Transmission system and electricity market

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The problem of the congestions

- This unconstraints model does not take into account the security constraints
- The energy is sold and bought at the same price
- All buyer and all produces receive the same price for energy

The problem of the congestions

- From the physical point of view, the EHV transmission network is characterized by several bottlenecks
- These bottlenecks limit the transmission capability between predefined areas/nodes:
  - for this reason, the PX can be designed according to a zonal/nodal model

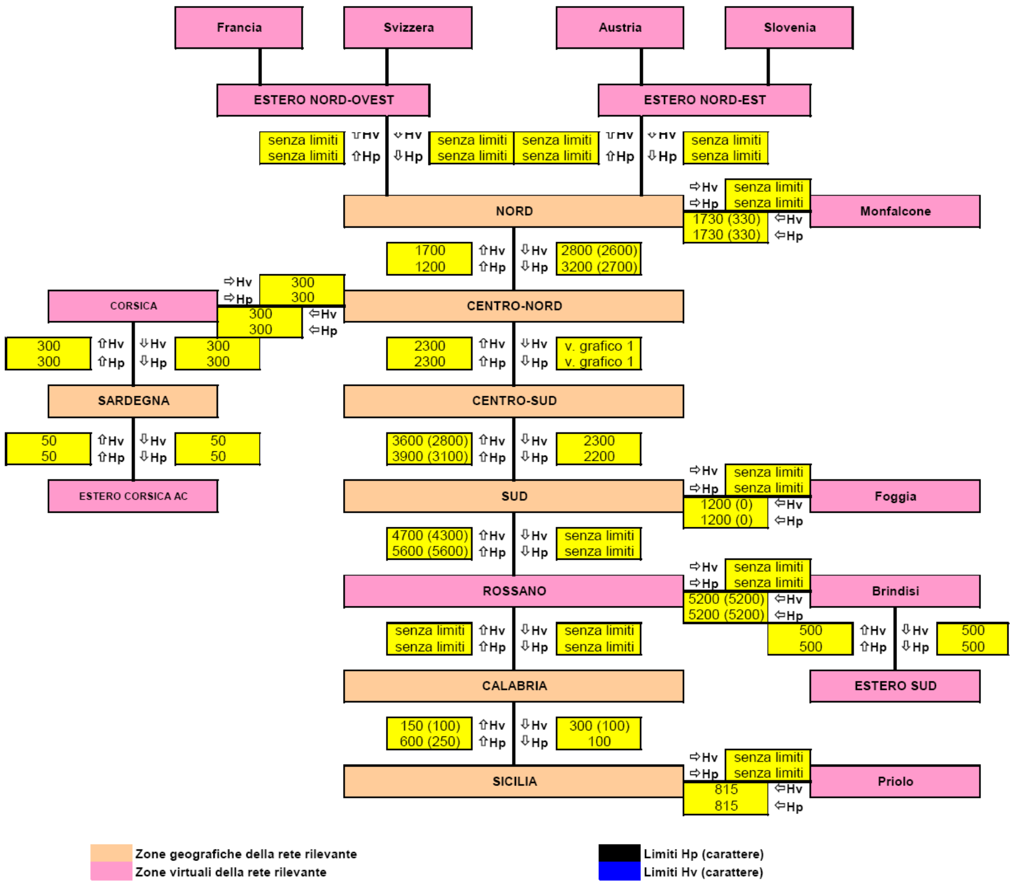
The zonal approach

- The grid is partitioned into zones
- The zonal approach is based on the *a priori* definition of the TTC from an area to another area without exceeding the security constraints
- Each area is considered as a single bus, and therefore the simple balance generation-load determines whether the operating point is feasible or not, and whether the PX results need corrections to attain the technical feasibility
- The basic assumption of the model is that the sensitivities of the power flows on the interconnecting lines with respect to each injection point belonging to the same area are the same

Advantages of the zonal approach

- The zonal approach is very simple, as it does not need any particular computational tool to find the market equilibrium
- It is very easy for market participants to understand the results and to modify their market strategy to improve their incomes
- However, sometimes, the simplicity jeopardizes the workability of the approach, especially for the non-linearity that characterizes the power systems operation
- In this case, it is necessary to undertake complex *post*-market separation corrective actions with the consequent doubt whether the initial adoption of a more detailed model would have been better

Italian Zonal Model



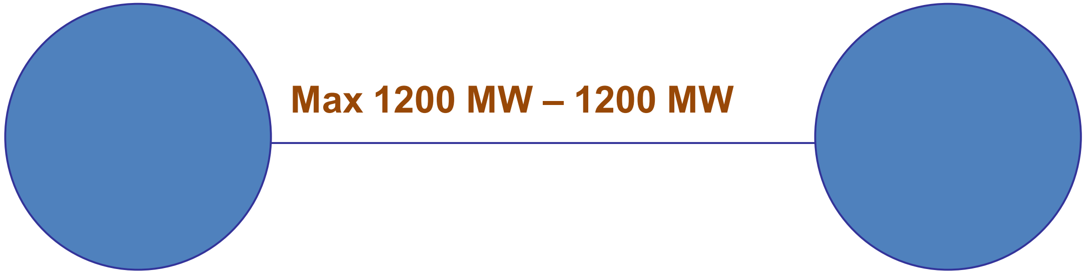
- The grid is partitioned into zones
- Under normal operating conditions there is little or no congestion within each zone, but transmission interfaces between zones may be congested

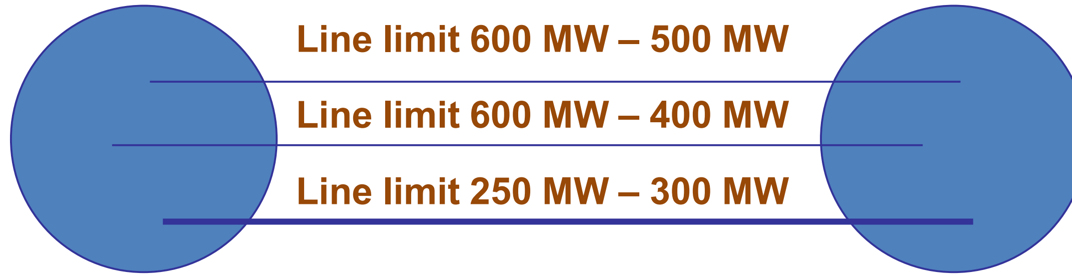
Critical issues of the zonal approach

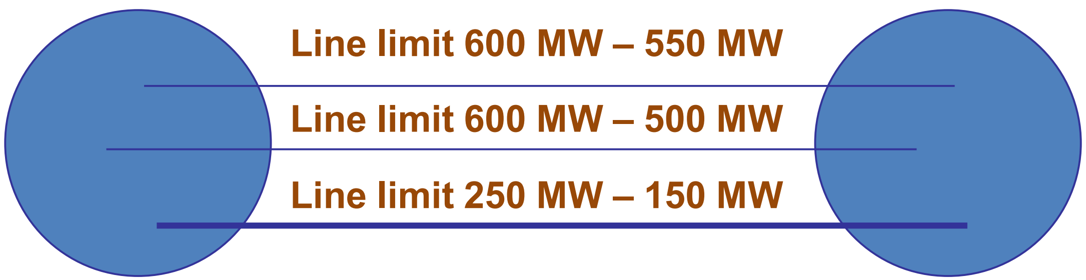
- Definition of zones
  - The zonal model is based on the *a priori* definition of zones.
  - The zones should be defined depending on the most frequent congested situations, i.e., based on the TSO experience.
  - This is a first step where the TSO can take arbitrary decisions.
    - If the system is radial, given a congestion, this definition can be unique, but in the presence of a minimum meshing degree, different zones can be identified for the same congestion
    - This freedom degree can produce arbitrary decisions
    - These decisions choices change the incomes of the market participants
    - Clear and well defined rules should be published in advance to decide the criteria for the definition of zones.

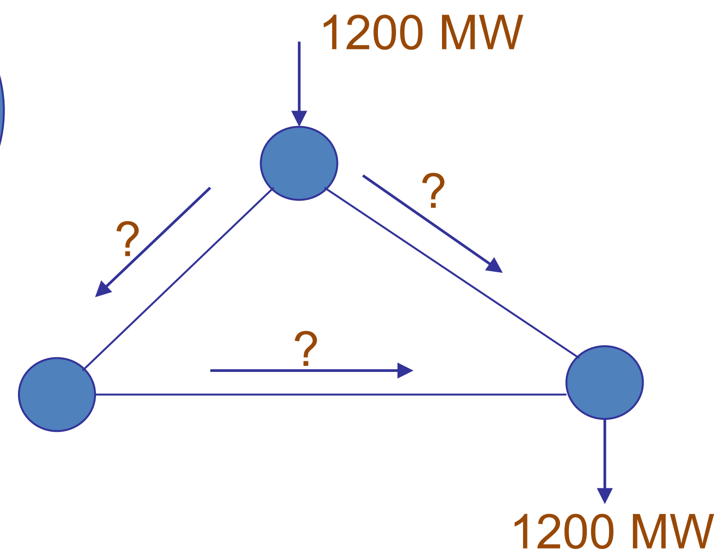
Critical issues of the zonal approach

- Computation of the TTC
  - The methods are based on a deterministic scenario as for generation and load
    - It is not possible to compute any meaningful TTC value when the generation and loading scenario is not known
  - The triggering of the market splitting is based on the fact that the area balance may be or may be not higher than a TTC value defined *a priori*, i.e., before the loading and generation pattern is known.
  - The *a priori* definition of the TTC can result in two situations:
    - the TTC is defined at a higher level than the actual TTC in the scenario resulting from the PX: in this case, the market splitting does not take place, even if one or more lines could be overloaded
    - the TTC is defined at a lower level than the actual TTC: in this case, the market separation takes place unnecessarily with discrimination among the grid users and reduced economic efficiency


Max 1200 MW – 1200 MW


Line limit 600 MW – 500 MW
Line limit 600 MW – 400 MW
Line limit 250 MW – 300 MW


Line limit 600 MW – 550 MW
Line limit 600 MW – 500 MW
Line limit 250 MW – 150 MW


1200 MW
?
?
?
1200 MW

The nodal approach

- The power flow equation are included in the market model
  - Each node balance equation in represented
- Different security criteria can be managed:
  - N security criterion
  - Corrective N-1 criterion
  - Predictive N-1 criterion
- Best use of the transmission facilities
- Two different network model:
  - DC power flow model
  - AC power flow model

