blackouts.

- VOLL is a useful concept because it helps us understand what happens if we set P > VOLL or P < VOLL.

- Like "utility," VOLL would be useful even if it could not be measured.

Why is P = VOLL short-run optimal?

- A few customers can and do respond to price.

- They should reduce consumption if power is worth less to them than to those blacked out.

- They should not reduce consumption if power is worth more to them.

- P = VOLL ⬜ optimal consumption for price responsive consumers.

- Similarly, a few generators can supply more power, but at great cost.

- P = VOLL ⬜ optimal generation.

Why is P = VOLL Long-Run Optimal?

- It will induce optimal investment.

- Assume 20 hours / year of blackouts.

- 1 more MW of capacity will reduce lost load by 20 MWh. Value of 1 MW = 20 × VOLL.

- Payment to 1 MW = 20 × VOLL.

- If capacity costs less than 20 × VOLL it will be built. If it costs more it will not be built.

  ☐ The optimal amount of capacity for blackouts costing VOLL / MWh will be built.

The economic theory of adequacy

- What can cause an adequacy problem?
  - Market flaws
    - Most load does not respond to price in real time
    - Load that has not purchased power cannot be cut off
    - Load that has purchased power with a bilateral contract cannot be protected from a blackout.
  - Regulatory flaws
    - Price caps that are too low (too little adequacy)
    - Capacity targets that are wrong (likely too high—too much)

Case 1: No real adequacy problem

With enough demand elasticity, there is no real adequacy problem.

Example. FC = 6 € / MWh, MC = 100 € / MWh. High demand 1% of the time.
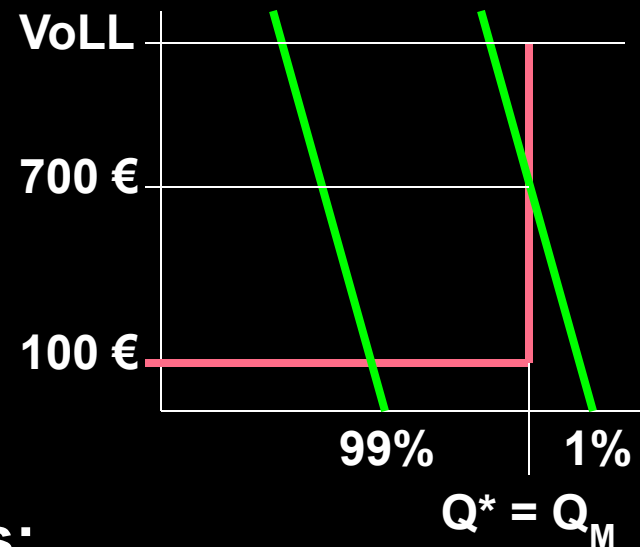
Two possible regulatory problems:

1. $P_{CAP} < P_{MAX} < VoLL.$ □ $Q_M < Q^*$
The regulator can set the price cap too low and cause too little market investment.

2. $Q_T > Q^*.$ □ $Q_R > Q^*$
The regulator can set the capacity target too high.

Case 2: Market price > VoLL

Supply and demand can intersect at a market-clearing price > VoLL. (60,000)

This can happen with a competitive or monopolistic supply curve.

The market will have an equilibrium Q_M > Q*.

The level of reliability is too high because consumers are paying more than the value of the power. They would prefer a blackout to paying so much.

60,000 €

VoLL

100 €

99%

0.01%

Q*

Q_M
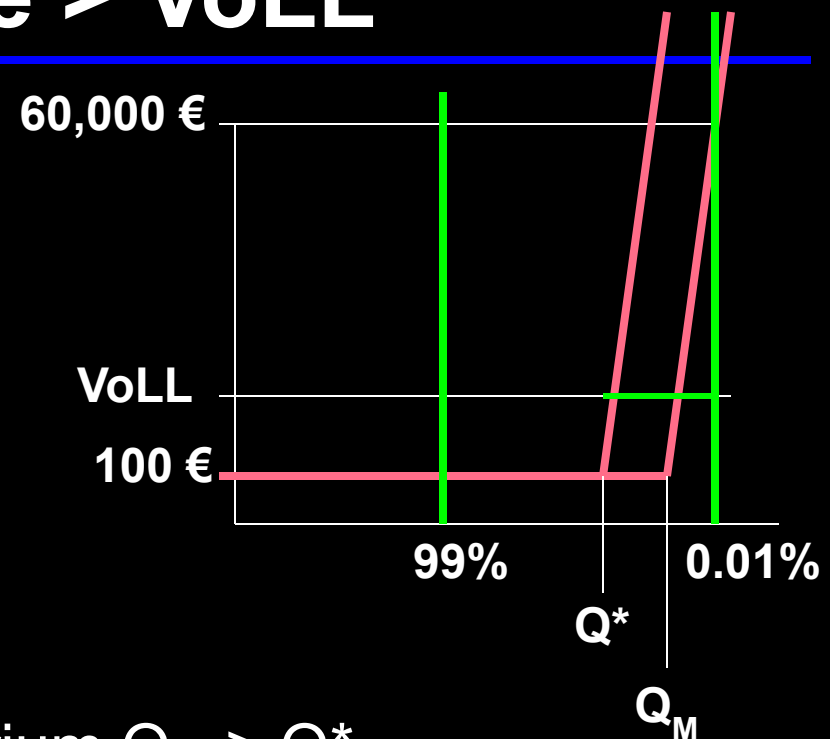
Case 2: Market price > VoLL

For the optimal Q* a peaker earns FC (6 € /MWh) from a price that is capped at VoLL.

$Q^* < Q_M$ because Q_M relies on prices > VoLL.

60,000 €

VoLL

100 €

99%   **0.01%**

Q*

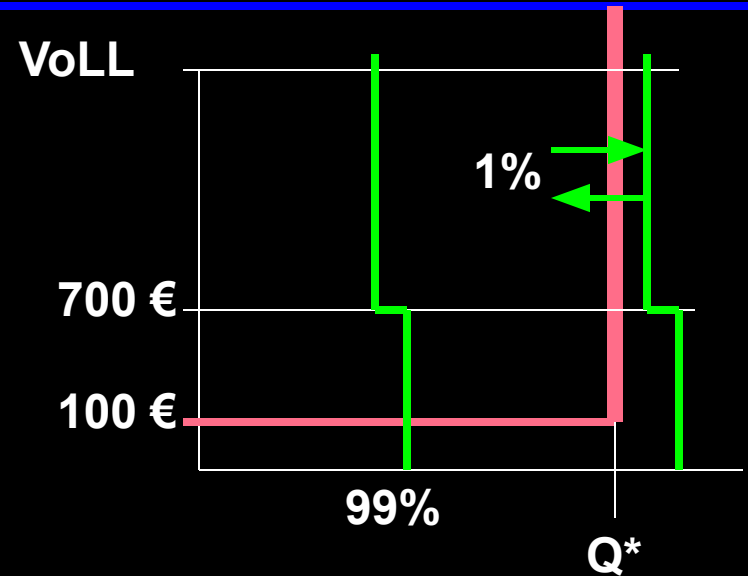**Q_M**
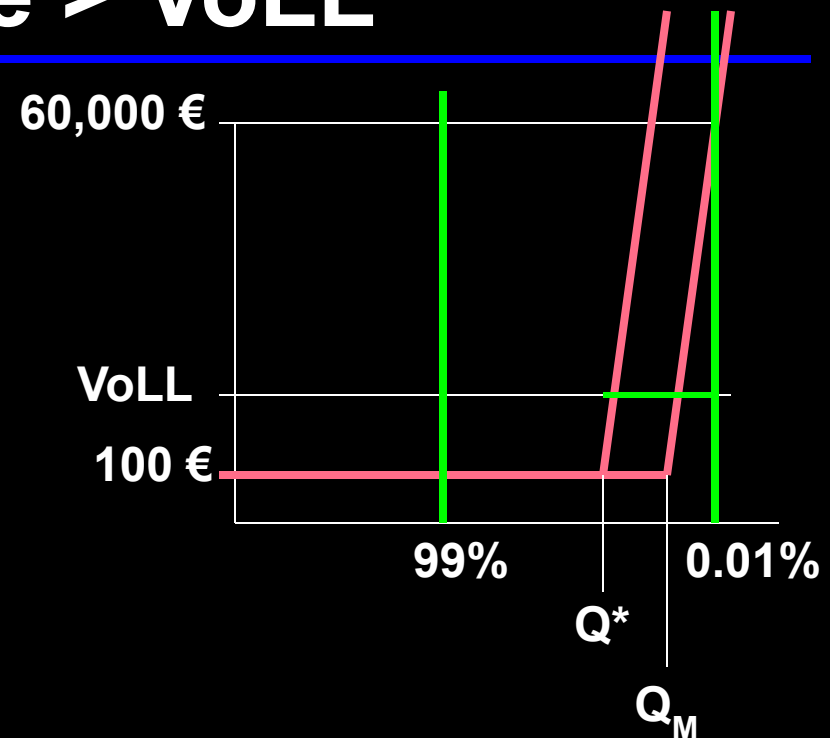
Regulatory improvement: P_{CAP} = VoLL.   □ $Q_M = Q^*$

Two possible regulatory problems:
- P_{CAP} < VoLL.   □ $Q_M < Q^*$
2. $Q_T > Q^*$.   □ $Q_R > Q^*$

Case 3: No market equilibrium

The demand curve moves up to its maximum as shown on 1% of the days, but it spends only 0.1% of the time intersecting the supply curve at Q*. This is the only time when P>100 € and P is defined.