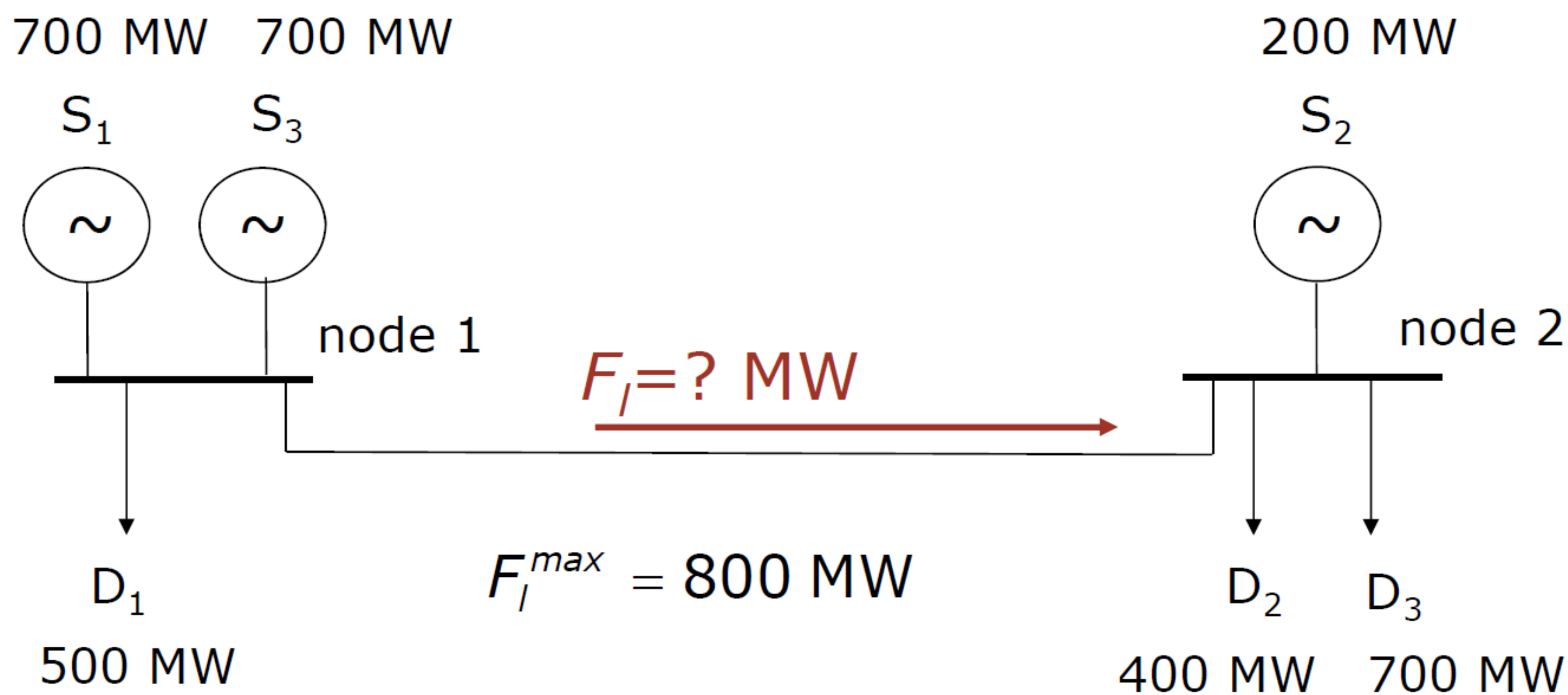
The nodal approach: DC power flow model

- The power flow on each line is represented by a linear equation
- Strong approximation in power flow calculation
  - Acceptable only for transmission system (not for sub transmission or distribution system)
- No information on reactive problem (voltage)
- Linear optimization problem for the pool market
  - Very easy to find the solution

The nodal approach: AC power flow model

- The power flow on each line is represented by a non-linear equation
  - Quadratic or quadratic-trigonometric equations
- No approximation in power flow calculation
  - Suitable for any network (transmission, sub transmission and distribution system)
- Complete information on the state of the system (real and reactive)
- Non-linear optimization problem for the pool market
  - Not easy to find the solution: numerical problem can arise, in particular when N-1 security criteria are represented)

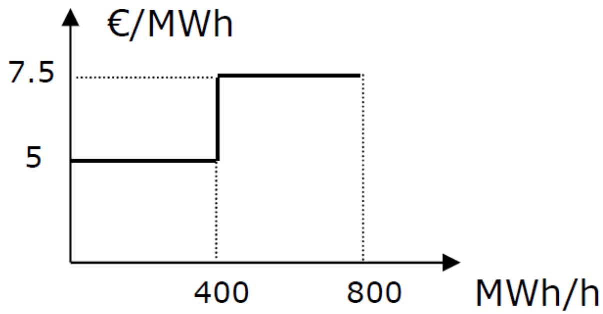
Example



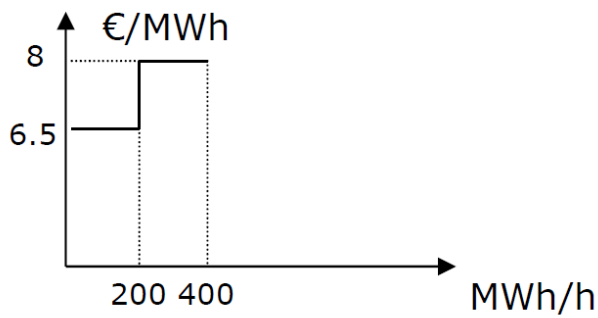
The is a maximum power transfer from node 1 to node 2

Example

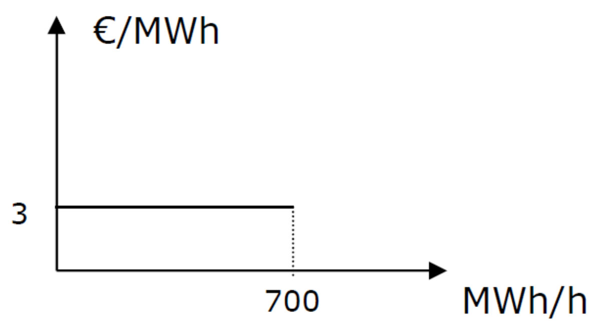
S1



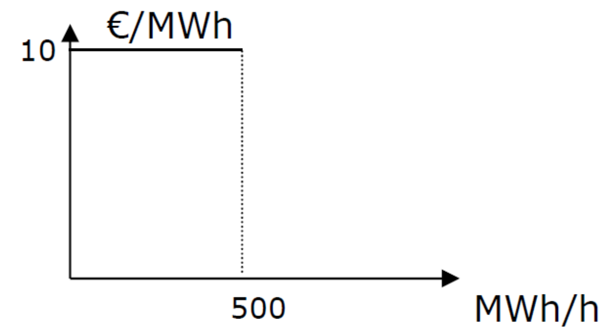
S2



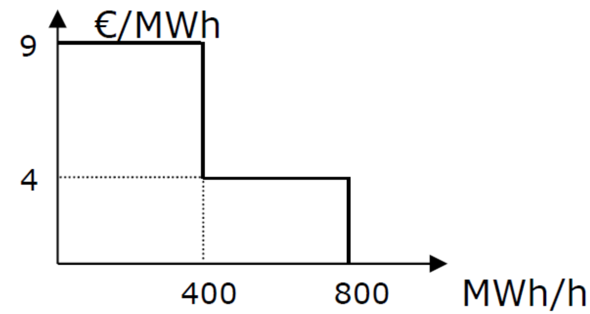
S3



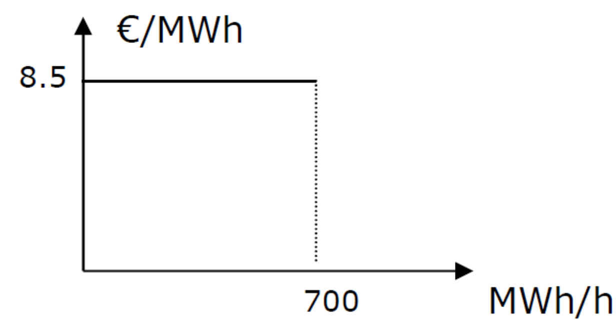
D1



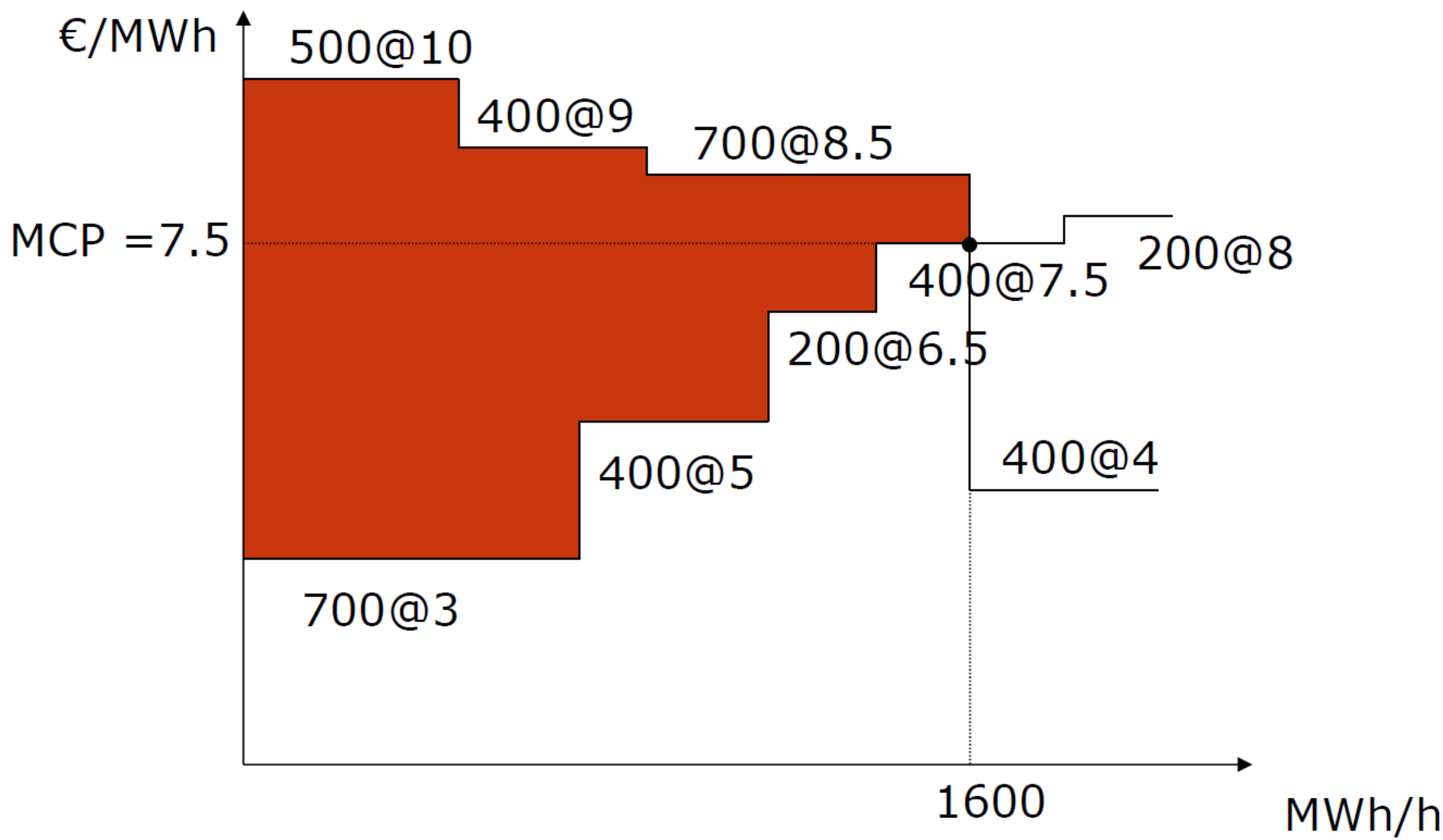
D2



D3



Example: the cumulative curves



The unconstraint solution

Operator	**Accepted quantity [MWh]**	**Out of merit [MWh]**	Revenues [€]	Payments [€]
S1	700	100	5250	-
S2	200	200	1500	-
S3	700	0	5250	-
D1	500	0	-	3750
D2	400	400	-	3000
D3	700	0	-	5250
Total	1600	-	12000	12000

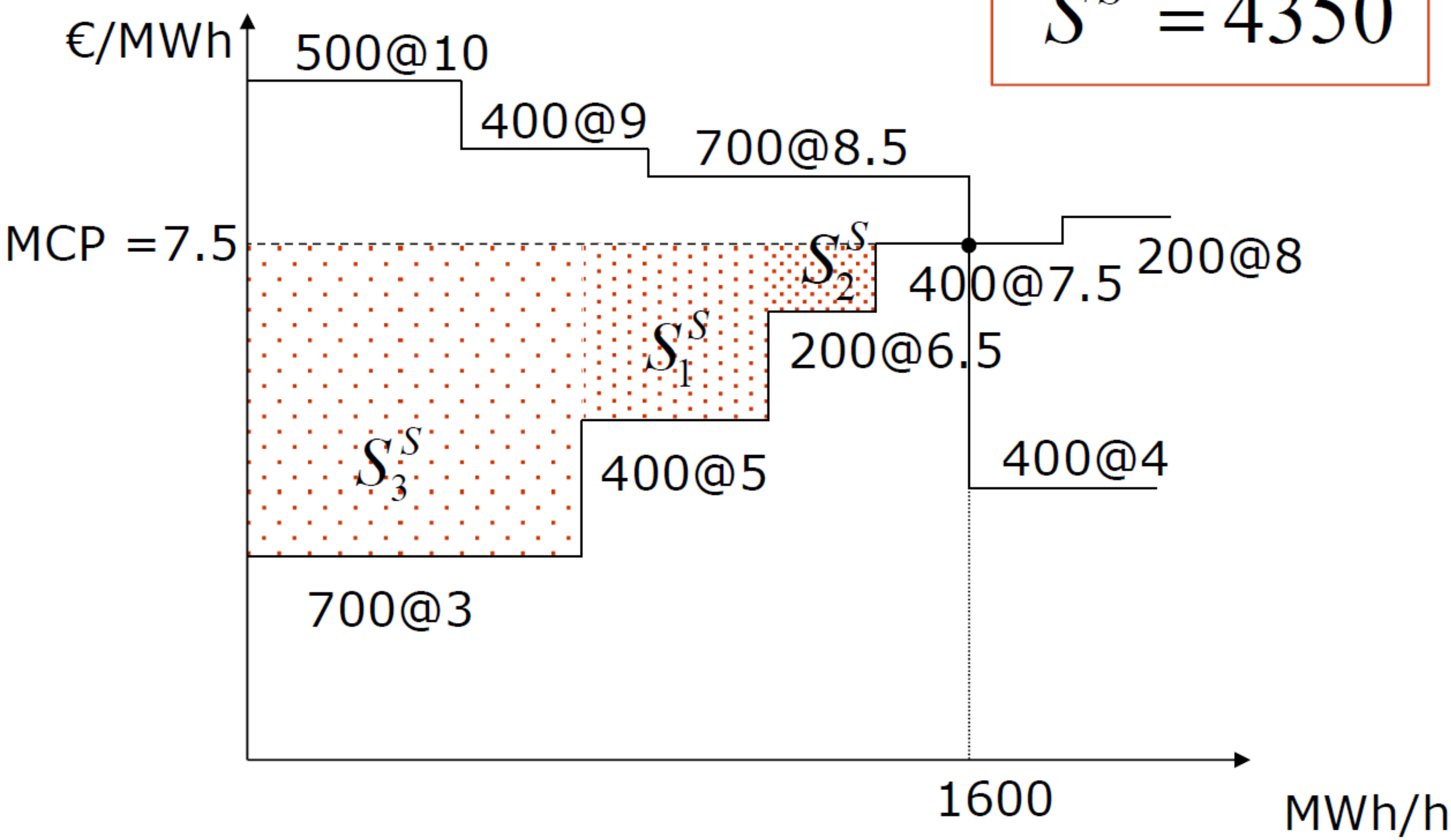
Power flow between node 1 to node 2

PF=S1+S3-D1=700+700-500=900 MW > TTC=800 MW

The solution is not feasible

Producer Surplus

$$S^S = 4350$$



Demand Surplus

- For each buyer *j* surplus measures the difference between the demand curve and the payments (accepted quantity x MCP):

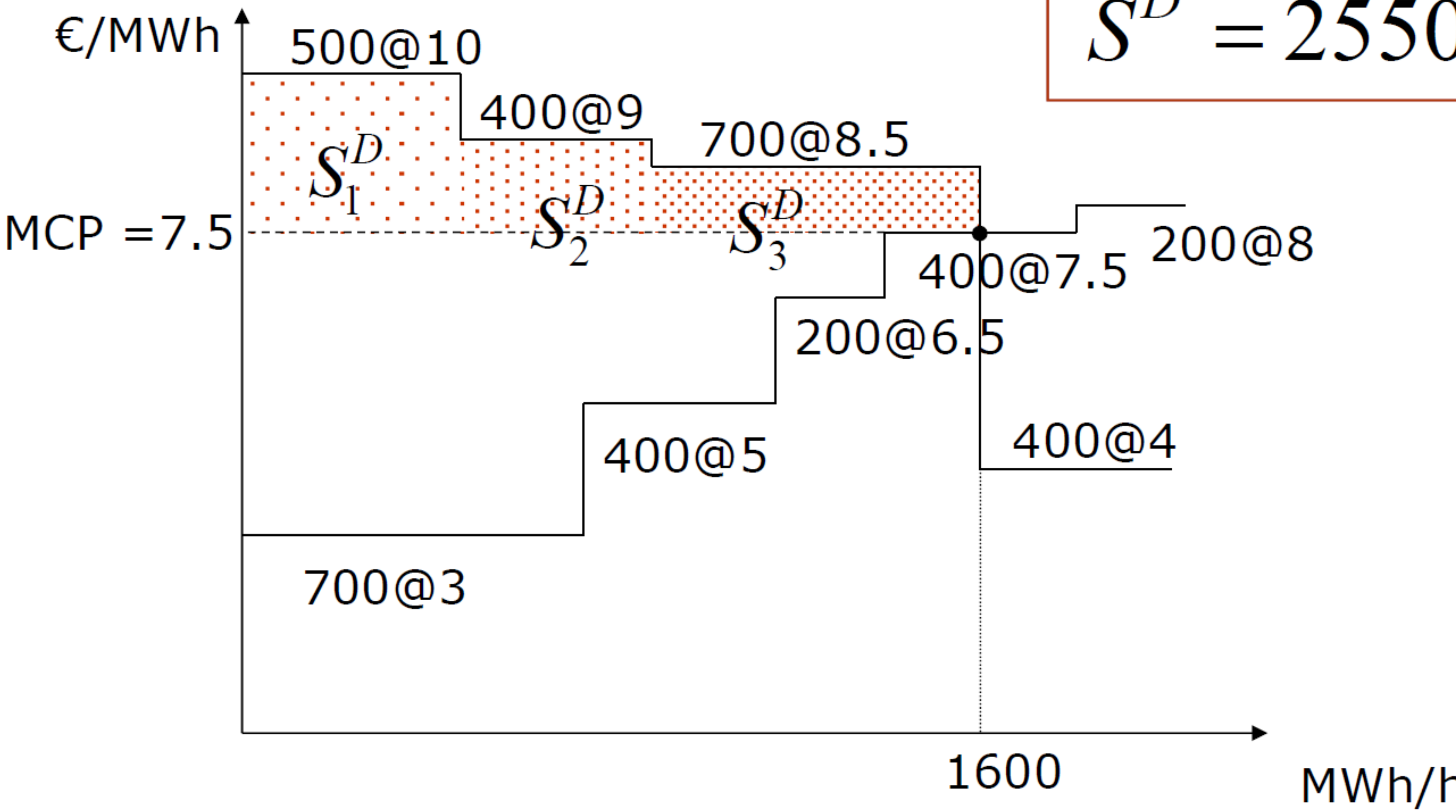
$$S_j^D = D_j\left(P_{Dj}\right) - MCP \cdot P_{Dj}$$