VoLL

700 €

100 €

1%

99%

Q*

Consequently, the market price cannot support the optimal level of Q, Q*.

If the regulator defines a price when S ≠ D, then there will be an equilibrium, but the market does not have an equilibrium of its own.

Interaction of regulation and market

$(\,Q_M\,,\,Q_R\,)$ Compares Market & Regulated Q with Q*		Regulatory Rules			
		1	2	3	4
		$P_{CAP} < V$	$P_{CAP} < V$	$P_{CAP} = V$	No P_{CAP}
		$Q_T > Q^*$	$Q_T = Q^*$	No Q_T	No Q_T
No market flaw	1	less, more	less, =	= , =	= , =
P sometimes > V	2	less, more	less, =	= , =	more, more
No equilibrium	3	less, more	less, =	= , =	?, ?

V = VoLL.   Assumes no market power or excess risk.

Q_R = Total capacity including regulatory purchases.

Q^* = optimal (adequate) capacity.

Q_T = regulator's target capacity.

121

Interpretation of table

- Column 4 is the pure-market approach because the market cannot set P = VoLL.

- The pure-market approach assumes cell (1, 1), and proposes to move to cell (1, 4).

- With market power, columns 3 & 4 could indicate (more, more) in all positions.

- In Columns 1 & 2, P_{CAP} must be less than the maximum market price in order to distort investment.

Could the market set P = VOLL?

- No.

- It would have to read our minds.

- Two problems:
  - Markets cannot read minds.
  - Our minds are blank.

- Do you know your VOLL?

- Have you ever told "the market" what it is?

- (But a market for individual blackouts could set the price of blackouts to VOLL.)

Pure-market theorem 1:

- A pure-market approach can solve the adequacy problem only if there is no market flaw causing an adequacy problem.

- If the pure-market approach solves the adequacy problem, it will make the market 100% reliable.

- If the market is currently too reliable, then the pure market approach cannot solve the adequacy problem.

Theorem Interpretation

- The pure market approach removes the price cap and capacity target. If these were the only market problems, then this will solve all of the problems.

- If the demand curve is severely distorted and this causes an adequacy problem, the market cannot solve this problem.

- If optimal capacity is determined by VoLL, the load duration curve, and the cost of peakers, then optimal capacity will not produce 100% reliability and the pure market approach cannot solve the problem.
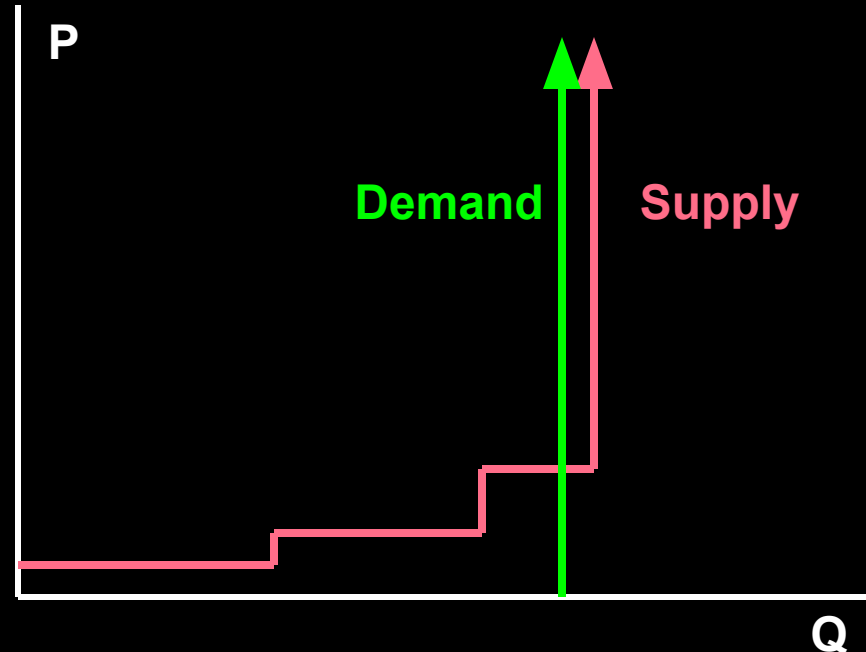
Super-peak market power

Before the super-peak, how much market power is there?

Say Supply > Demand by 290 MW

Any supplier that owns 500 MW can turn off 300 MW and raise the price from 150 € to 10,000 €.

Problem: How profitable is this?

P

Demand   **Supply**

Q

Near the super-peak, GTs will make a profit only from market power. During the supper peak, they will make a profit according to the arbitrary 10,000 € price set by the system administrator.

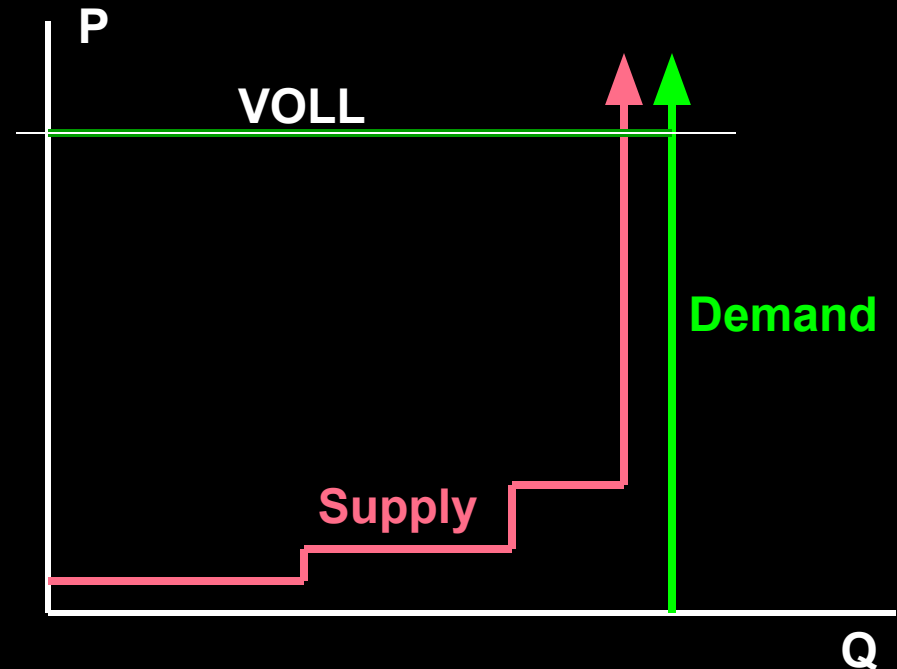Their profit will never come from a competitive market price.

Super-peak risk

Assume the SO sets P = VOLL when demand > supply.

Assume no market power.

US reliability ⟹ VOLL = 180,000 €.

GT investors make their profits when P = VOLL, They need 60,000 € per year.

P

VOLL

Demand

Supply

Q

Investors cover their fixed costs with 20 minutes of short-term profits.

But those 20 minutes do not happen every year. Sometimes there may be 4 hours of rolling blackouts, and then none for 11 more years. It averages out to 20 minutes per year. Investors think this is risky business. Risk is expensive.

"Pure-market" summary

- SO sets arbitrary high cap on monopoly power.

- SO sets price high when Demand > Supply.

- SO sets a medium high price when short of reserves.

- Investment is determined by SO and market power.

- Investment is not related to optimal reliability or to minimizing long-run costs.

- Investor risk is high because price spikes are rare.

- Actual "Pure-Market" proposals are not at all pure. They will induce adequate capacity only if the regulator does a good job. The market will not help out.

"Pure-market" summary

- The "pure market" approach can work only if there is no market flaw. In this case the market will make the equilibrium capacity adequate by controlling demand to prevent all blackouts.

- Advocates do not believe this will happen.
  - They say reliability is too high.
  - They propose price caps in case of market power.
  - These caps set the price during a blackout.
  - They suggest the regulator raise prices when operating reserves are short.

The ICAP market approach

- While the market still has an adequacy problem,
  - Engineers should
    - determine the adequate level of investment.
  - The regulator should:

    (1) use an installed capacity (ICAP) market.

    (2) use high prices for performance incentives.

    (3) use a hedge to reduce risk and market power.

Two old approaches

The "pure" approach:

- high prices for
  - Determining installed capacity
  - Good performance incentives
- A hedge to reduce market power

The old capacity-market approach

- Low prices to reduce market power
- A capacity market to determine installed capacity

The new convergence

- high prices for good performance incentives
- A hedge to reduce market power and risk
- A capacity market to determine installed capacity.

- The trick is to use the hedge to prevent the high prices from controlling capacity and to keep the capacity market from hurting incentives.