- Total consumers' surplus

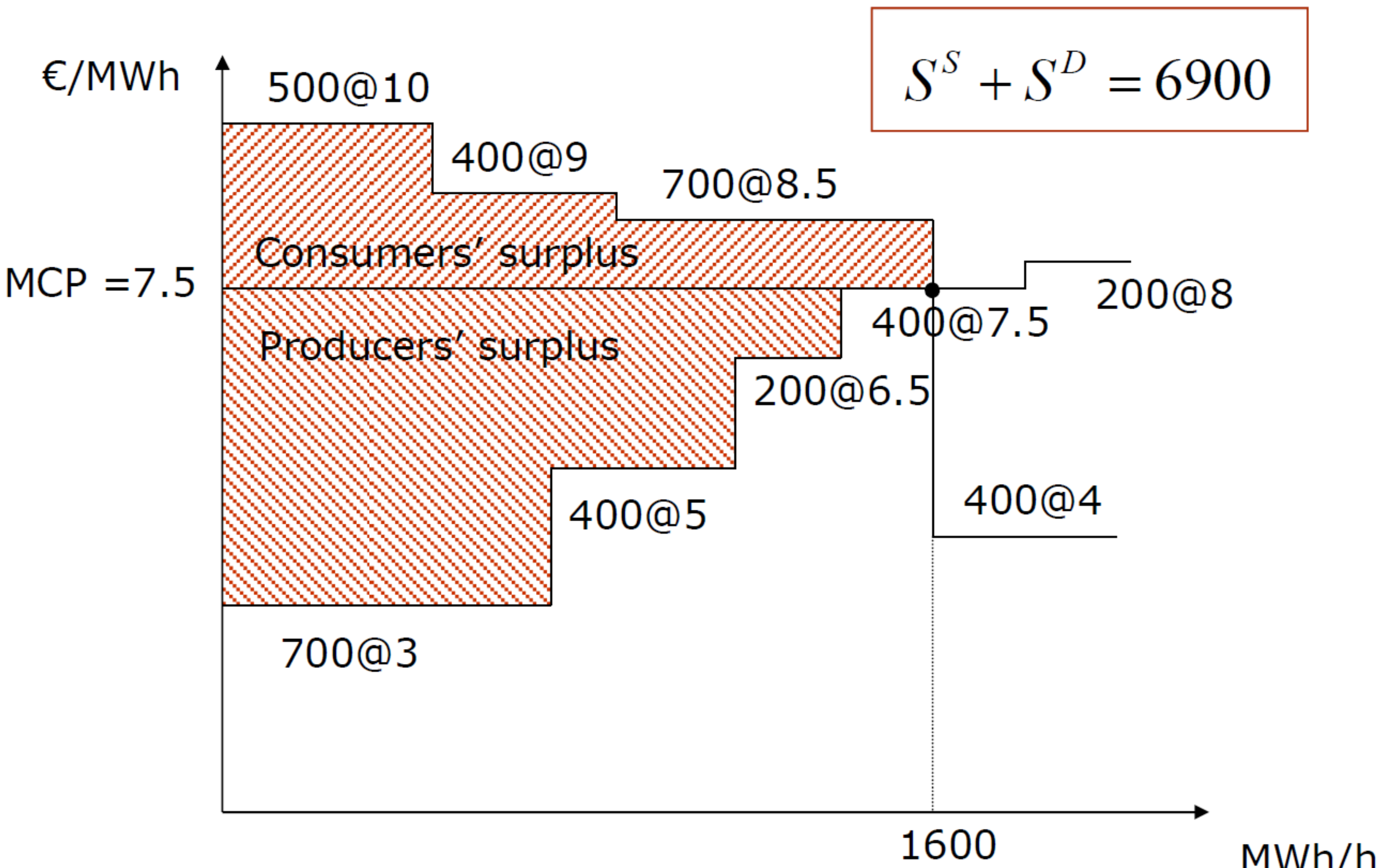
$$S^s = \sum_{j=1}^{M} S_j^S$$

Demand Surplus

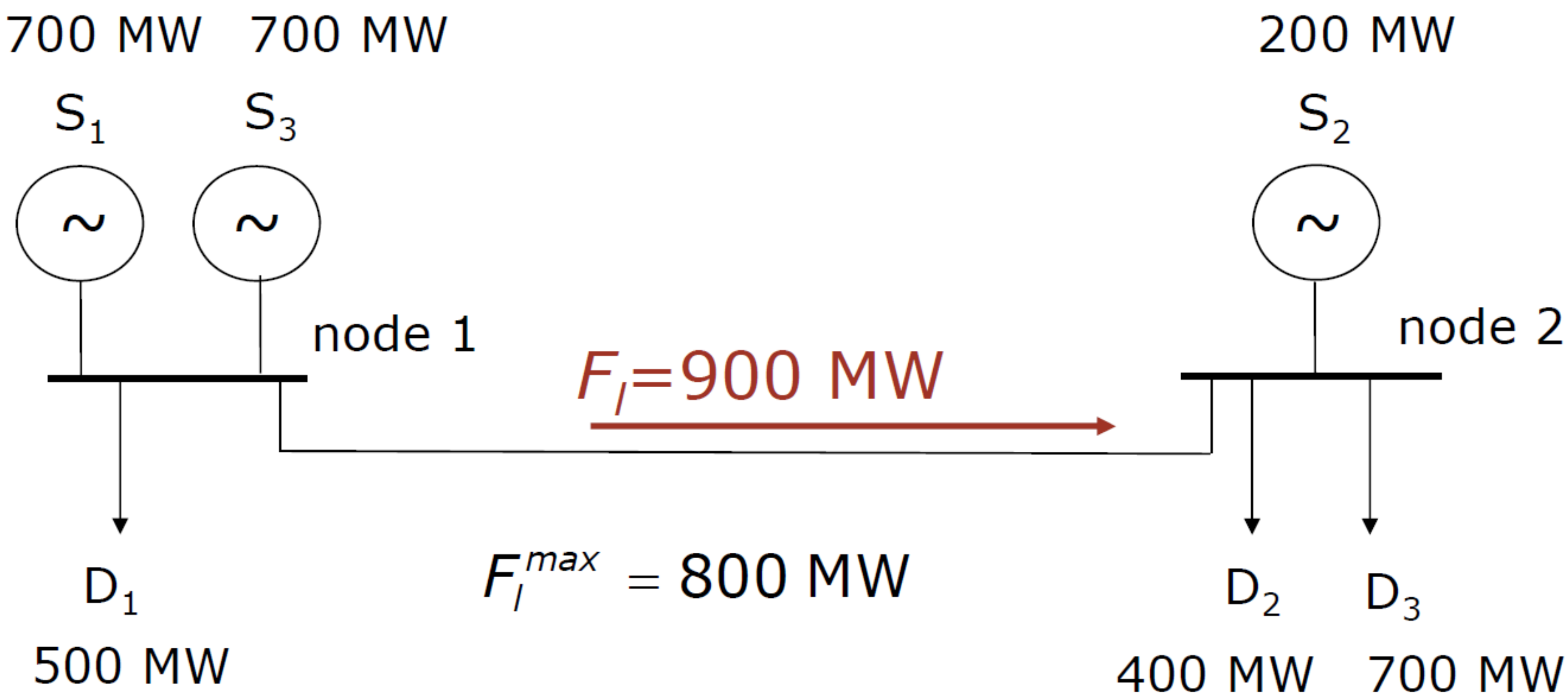
$$S^D = 2550$$



The social welfare



The unconstraint solution

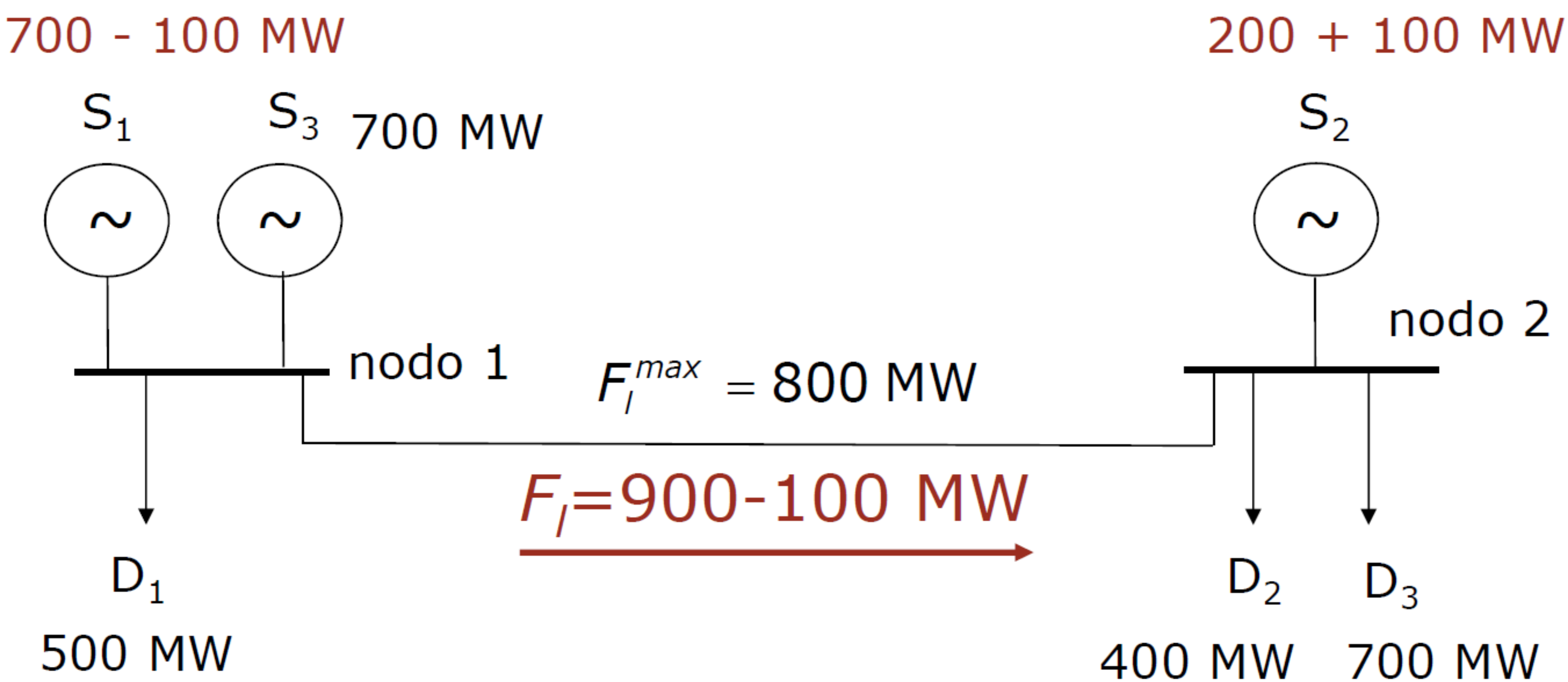


What it is necessary to do

- To eliminate the line overload:
  - First possibility
    - reduce the sale from S1 by 100 MW and
    - instead use the higher-priced energy from S2
  - Second possibility
    - reduce the sale from S2 by 100 MW and
    - instead use the higher-priced energy from S2

  - Which is the best choice?
  - It is necessary to choose the least costly one
  - But how?!?

What it is necessary to do



Some considerations

- The power flow from bus 1 to bus 2 in the unconstraint market is higher than the TTC
- This means that the most convenient generation is located in area 1
  - From an economic point of view to maximise the SW it is necessary to export energy from bus 1 to bus 2
- Due to a transmission constraint we impose that the export is only 800 MW (the TTC value)

Consequence on price

- If we improve the load in bus 1 it is possible to improve the generation located in bus 1
- If we improve the load bus 2, it is not possible to improve the generation located in bus 1
  - The transmission constraint should be violated
  - It is necessary to improve the generation in area 2 using a generation unit bidded with a difference price

We have two different marginal price

The solution of the problem

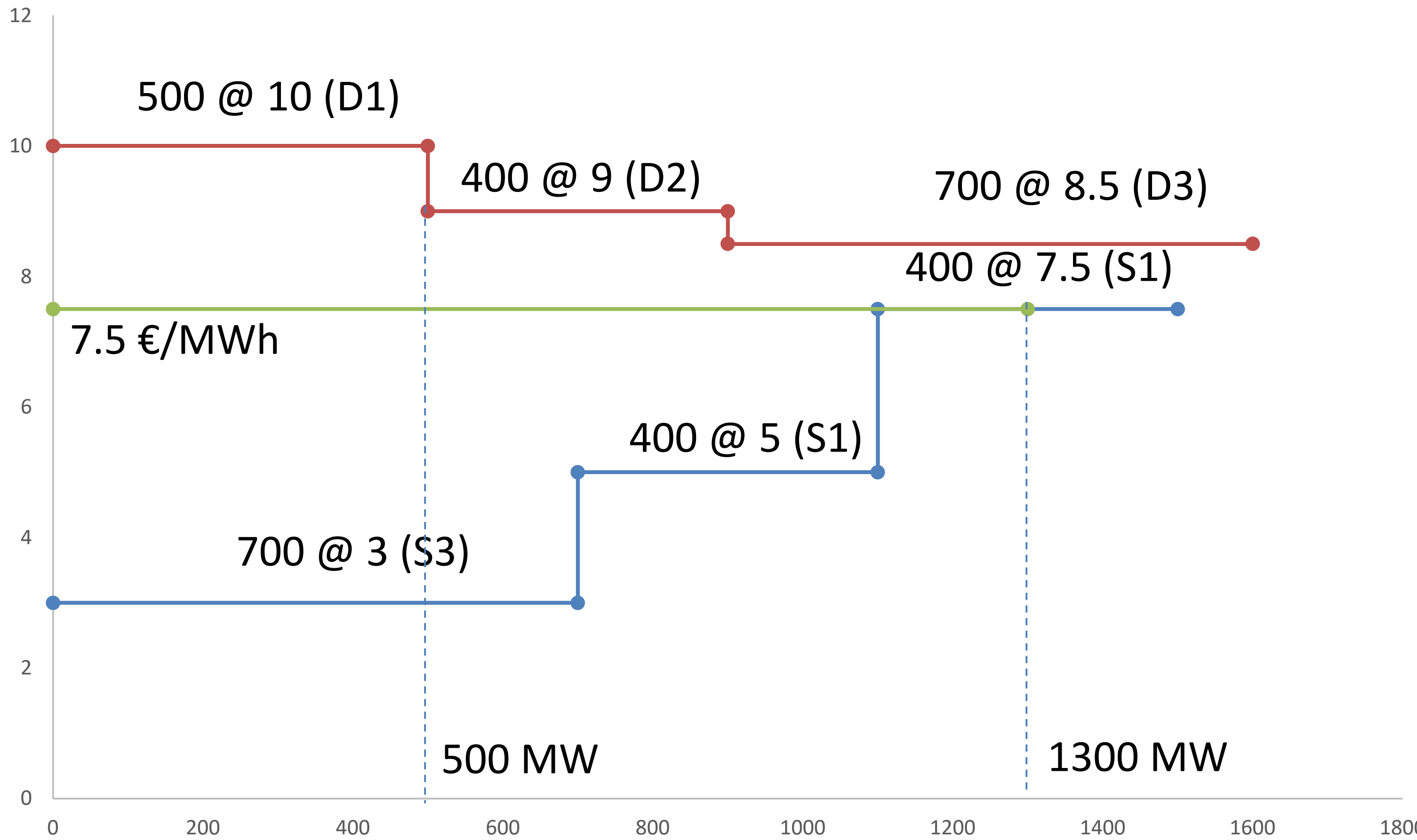
- The line flow limit splits the system into two markets, one at each node
- The economic generation at node 1 is used to the extent physically feasible to meet the load at node 2
- The demand in node 1 is modified to incorporate the demand from node 2
- The remaining demand at node 2 is supplied locally
- The two markets have different clearing prices: higher in the importing node than in the exporting one

The solution of the problem

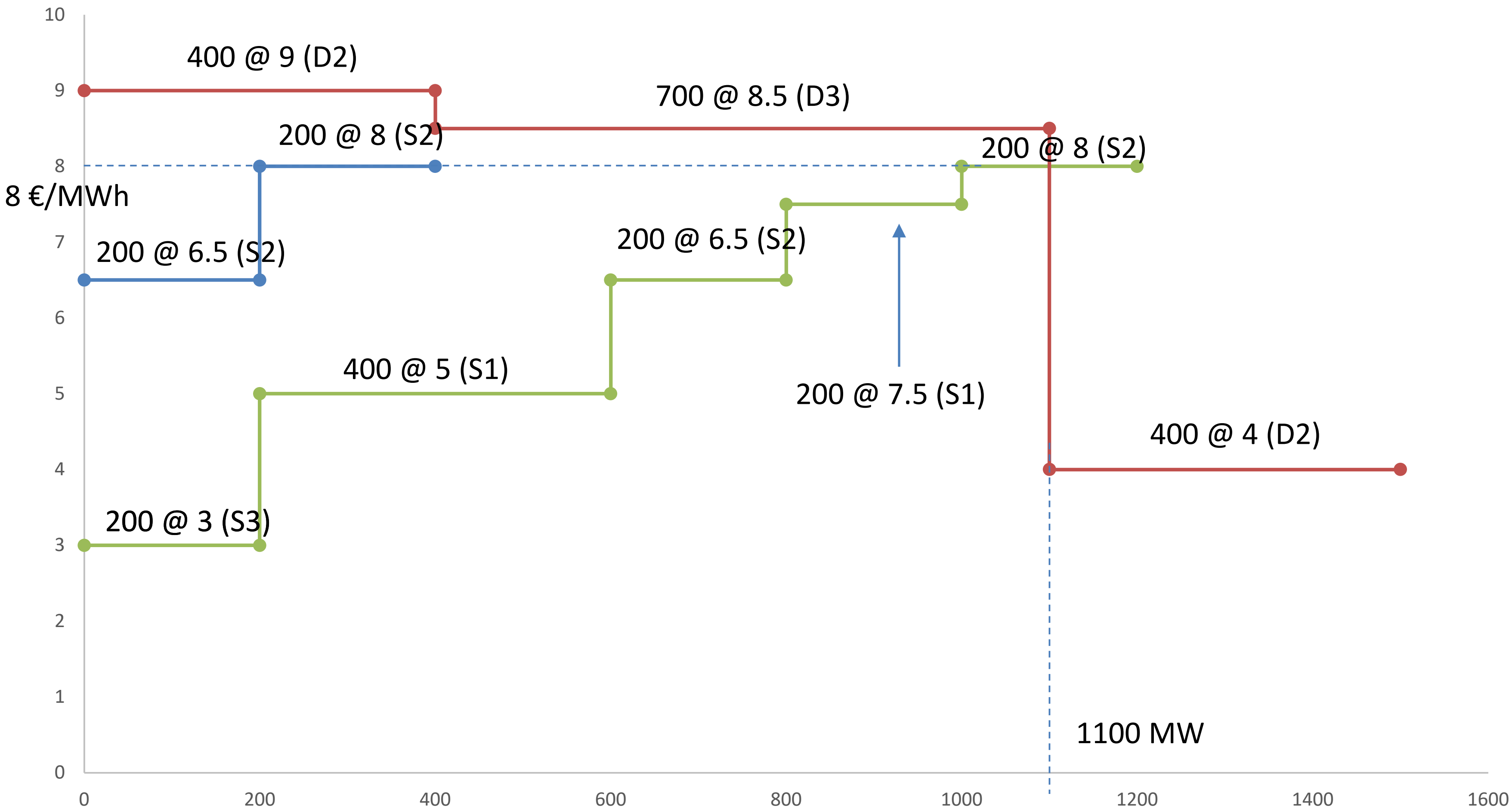
- In the sub market 1 (bus 1) the load is given by the load of bus 1 + TTC value

- In the sub market 2 (bus 2) the generation in area 2 is given by the local generation + a virtual generation with capacity TTC with a very low bid

Market results: node 1



Market results: node 2



Market results

Operator	**Accepted quantity [MWh]**	**Price [€/MWh]**	Revenues [€]	Payments [€]	**Difference [€]**
S1	600	7.5	4500	-	-750
S2	300	8	2400	-	900
S3	700	7.5	5250	-	0
D1	500	7.5	-	3750	0
D2	400	8	-	3200	200
D3	700	8	-	5600	350
Total			12150	12550	