What works and what doesn't

- Competitive locational prices are excellent for:
    - Dispatch
    - Consumption
    - Inducing investment of the right quality and type of generation.

- But they have problems:
    - They are risky and risk is expensive.
    - They invite market power.
    - They are a poor signal for total investment

What works and what doesn't

- Hedges (call options)
  - Greatly reduces risk
  - Greatly reduces market power
  - Do not block the good incentives of CLPs

- A market-determined capacity payment
  - Is an excellent signal for total investment
  - Sends no performance signal

How the ICAP market works (without a hedge)

- Engineers estimate needed capacity in 2011.
    - 52 GW is needed
    - 50 GW exists (or is being built).

- Old and new capacity bid B € / MW capacity.

- The SO accepts cheapest bids, up to B*.

- All the winners are paid B* in 2011.

- New suppliers lock in B* for 5 or 10 years.

- Short-run profit = Annual ∑ (P – MC) + B*

- Competition limits short-run profits to just enough to induce investment.

Adding a Hedge (call option)

- Payment to generators works like this:

- P* = strike price = about 250 € / MWh.

- ∑ (P – P*) is hedge payment to load

- Generators are paid B* – ∑ (P – P*) for ICAP.
   (when P > P*)

- This eliminates most price-spike risk,

- And eliminates most on-peak market power.

- Keeps performance incentives.

Total short-run profit (net revenue)

= Annual $\sum$ (P – MC) + B* – (P – P*)

= Scarcity rent + ICAP payment – Hedge payment

= Hedge payment only when P > P*.

Let P_H = minimum (P, P*)

= Annual $(P_H – MC)$ + B*

= (Scarcity rent as if P* = price cap) + ICAP payment

How the hedge reduces risk

Price cap = 10,000 €

10 x higher

Hedge payments

5 hour price spike to cap
49,800 €/MW without hedge
800 €/MW with hedge

Scarcity rents

P* = 200 €

Short-run profit

MC = 40 €
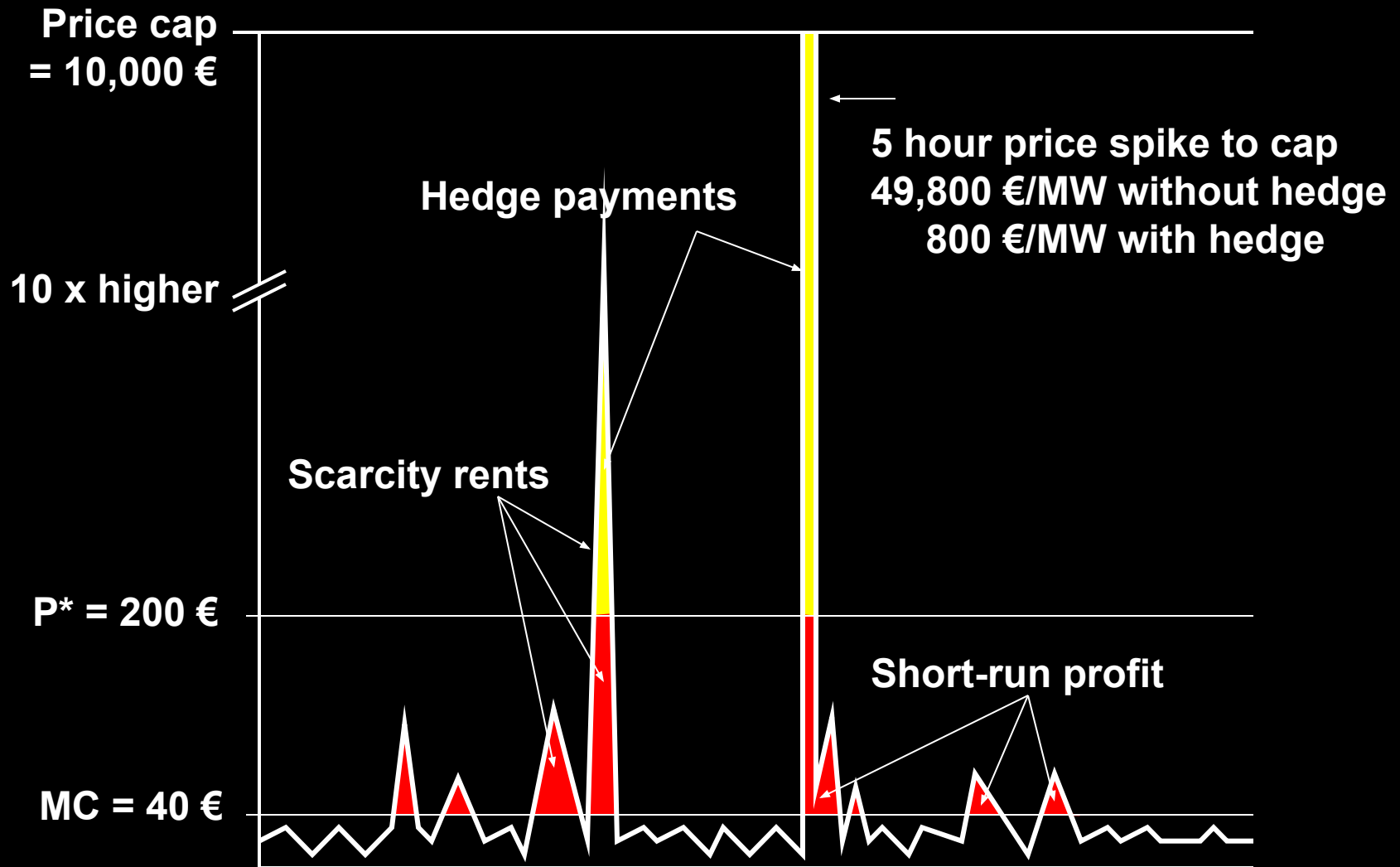
The hedge does not hurt generators

- The generators lose the tops of the price spikes.

- Suppose these are worth 40,000 € / MW-year on average.

- They bid 40,000 € / MW-year higher in the ICAP auction and the clearing price, B*, is 40,000 € higher.

- A very random 40,000 € is replaced with a very steady 40,000 €.

- The same is true for consumers.

The hedge eliminates most market power

- Suppose a generator exercises market power and turns a 100 € price spike into a 10,000 € price spike.

- Without a hedge, profit = 9,900 € / MWh.

- With the hedge, profit = 160 € / MWh.

- But this is only half the story.

- Next consider the incentive to produce.

Hedge does not affect incentives

- Is it stupid to pay a 10,000 € price and then take back 9,800 € in hedge payments?

- Why not just have a 200 € price cap?

- Because of the incentive.

- If there is a 10,000 € price spike for 1 hour, and the generator does not produce,
  - The generator does not make 10,000 € / MW.
  - The generator must still pay its 10,000 € / MW hedge payment.

- The incentive is the same as with a 10,000 price.

2nd Half of market-power story

- In order to raise the price from 100 € to 10,000 €, the supplier must withhold some MW.

- These MW will earn no revenue but must pay a 10,000 hedge payment.

- The call option (hedge) makes it expensive to withhold and exercise market power.

Incentives for consumers

- With a hedge and a high price cap, industrial consumers who pay the real-time price will have a strong incentive not to consume.

- In a near emergency, when the price goes to the cap, it is good to have strong incentives for both producers and consumers.

Summary of a good ICAP Market

- The engineers decide:
  - Reliability level, VOLL, level of installed capacity
  - These are all equivalent (1 decision)
- This is because the market cannot do this.
- But the market can and should decide
  - Which types of generators
  - Which suppliers are cheapest
  - The level of performance
- The market can and should avoid
  - Price risk (but not performance risk)
  - Market power

Is this market failure surprising?

- "Adequate generation" solves the problem of
  "demand > supply."

- This is both a reliability problem and a severe market failure—there is no competitive price and not even a market-clearing price.

- It would be strange if a market could solve a problem that happens only when the market fails.

- Of course if the market does not fail (if there is perfect reliability) then we expect the market to work, and it does.

What about excess-reliability cost?

- The advocates of the pure-market approach, claim that regulators buy too much reliability and this is costly.

- If so, then there is more time when

  Demand > Supply.

- There should be more market failure.

146

What about excess-reliability cost?

- There will be market power during super peak hours, unless no supplier is larger than about ~2% of the market.

- So prices will be higher than competitive prices.

- The investment signal will be too strong,

- There will be more than optimal capacity and more than optimal reliability—possibly 100% reliability.

Pure-market Theorem 2

- If a pure market approach works efficiently it will provide 100% reliability (theorem 1).

- If a pure market approach provides 100% reliability that does not imply it is working efficiently (it may only indicate excess capacity caused by market power).

What about excess-reliability cost?

- Suppose pure-marketers are right, that engineers buy too much reliability.

- Typical: capacity > peak load by 18%

- Maybe 10% extra is enough (all engineers would disagree). That's 8% savings.

- But there is no fuel cost savings: 8% ⬜ 4%

- Peaker capacity is very cheap: 4% ⬜ 1.5%

- That's wholesale savings.

- Retail savings is about 0.7%

What about the cost of risk?

- Risk premium for peaker equity might drop by 4% because of the mandatory hedge.

- 50% equity financing ⬜ 340/2 €/kW at risk.

- 170 € × 4% / (60% × 8760) = 1.3 €/MWh

   60% is the average capacity factor of all capacity.

- Typical wholesale cost = 35 € ⬜ 3.7% increase.

- Large because all capacity earns the same revenue from price spikes and has the same risk.

The "theory" of too-little risk

- The energy-only approach (pure market) argues that we should create more risk so that generators can make more money selling insurance (hedges) to consumers.

- Fire insurance is good, but people may not buy enough. If not, then we should burn down some house so there is more risk. They will buy more insurance.

- Risk is costly. Increasing cost, so that people will try harder to reduce cost is not economics.

Which problems are most important?

- Buying too much capacity is cheap, and there is currently no way to have a competitive market determine capacity. Optimizing reliability is one of the least important problems.

- Creating too much risk with super-high price spikes (energy-only approach) is more costly.

- High price spikes cause political problems that can destroy the market.

- High prices exacerbate market power.

Problem #4

Transmission Investment:
Is the Market
# Better than Planning?

Fixed and Marginal Cost Definition

- Previously "Fixed Cost" meant cost that is not related to the energy production or transmission.

- Marginal Cost meant cost that is proportional to energy. So transmission lines had MC = 0.

- **New Definition for Transmission:**

- **Marginal Costs** are proportional to line capacity.

- **Fixed Costs** are unrelated to line capacity

Congestion Should Not Be Eliminated

Wind Turbine 0 € / MWh	MC = 10 € / MWh →	City 50 € / MWh

With free electricity why have <u>any</u> congestion?

100 MW

Wind turbine output
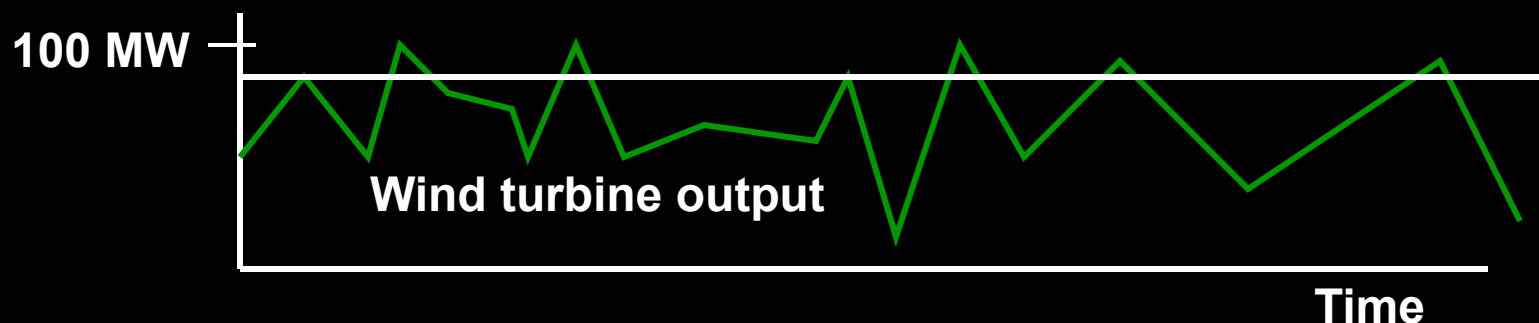
Time

Line capacity = Q. Wind output = W.
Probability (W)= (100 – W) %
So a 99 MW line will be fully used only 1% of the time.
Adding 1 MW of line capacity will cost 10 € / h,
but it will supply on 1% of 1 MW to the city.
This is worth only 0.5 € / h.
It is better to have a little congestion than to pay for a 100 MW line.

A Market for Transmission?

- In "The Complete Market Example" investors were paid the congestion rent on a line.

- Other rules are possible and may be better.

- How the market for transmission investment works depends on the rule for paying investors.

- The first rule to analyze is this:

   Pay the line owner the line's congestion rent.

Congestion Rent

- Generators are paid CLP at injection node.

- Loads are charged CLP at withdrawal node.

- A line is like both at once.

Line = Load   **Line = Gen**

Remote $\rightarrow$ ———————————————— $\rightarrow$ **City**

- If W_{RC} is the power flow from R to C, the line owner is paid "**congestion rent**" =
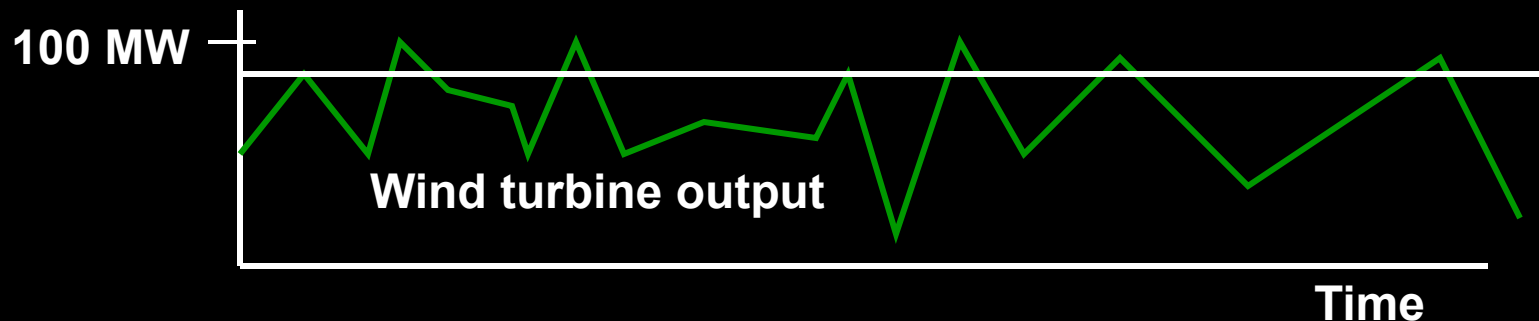
$$W_{RC} \times P_C - W_{RC} \times P_{RC}.$$

Line = Gen   **Line = Load**

A transmission monopolist

Wind Turbine 0 € / MWh	→ MC = 10 € / MWh →	City 50 € / MWh

Assume the congestion % = 100 – Q,   where Q = line capacity

100 MW

Wind turbine output

Time

How big a line would you build?
10 MW ?   Cost = 100, congestion = 90%, Rent = 10 × 0.9 × 50
40 MW ?   Cost = 400, Rent = 40 × 0.6 × 50 = 1200
50 MW ?   Cost = 500, Rent = 50 × 0.5 × 50 = 1250

But going from 40 ☐ 50 MW, saves about 10 × 50% × 50 €,
Which is 250 € / h. And, the cost is only 100 € / h.

158

Competitive transmission investment

Wind Turbine		City
0 € / MWh	MC = 10 € / MWh →	50 € / MWh

Assume the congestion % = 100 – Q,   where Q = line capacity

Starting with the monopoly analysis:
10 MW ?   Cost = 100, congestion = 90%, Rent = 10 × 0.9 × 50
40 MW ?   Cost = 400, Rent = 40 × 0.6 × 50 = 1200

What if someone else owned the line, but you could add 10 MW to it.
Add 10 MW?   Cost = 100, congestion = 50%,
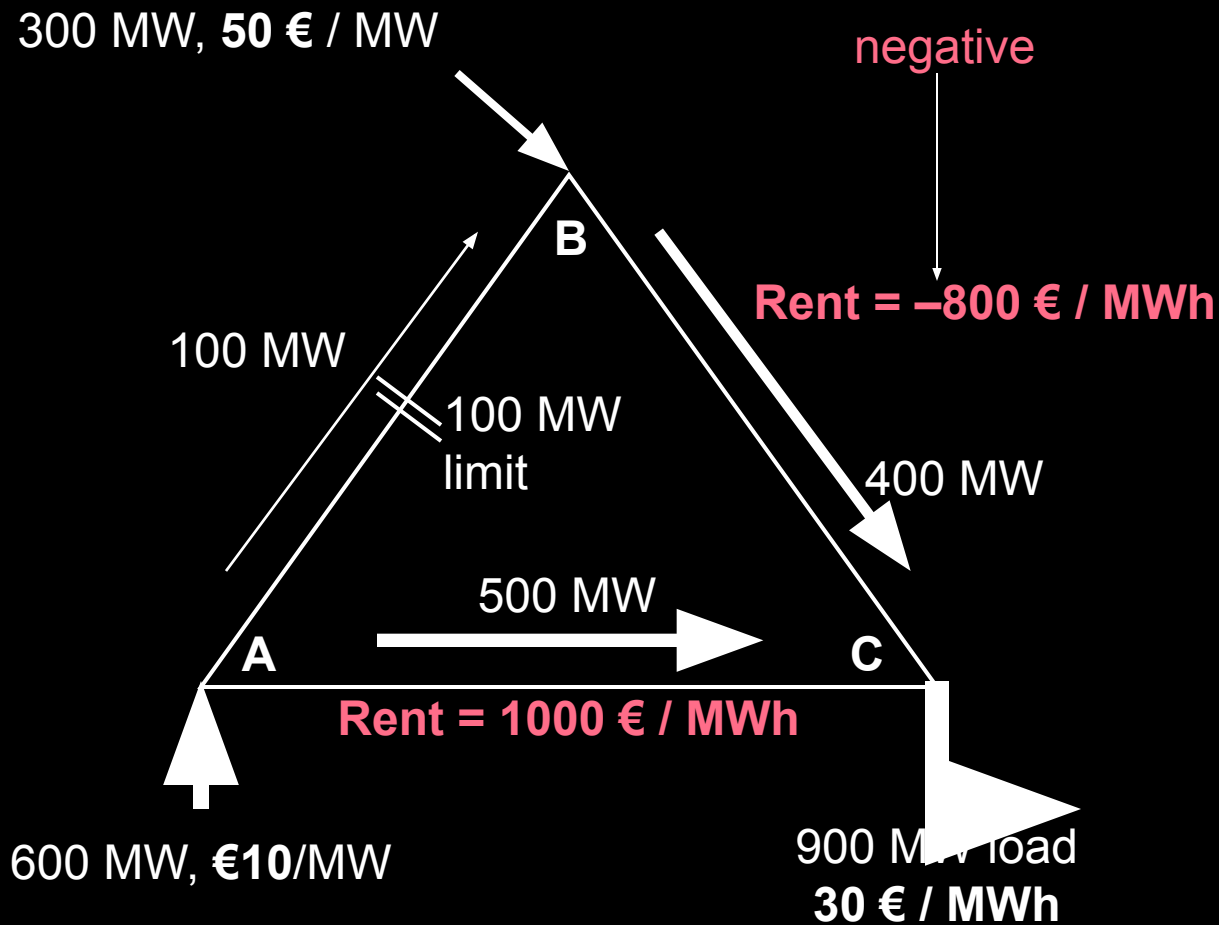   Your rent = 10 × 50% × 50 € = 250 € / h