From the point of view of the PX the total income and output is difference

Congestion

- Congestions lead to changes:
  - from a single market equilibrium point to different, nodal equilibrium points
  - Possible curtailment in production or consumption
  - Revenues/payments for sellers and buyers
- The impact of congestions can be measured in terms of
  - Congestion rent (part of welfare
  - Congestion cost (welfare deadweight loss)

Congestion rent

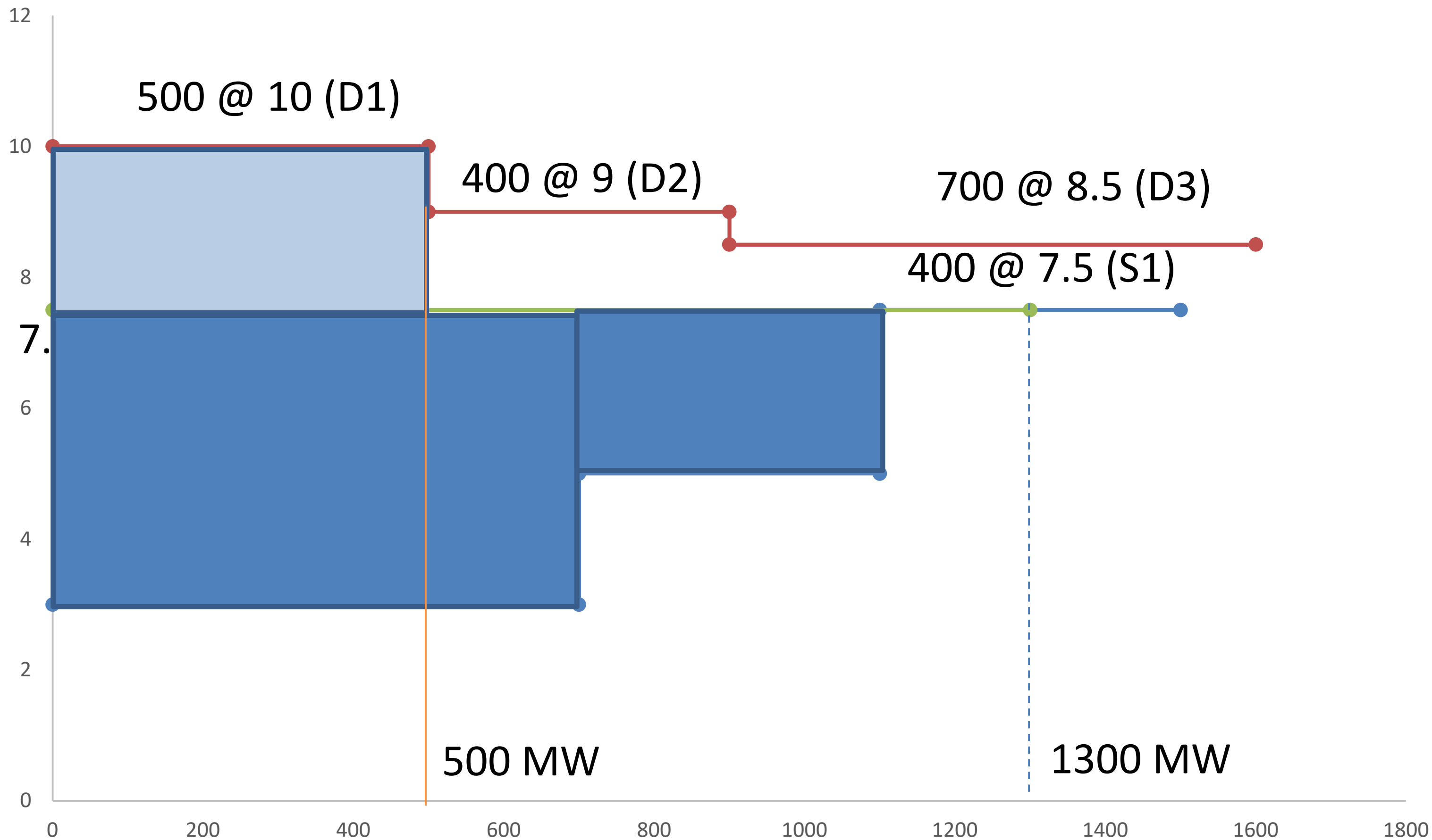
- Difference between the amounts paid by buyers and the amounts received by sellers
- It is collected by the TSO
- It is part of the social welfare

$$k = \sum_{j=1}^{M} MCP_j \cdot P_{Dj} - \sum_{i=1}^{N} MCP_i \cdot P_{Sj}$$

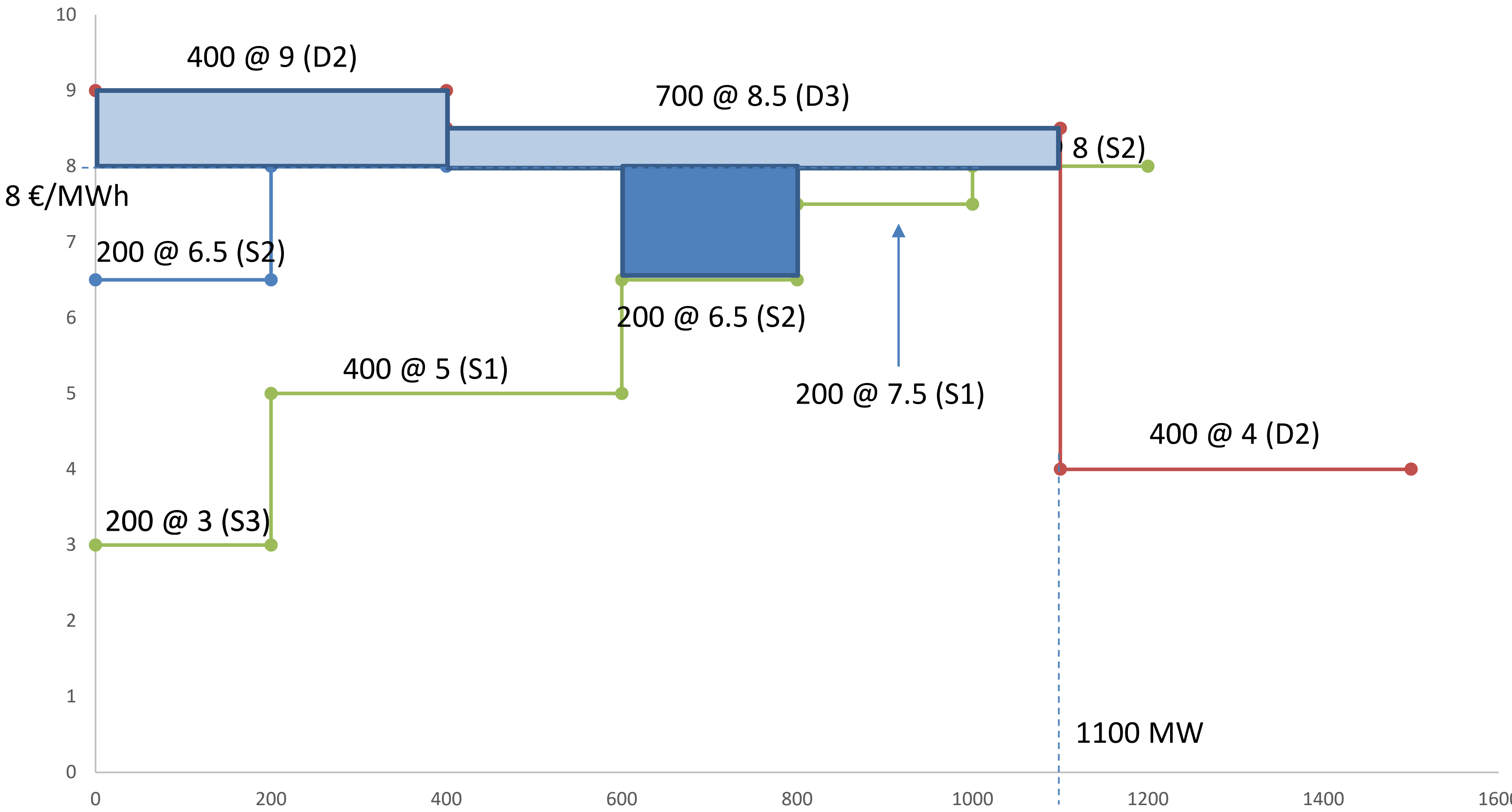
- Constrained social welfare:

$$\overline{S} = \overline{S^D} + \overline{S^S} + k$$

Congestion rent: surplus



Congestion rent: surplus



Congestion rent: surplus

Sellers	Surplus	Byers	Surplus
S1	1000	D1	1250
S2	300	D2	400
S3	3150	D3	350
Total	4450	Total	2000
Congestion rent	12550-12150=400		
Welfare	4450+2000+400=6850		

Congestion rent

- For a two-node system, it is more easily calculated as:
  - Maximum interconnection flows times zonal difference in price
  - 800 MW x (0.5 €/MWh) = 400 €
- TSO is a regulated company: two possible uses of congestion rents:
  - Transmission investments
  - Tariff reduction