So you would expand the line.
But this would lower the profits of the owner of the line.

Congestion rent and monopoly

- Paying congestion rent is not a good incentive for monopolists.

- But it is a good incentive for competitors.

- This is just like market-clearing prices.

- But we need to have competition on every group of parallel lines.

- It is difficult to have competition in many small markets.

Example of Congestion Rent

300 MW, **50 €** / MW

negative

B

Rent = –800 € / MWh

100 MW

100 MW limit

400 MW

500 MW

A

C

Rent = 1000 € / MWh

600 MW, **€10**/MW

900 MW load
30 € / MWh

Negative Congestion Rent

- When a line carries power from an expensive location to cheap location, congestion rent is negative.

- CLPs = true value of power

- If power is moved from high value to low value then total system value is reduce.

- Negative congestion rent makes sense.

Is negative rent good for investment?
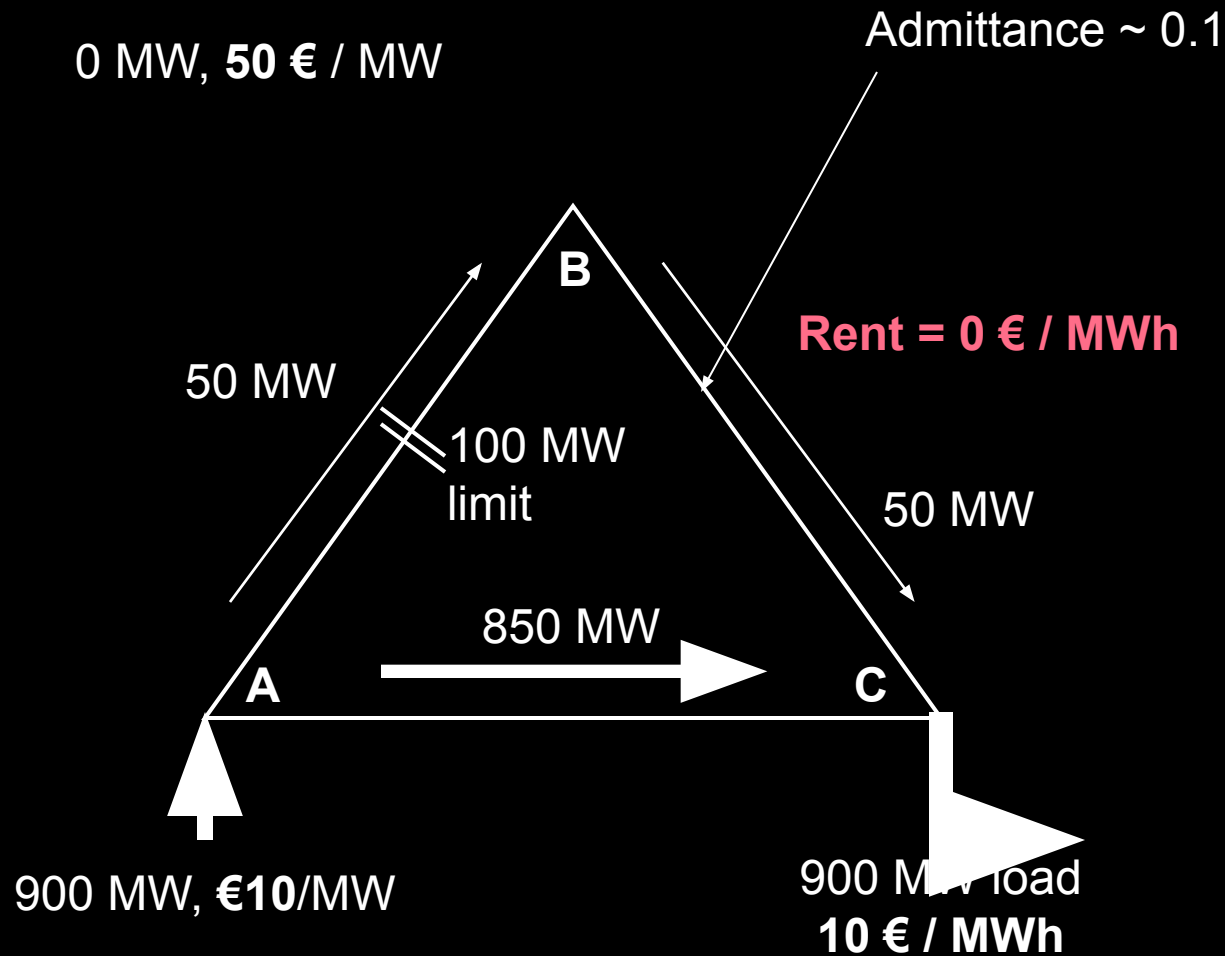
What can investors do?

1. They can change the line's capacity
   (how many MW it can carry).
2. They can change the line's "admittance"
   (how easy it is for power to flows).

Admittance = 1 / Impedance

Admittance = how easy.

Impedance = how difficult.

If line B—C has low admittance

Admittance ~ 0.1

0 MW, **50 €** / MW

B

Rent = 0 € / MWh

50 MW

100 MW
limit

50 MW

A

850 MW

C

900 MW, **€10**/MW

900 MW load
10 € / MWh

Negative congestion rent works

- Negative congestion rent on line B—C causes the owner to decrease it's admittance.

- Less power flows through this line.

- Line A—B is no longer congested.

- More power can go from A (cheap) to C.

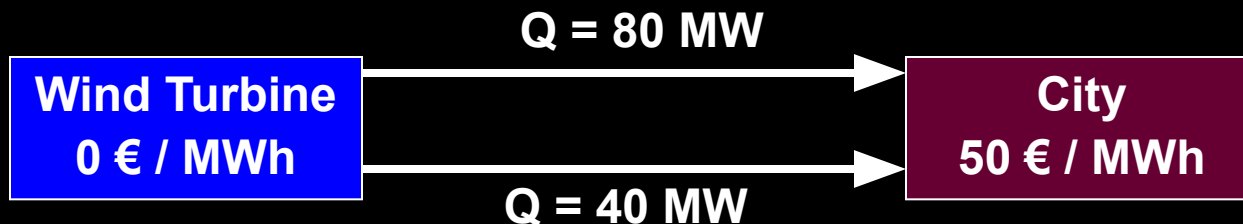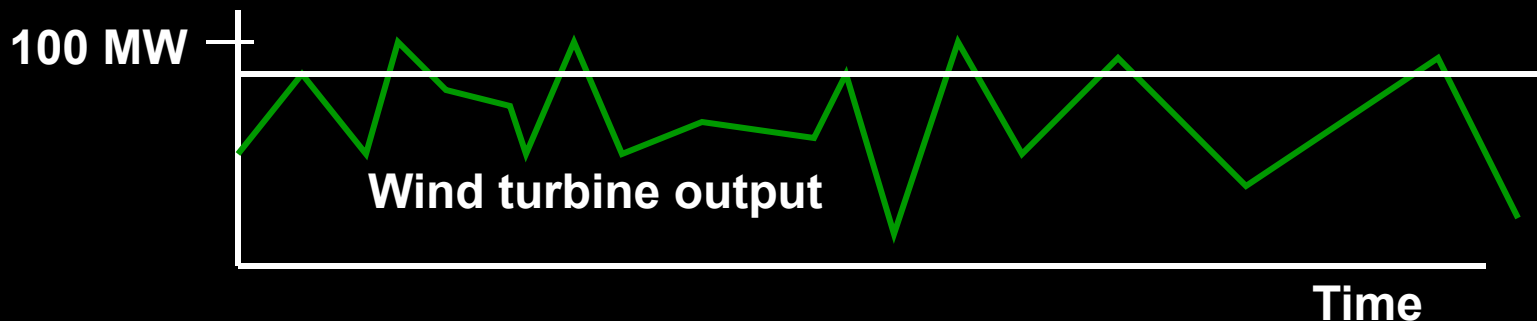- The negative congestion rent on B—C goes away.

Admittance causes problems

- Sometimes congestion rent means "chance the line's capacity."

- Sometimes congestion rent means "change the line's admittance."

- Can one price work for both?

- No.

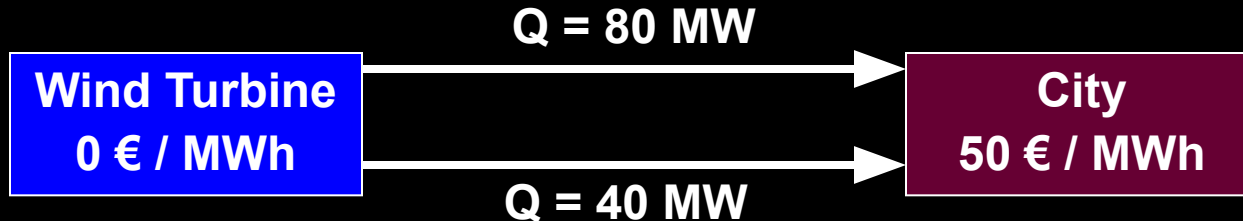- Here's an example.

Changing admittance causes problems

| Wind Turbine 0 € / MWh | Q = 80 MW →
 MC = 10 € / MWh | City 50 € / MWh |

An 80 MW line is optimal. Assume it has admittance = 1.

100 MW

Wind turbine output

Time

| Wind Turbine 0 € / MWh | Q = 80 MW →

 Q = 40 MW → | City 50 € / MWh |

Someone builds a new line with admittance = 2

Changing admittance causes problems

Q = 80 MW

Wind Turbine	→	City
0 € / MWh		**50 € / MWh**

Q = 40 MW

Someone builds a new line with admittance = 2

Twice as much power flows on the 2nd line.
But it has a limit of 40 MW,

So only 20 MW can flow on the first line.
Only 60 MW total.
This is less than before, so now there is more congestion.
40% congestion instead of 20% congestion.

So the new line makes as much money as the old line used to,
And the old line makes half as much.

And the city is worse off.

When does congestion rent work?

- Paying investors the line's congestion rent will only work if

  Every change in a line increases or decreases the lines capacity and admittance proportionally.

  If capacity is increased 10%, admittance must be increased 10%.

When congestion rent works

- So we have two rules for congestion rent:

  1. Every group of parallel lines (transmission path) must have a competitive market for improvements.

  2. All upgrades must change admittance and capacity proportionally.

  Will that make congestion rent work?

Returns to scale

Wind Turbine 0 € / MWh	Q = 80 MW MC = 10 € / MWh →	City 50 € / MWh

An 80 MW line is optimal.

This line is congested 20% of the time.
So competitive 1 MW investor makes: 1 MW × 20% × 50 € / MWh.
This is exactly 10 € / h, which is the cost of the line.

Investors break even.

But what if the first MW cost 20 € and then each MW of capacity was a little cheaper? The last MW cost 10 €.

This would still be an optimal line.
It would still save the city more than the line cost.
But, all of the investors would lose money.

Returns to Scale

€/h

Congestion
Rent

Effective
Fixed
Cost

Line Cost

Optimal Line Size

MW
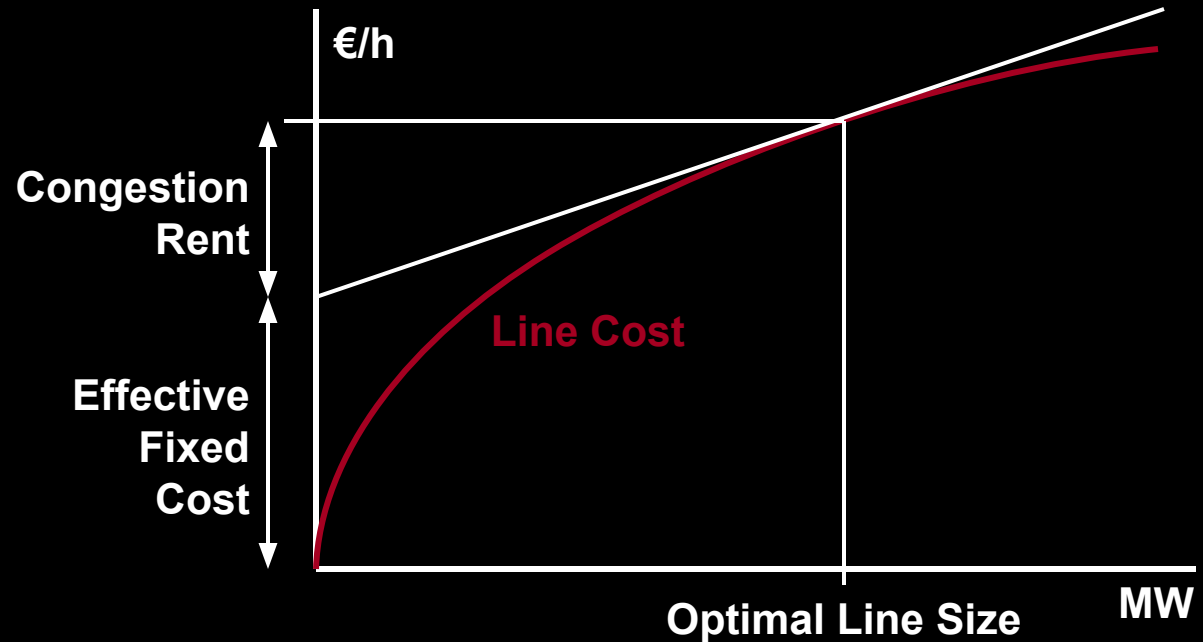
- Returns to scale in line construction cause "fixed costs."

- These are not covered by congestion rent.

Returns to scale

- Generally bigger lines are cheaper per MW.

- This means there are generally returns to scale.

- In this case, perfect competition and congestion rents will not cover the investors costs.

When congestion rent works:

- Now we have 3 rules for congestion rent:

  1. Every group of parallel lines (transmission path) must have a competitive market for improvements.

  2. All upgrades must change admittance and capacity proportionally.

  3. There must not be returns to scale.

Conclusion:

- Paying investors congestion rent works only in a special world where admittance and cost are proportional to line capacity and where there is competition on every transmission path.

- The real world is not like this.

- We need another system.

Forget about paying congestion rent

- In a nodal market the system operator buys power cheaply from generators and sells at a higher price to load, whenever there is congestion.

- The SO collects the congestion rent.

- Below, the SO collects 2000 € / h.

$$P_A = 20 € \xrightarrow{\text{100 MW}} P_B = 40 €$$
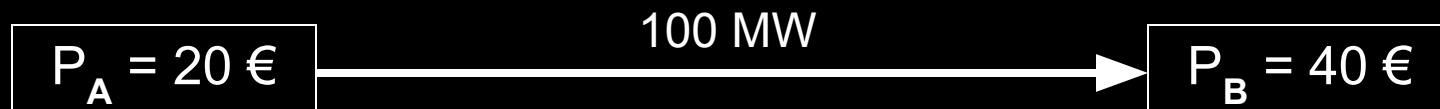
Congestion revenue collected on a line is $Q \times (P_B - P_A)$, where Q is the energy flow from A to B.   (The same a congestion rent.)
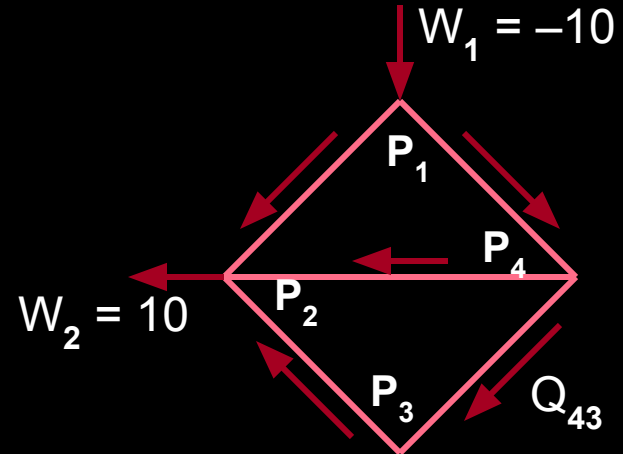
Congestion Revenue Accounting

Congestion revenue for the grid is the sum of congestion revenues on all lines.