Congestion cost

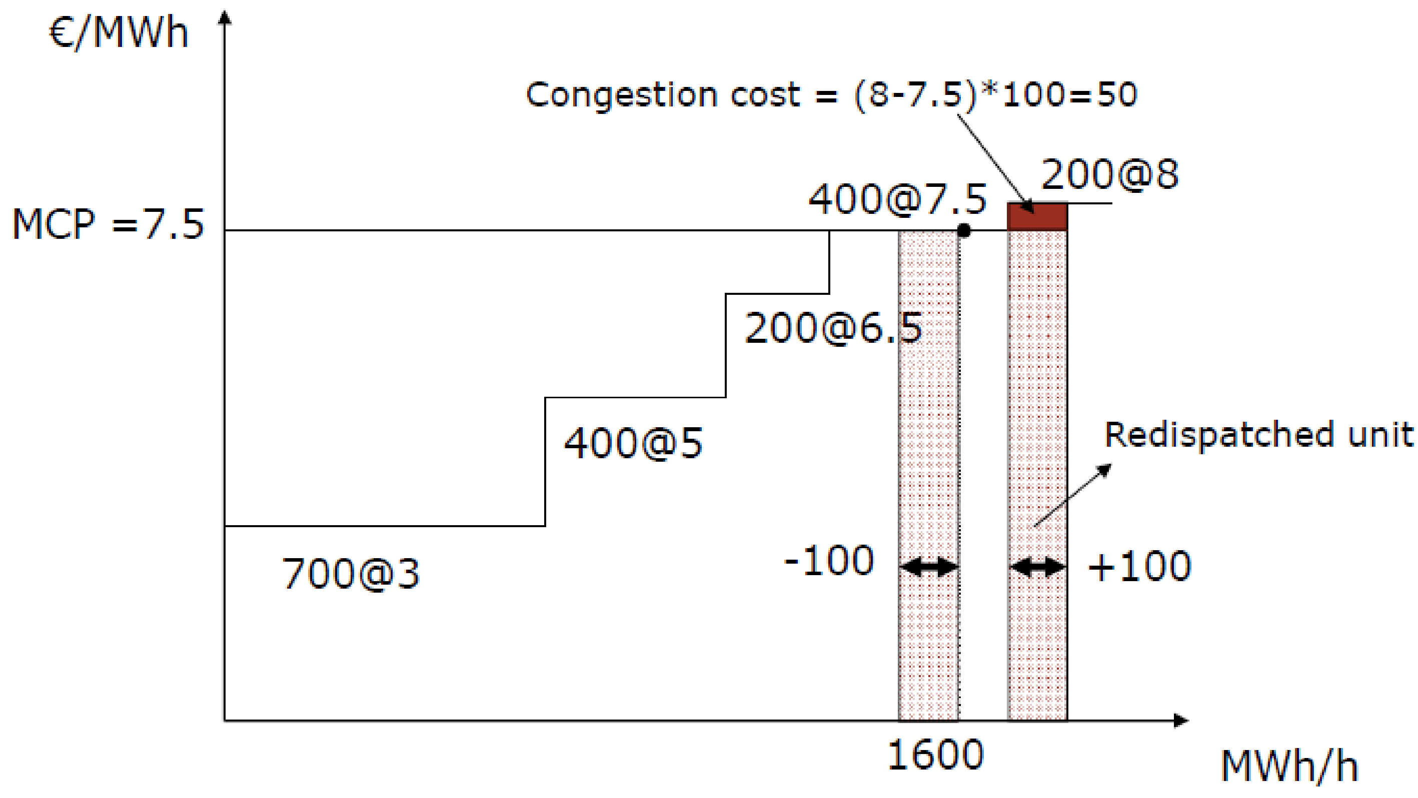
- Congestions produce a reduction in welfare
- This reduction is called deadweight loss

$$\varepsilon = -\left(\overline{S} - S\right)$$

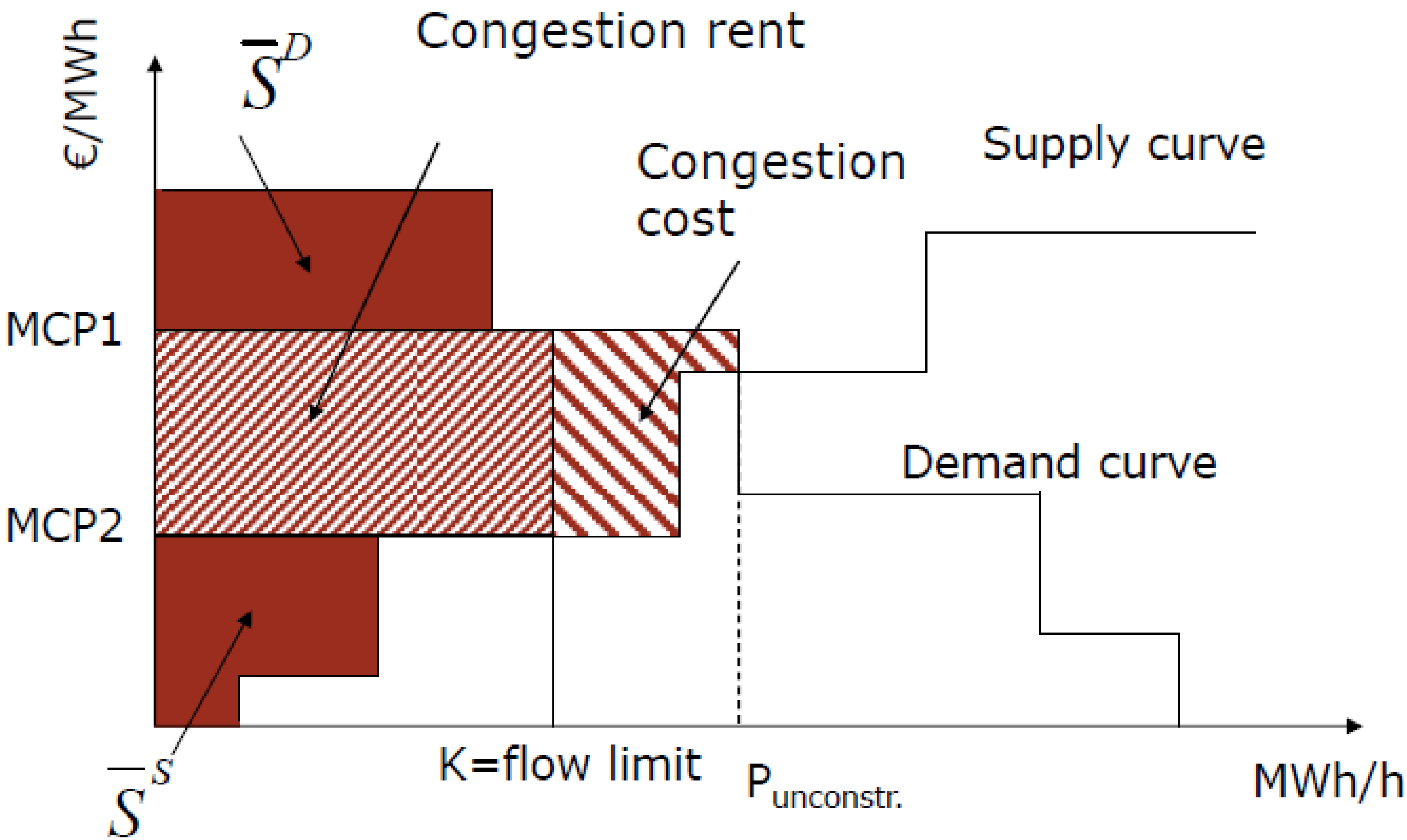
$$S = 6900\ €$$
$$\overline{S} = 6850\ €$$
$$\varepsilon = 50\ €$$

Congestion cost

- The efficiency loss represent the redispatch costs: the costs incurred because of the use of *out-of-merit* units to avoid violations of the network constraints



Congestion cost, congestion rent and welfare



The market splitting

- All the supply bids with price equal or lower than the corresponding zonal price are accepted
- All the demand bids with price equal or higher than the zonal are accepted
- The value of the transmission rights is implicitly given by the difference between the zonal prices:
  - a power plant located in an exporting area is paid less than a plant located in an importing area
  - a buyer located in an exporting area pays less than a buyer located in an importing area

$$\text{congestion rent} = TTC \cdot \left(p_{import} - p_{\mathrm{exp}ort}\right) = 800 \cdot (8 - 7.5) = 400$$

The market model

- Constrained market model

$$\max_{P_{Si},P_{Dj}} W = \sum_{j=1}^{M} D_j\left(P_{Dj}\right) - \sum_{j=1}^{N} C_i(P_{Si})$$

s.t.

$$\sum_{j=1}^{M} P_{Dj} - \sum_{j=1}^{N} P_{Si} = 0$$

$$0 = \underline{P_{Si}} \leq P_{Si} \leq \overline{P_{Si}} \qquad \forall i$$

$$0 = \underline{P_{Dj}} \leq P_{Dj} \leq \overline{P_{Dj}} \qquad \forall j$$

$$\underline{F_k} \leq \ F_k(P_{D1},\cdots,P_{DM},P_{S1},\cdots,P_{SN}) \leq \overline{F_k} \qquad \forall k$$

Impact of congestions

- Short-term effects
  - Redispatching
  - Multiple prices
  - Change in producer and consumer surplus
  - Congestion rents
  - Redispatch costs
- Long-term-effects: price signals
  - Price difference: siting of power plants in nodes with higher prices
  - Congestion rent: transmission expansion necessary

Zonal transmission model

- Also known as “market splitting”
- Allocation of “transmission rights” is done at the same time as the allocation of the “production/consumption rights” (permit to produce or consume energy)
- This allocation method is also known as an “implicit auction” for Transmission Rights (TR)
- There is another TR allocation method, known as an “explicit auction”

Congestion management in the pool model

- The Pool model considers implicitly the impacts of the transmission network constraints
- The Pool model assumes implicitly the commitment of generators which are bidding to supply power
- The determination of the economic optimum is done with the implicit consideration of congestion

Bilateral trading congestion management

- If all contemplated transactions can be undertaken without causing any limit violations under postulated contingencies, the system is judged to be capable of accommodating these transactions and no congestion management is needed
- On the other hand, the presence of any violation causes transmission congestion and steps must be taken by the SO to re-dispatch the system to remove the congestion

Bilateral trading model congestion management

- Objective function: subsequent re-dispatching costs
- Decision variables are incremental / decremental adjustments to the generator outputs and decremental adjustments to the loads
- Constraints
  - transmission constraints
  - maximum/minimum incremental/decremental amounts bid
- OPF solution: optimal re-dispatch in generation/load increment/decrement at participating buses

The real market

- Pool model and bilateral model are present
  - A player can chose where to buy/sell energy
- The use of the transmission network depends on the trade defined by both pool market and bilateral contracts
- In the pool market model it is necessary to take into account the power flow due to bilateral contracts
- Bilateral contracts take precedence over trade in pool market for the use of the transmission system

The real market

- To guarantee this precedence and to take into account their influence on the power flow, the bilateral contracts are included in the pool market with the following approach:
  - The produced energy involved in a bilateral contract is submitted in the pool market with a price equal to ZERO
  - The withdrew energy involved in a bilateral contract is submitted in the pool market with the highest price possible

The congestion charge for bilateral contract

- In case of market splitting, a bilateral contract signed between two different zones with different price are charged of an hourly congestion charge for the use of the transmission system

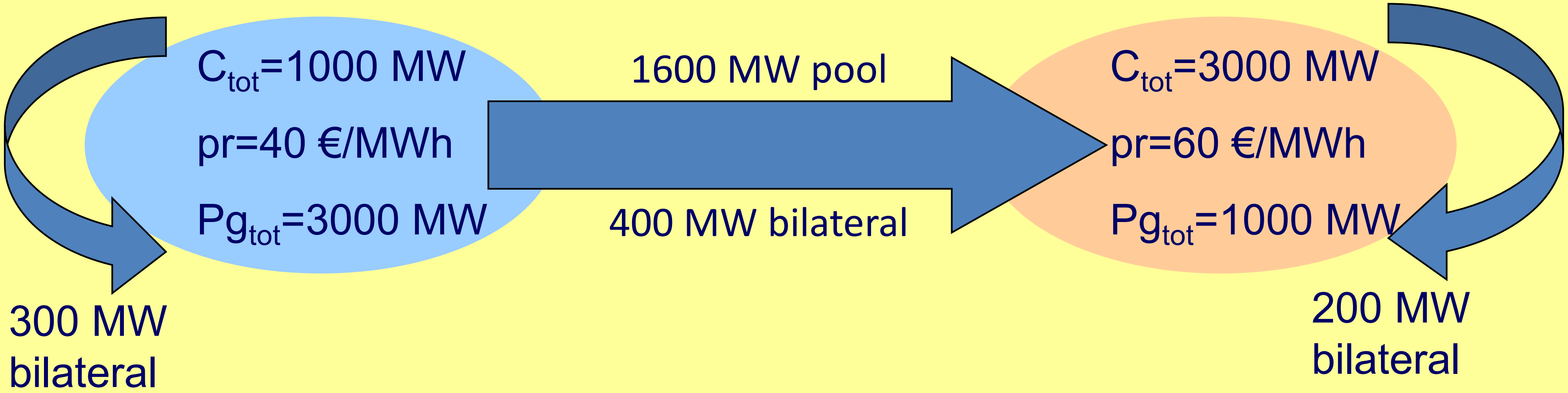
$$CC = E \cdot (p_i - p_e)$$

E: hourly energy involved in the bilateral contract

p_i: energy price given by the pool market in the zone where the energy is withdrew (import zone)

p_e: energy price given by the pool market in the zone where the energy is injected (export zone)

The standard zonal market with bilateral contracts



Economic Balance

Generator A

```
Receives 40*(700+1600) = 92000 €
Pays       (60-40)*400 =  8000 €
```

Generator B

```
Receives      60*800=48000€
```

Load A

```
Pays      40*700 = 28000 €
```

Load B

```
Pays  60*(800+1600)=144000 €
```

PX

```
Pays       92000+48000        = 140000 €
Receives   28000+144000+8000  = 180000 €
Income     180000-140000      =  40000 € =(60-40)*2000 €
```

An example

- Consider two electricity transmission zones. Zone A has generating capacity of 1,000 MW at a marginal cost of USD 38 and Zone B has generating capacity of 500 MW at a marginal cost of USD 62. Transmission between Zone A and B is limited to 300 MW. What is the locational marginal price (LMP) in Zone B if the total aggregate demand for power in both transmission zones is 1,200 MW?

a) USD 38

b) USD 50

c) USD 57

d) USD 62

Correct answer: d

- Because the total aggregate demand in both zones exceeds the generating capacity of Zone A, Zone B generation needs to be dispatched at USD 62.00, therefore the Zone B LMP is USD 62.00. If generation in Zone B was not needed, then the LMP would be USD 38 because Zone A generation would provide for all load. This might be the case during off-peak hours.

Constrained market model

ATC model

$$\max\ SW = \sum_{j=1}^{NL} p_{b,j}Q_{b,j} - \sum_{m=1}^{NG} p_{s,m}Q_{s,m} = \min(-SW) = min\sum_{m=1}^{NG} p_{s,m}Q_{s,m} - \sum_{j=1}^{NL} p_{b,j}Q_{b,j}$$

s.t.

$$\sum_{m=1}^{NG} Q_{s,m} - \sum_{j=1}^{NL} Q_{b,j} = 0$$

$$\underline{TR_k} \leq TR_k \leq \overline{TR_k} \qquad \mathrm{k} = 1 \ldots \mathrm{N_k}$$

$$TR_k = \sum_{n=1}^{NA} PTDF_{k,n} y_n \qquad \mathrm{k} = 1 \ldots \mathrm{N_k}$$

where

$$y_n = \sum_{i \in n} Q_{s,i} - \sum_{i \in n} Q_{b,i}$$

$PTDF_{k,n}$ represents the contribution of the power injected in the area n on the interface k

DC nodal model

$$\max\ SW = \sum_{j=1}^{NL} p_{b,j} Q_{b,j} - \sum_{m=1}^{NG} p_{s,m} Q_{s,m} = \min(-SW) = min \sum_{m=1}^{NG} p_{s,m} Q_{s,m} - \sum_{j=1}^{NL} p_{b,j} Q_{b,j}$$

s.t.

$$[\boldsymbol{y}] = [\boldsymbol{B}][\boldsymbol{\delta}]$$

$$\underline{TR_l} \leq TR_l \leq \overline{TR_l} \qquad l = 1 \ldots N_l$$

$$TR_l = \sum_{n=1}^{NA} PTDF_{l,b} y_b \qquad l = 1 \ldots N_l$$

where

$$y_b = \sum_{i \in b} Q_{s,b} - \sum_{i \in b} Q_{b,b}$$

DC nodal model

$$[y] = [B][\delta]$$

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix} = \begin{bmatrix} B_{11}\, B_{12} \cdots B_{1N} \\ B_{21}\, B_{22} \cdots B_{2N} \\ \vdots \quad \vdots \quad \cdots \quad \vdots \\ B_{N1} B_{N2} \cdots B_{NN} \end{bmatrix} \begin{bmatrix} \delta_1 \\ \delta_2 \\ \vdots \\ \delta_N = 0 \end{bmatrix}$$

Bus N=Slack bus

Variables of the market model: $\boldsymbol{Q_b}$, $\boldsymbol{Q_s}$, $\boldsymbol{\delta}$ ($\delta_{Slack} = 0$ is a parameter)

$PTDF_{k,b}$ represents the contribution of the power injected in the bus b on the line l

AC nodal model

$$\max\ SW = \sum_{j=1}^{NL} p_{b,j}Q_{b,j} - \sum_{m=1}^{NG} p_{s,m}Q_{s,m} = \min(-SW) = min\sum_{m=1}^{NG} p_{s,m}Q_{s,m} - \sum_{j=1}^{NL} p_{b,j}Q_{b,j}$$

s.t.

$$Q_{s,i} - Q_{b,i} = E_i \sum_{j=1}^{N_b} E_j Y_{i,j} \cos\left(\delta_i - \delta_j - \vartheta_{i,j}\right) \qquad \forall\ PQ, PV\ and\ Slack\ bus$$

$$RQ_{s,i} - RQ_{b,i} = E_i \sum_{j=1}^{N_b} E_j Y_{i,j} \sin\left(\delta_i - \delta_j - \vartheta_{i,j}\right) \qquad \forall\ PQ\ bus$$

$$I_{l,from} \le I_{max,l} \qquad l = 1 \dots N_l$$
$$I_{l,to} \le I_{max,l} \qquad l = 1 \dots N_l$$

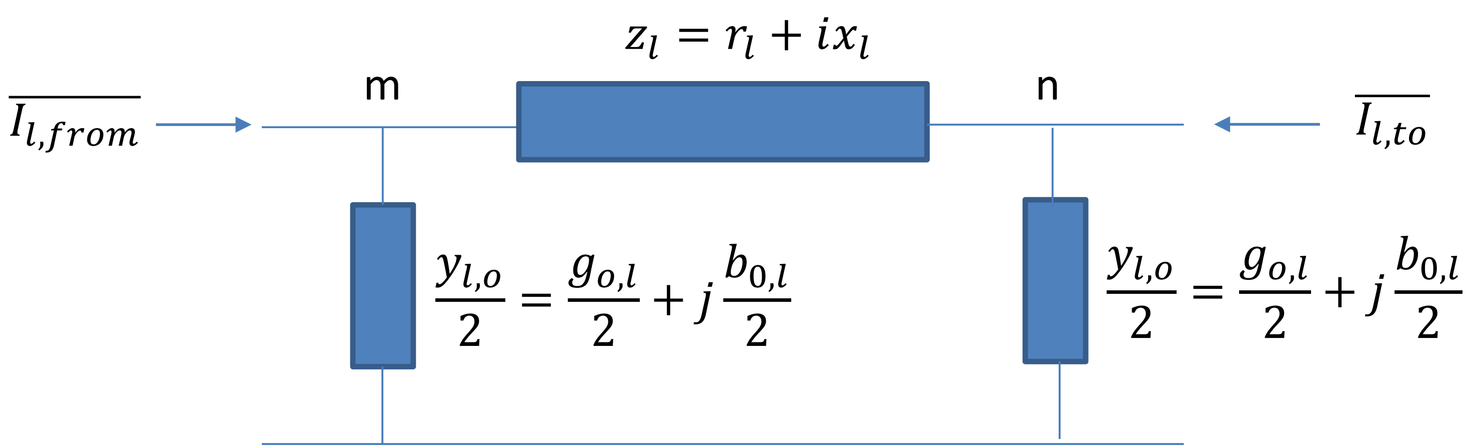
where

$$I_{l,from} = abs\left(\overline{I_{l,from}}\right) \qquad I_{l,to} = abs\left(\overline{I_{l,to}}\right)$$

$$\overline{I_{l,from}} = \left(\overline{E_m} - \overline{E_p}\right) y_{l,from} \qquad \overline{I_{l,to}} = \left(\overline{E_p} - \overline{E_m}\right) y_{l,to}$$

Line l between bus m and n

Model of the line



$$\overline{I_{l,from}} = \overline{E_m}\left(\frac{g_{o,l}}{2} + j\frac{b_{0,l}}{2}\right) + \frac{(\overline{E_m} - \overline{E_n})}{(r_l + ix_l)}$$

$$\overline{I_{l,to}} = \overline{E_n}\left(\frac{g_{o,l}}{2} + j\frac{b_{0,l}}{2}\right) + \frac{(\overline{E_n} - \overline{E_m})}{(r_l + ix_l)}$$

Equations in per unit

Variables of the model: **Qs, Qb, δ** ($\delta_{Slack} = 0$ is a parameter!)

Voltage Magnitudes are parameters