$W_1 = -10$

P_1

P_4

P_2

$W_2 = 10$

P_3

Q_{43}
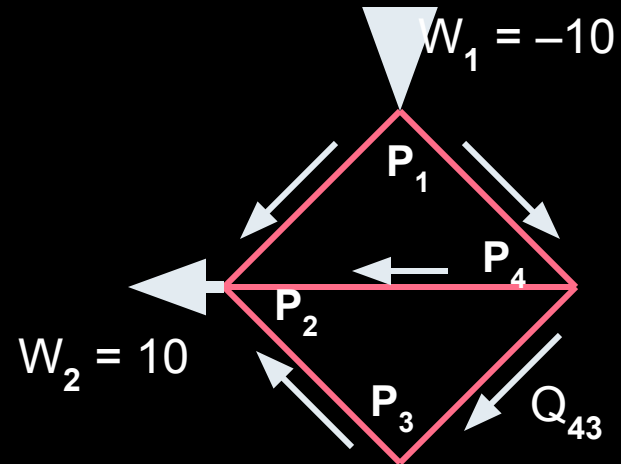
This can also be computed from the energy withdrawals (W_i) by this formula for Grid revenue

Revenue = $\sum W_i P_i$ = 200 € if P_1 = 20 and P_2 = 40.

Congestion Revenue Accounting

$W_1 = -10$

P_1

P_4

$W_2 = 10$

P_2

P_3

Q_{43}

For a bilateral trade from A to B, the congestion revenue is calculated with the same formula as for a line. Even if there are many lines in between.

The total congestion revenue on a set of bilateral trades
= sum of congestion revenue on each line
= congestion revenue from power injections and withdrawals

A Congestion Revenue Right

- A **CRR** for Q from A to B pays:

    $Q \times (P_B - P_A)$ while in effect

- A **CRR** is a financial right. The owner is paid for an amount Q even if no power flows from A to B.

- The owner of the right does not need to own a power line.

Congestion Revenue Rights

- If $P_A > P_B$, then a CRR from A to B has negative value.

- CRRs may be given by the SO to line owners.

- CRRs may be sold in auctions and traded.

- If you have a generator a A and sell power to B, then a CRR from A to B will hedge the cost of congestion.

Using a CRR as a hedge

- If there is no congestion, then the CRR pays you nothing

- If the congestion rent on the line from A to B is 10 € / MWh, then the generator will be paid only 30 € for power when his customer a B buys his power for 40 €.

- But if the generator has a CRR, the CRR will pay him 10 €. 10 + 30 = 40, so it's just like he sold his power to B with no congestion rent.

Using CRRs for investment

- In order to reward investors, we can give them CRRs.

- But what CRR should be given for an investment?

- Remember, reducing the admittance of a line can reduce congestion on another line.

- Changing one line can affect the usefulness of other lines.

- The network effects are very complicated.

Giving CRRs to investors

- The best rule for giving CRRs to investors is very tricky.

    1. First give out as many CRRs as possible.

    2. When an investor improves the network, more CRRs will be possible.

    3. Give the investors the extra CRRs that are possible because he improved the network.

    But what does "possible" mean?

As many CRRs as possible

- Each CRR is for a power flow Q from A to B.

- A set of CRRs is possible ("feasible") if we could actually make Q MW of power flow from A to B for every CRR in the set and it would not violate any transmission limit.

- With a maximal set of CRRs, it is impossible to increase any CRR in the set and still have a possible (feasible) set.

Giving CRRs to investors

- The best rule for giving CRRs to investors is very tricky.

  1. First give out a maximal set of CRRs

  2. When an investor improves the network, more CRRs will be possible.

  3. Let the investor choose addition CRRs which combined with the previous set makes a new maximal set.

Giving CRRs to investors

- This rule for giving CRRs to investors, is the best rule anyone has come up with in the last 10 year.

- It does reward investors for good investments, but the reward is not enough.

- It also punishes investors for bad investments (it forces them to accept CRRs with negative value).

- But it does not induce optimal investment.

DC power lines

- Investors can control the flow of power on DC power lines.

- The can make more or less power flow and increase or decrease congestion.

- Essentially they buy power at the cheap end and sell it at the expensive end.

- They will never have negative congestion rent, but cause the control the direction of flow.

- The can maximize their profit by controlling the amount of the flow.

DC power lines

- With DC power lines there is no question of admittance, only a question of capacity.

- Because investors have more control and can maximize their profits better, some DC lines have been privately built.

- But very few have been built so far.

- The bad news is: DC lines are much more expensive.

Can the market build transmission

- So far, we have no theory of how a real market for transmission investment should work.

- I do not know of any AC lines being built.

- Some DC lines have been build, but these are special cases.

- Almost all investment is still public.

How

- CRRs are not physical, but they specify a power flow, Q and a path A□B.

- We can pretend they are power flows.

- What if we put all of these power flows into the grid at once? Would it violate a transmission limit?

- If not, it is a "feasible" set of CRRs.

- Could the CRR on any line be increased without violating a limit?

- If not, it is a "maximal" set of CRRs.

How Many CRRs Should the SO Sell?

- CRRs are not physical, but they specify a power flow, Q and a path A□B.

- We can pretend they are power flows.

- What if we put all of these power flows into the grid at once? Would it violate a transmission limit?

- If not, it is a "feasible" set of CRRs.

- Could the CRR on any line be increased without violating a limit?

- If not, it is a "maximal" set of CRRs.

Congestion Revenue vs. CRRs

- If the SO sells a maximal, feasible set of CRRs,

- and the SO buys all the power from generators and sells all the power to consumers, at nodal prices,

- The SO will collect enough revenue to pay for the CRRs.

- This is Bill Hogan's "revenue adequacy theorem." In real networks it is almost exact.

CRRs and Transmission Investment

- CRRs can be used to reward transmission investment.

- If someone builds a line, they can be given the CRR for that line.

- But building a line has a complex affect on power flow limits on other lines.

- There is a better and more general reward rule.

The Feasible Allocation Rule for CRRs

- Before someone builds a line or otherwise changes the network, there is a set of publicly owned CRRs that is a maximal feasible set.

- After they build the line, that set may not be maximal or feasible.

- The investor must choose a set of CRRs, which combined with the existing set, forms a maximal, feasible set for the new network.
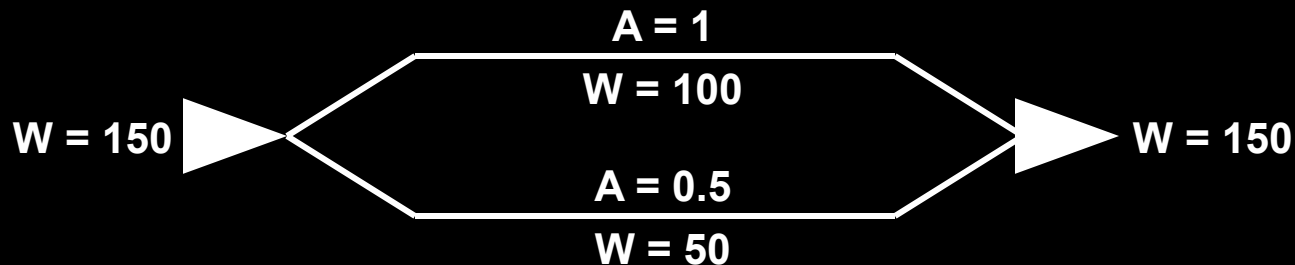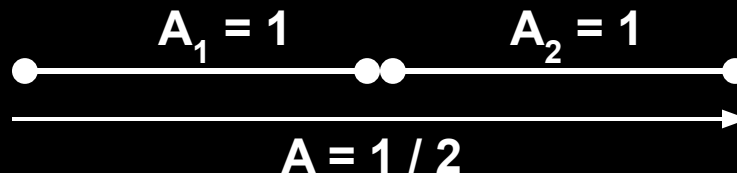
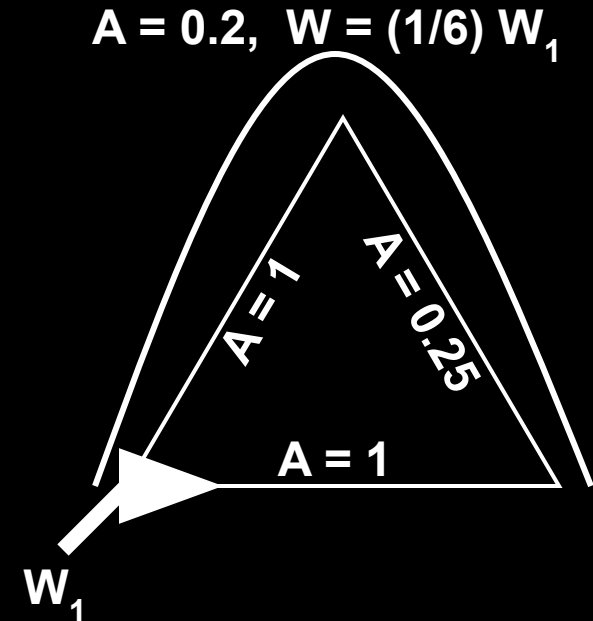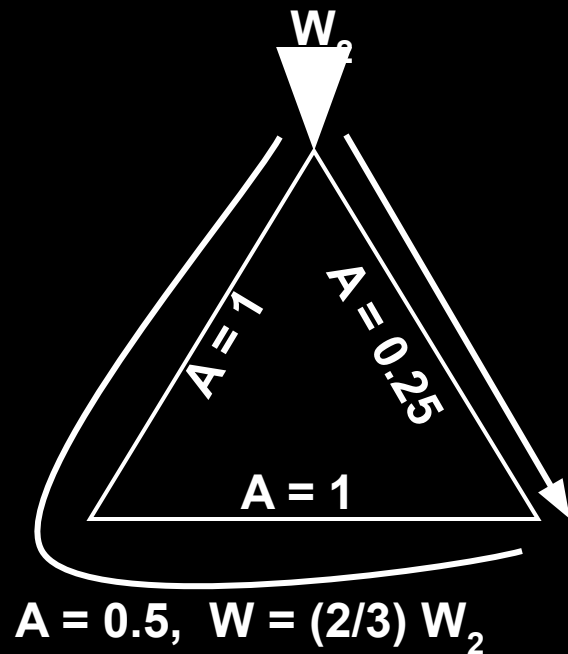# Negative Rent ⯈ Reduce Admittance

- If the owner of the line reduces the admittance, there will be less flow and less negative rent.

- Admittance = 0 means take down the line.

- Ohms law adapted for power flow, says

$A = 1$
$W = 100$

$W = 150$ ⯈ ⯈ $W = 150$

$A = 0.5$
$W = 50$

Power flow on parallel lines is proportional to admittance.
$A = 1 / (1/A_1 + 1/A_2)$ **for 2 lines in series**

$A_1 = 1$ $A_2 = 1$

$A = 1 / 2$

Investor reduce admittance

W_2

A = 1

A = 0.25

A = 1

A = 0.5, W = (2/3) W_2

A = 0.2, W = (1/6) W_1

A = 1

A = 0.25

A = 1

W_1

Line limit of 100 ⟹ (1/6) W1 – (2/3) W2 = 100.

Load = 900 ⟹ W1 + W2 = 900

⟹ W1 = 840, W2 = 60.   ⟹ P3 = (840×10 + 60×50)/900 = 12.67

Conclusion about negative rent

- Negative congestion rent on a line signals that the line is carrying too much power.

- Reducing the power flow will save the owner money, so the signal is in the right direction.

- The line is not congested (the power flow is not equal to the lines limit).

- A marginal reduction in capacity will not help.

- A marginal reduction in admittance will help.

- **Congestion rents signal needed changes in admittance and capacity.**

Conclusion about positive rent

- In most cases of positive congestion rent, the line is not congested (power flow < limit).

- Increasing line capacity will not help because there is more than enough.

- The positive rent signals investors to increase admittance (decrease impedance).

Is line-by-line rent the right investment signal?

- Yes, but under extremely limited conditions.
- First consider market power:

MC = 20 €   VC = 10 €   MC = 50 €

Remote ⟷ ⟶ ⟹ **City**

100 MW

Load

40 MW
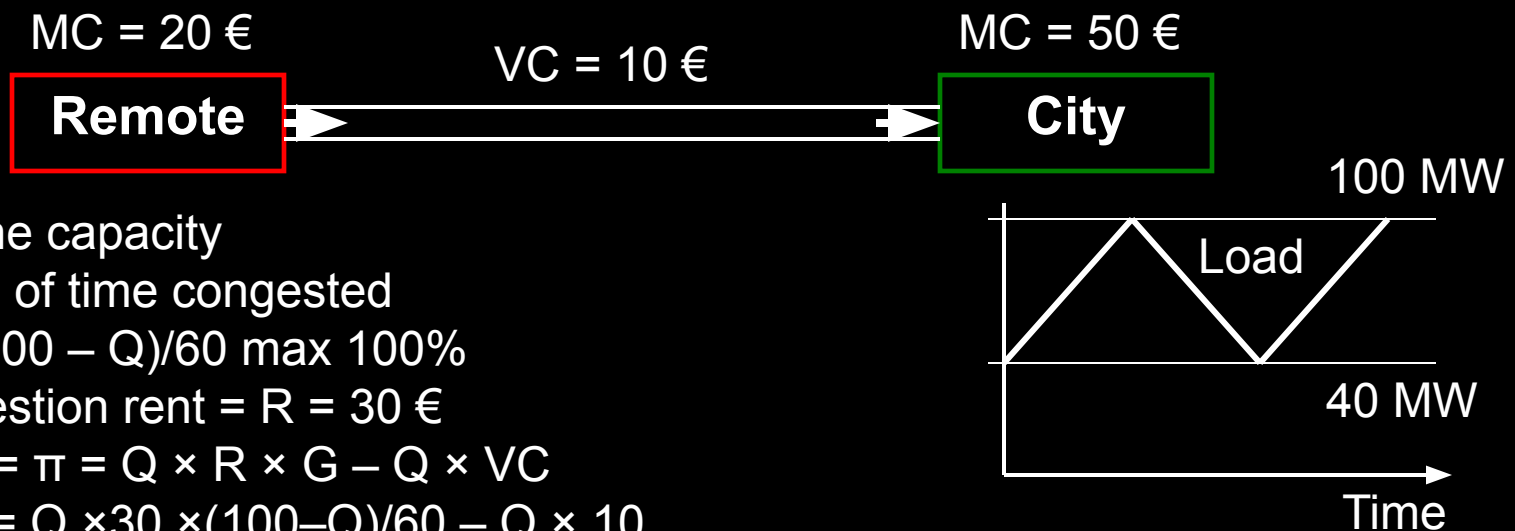
Time

Q = line capacity
G = % of time congested
G = (100 – Q)/60 max 100%
Congestion rent = R = 30 €
Profit = π = Q × R × G – Q × VC
$$= Q \times 30 \times (100-Q)/60 - Q \times 10$$
$$= Q \times 50 - (1/2) Q^2$$
dπ/dQ = 50 – Q = 0.
　Q = 50 MW, and G = 80% congestion. The monopoly outcome.
But 33% congestion will cover the €10 VC □ **Q = 80 MW is optimal**.

209

Perfect Competition

- Market power is a problem (no surprise), so we need to assume perfect competition.

- But what does this mean.

- Many different investors can expand a line.

Optimal Investment with Competition

Wind Turbine 0 € / MWh	80 MW → FC = 10 € / MWh	City 50 € / MWh

The previous investor was a monopolist.

If a competitor could now add 1 MW to the line, her profit would be €25 – €10. So competition would expand the line.

This would continue until the line reached 80 MW.
Profit would then fall to Rent – Cost = (20% × 50 – 10) € / MWh,
     = 0 € / MWh.

Social Benefit vs Profit

Wind Turbine 0 € / MWh	→ 80 MW FC = 10 € / MWh	City 50 € / MWh

The net benefit of an 80 MW line is:

[80 (20% + 100%)/2] × 50 – 80 × 10
= 48 × 50 – 800 = 1600 € / h

80 MW

Power flow on line

0%   100%

Profit = (20% × 80) × 50 – 80 × 10 = 0 € / h
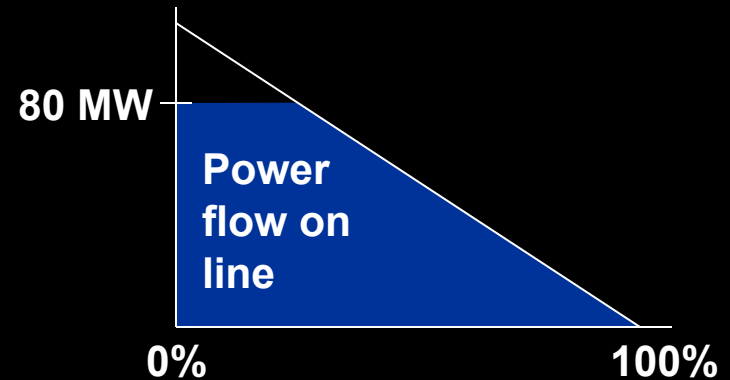
What if the line cost: 2,000,000 € + 10 € / MWh ?

Net social benefit = 1600 × 8760 € / year - 2,000,000 €
= 1,400,000 € / year - 2,000,000 €
If the line lasts more than 2 years, it is worthwhile.

Profit = –2,000,000 €. A competitive market cannot build this line!

212

Restatement of Controversy

- Are we sure the supply and demand curves will always intersect and there will never be a controlled blackout?

  Yes ⬜ pure-market view is right (in an ideal world*)

  No ⬜ The pure-market view still has a chance ⬜

- Will the market set P = VOLL during blackouts?

  Yes ⬜ pure-market view is right (in an ideal world*)

  No ⬜ externality view is right

  * Ideal world = No problems with risk or market power and market price is always < VOLL.

?????

- What are the incentive to produce and not withhold when the supplier is producing more than its share of output?

- Compare real time and forward ICAP markets

- Discuss Icap market power.

Quiz

- What is the nodal price in a 3 node network.