Electricity Market Design : Experience from the Nordic electricity market NORDPOOL

Kurt Jörnsten

Department of Business and Management Science,
Norwegian School of Economics

Objectives for the deregulated power market

- Overall short run and long run efficiency through
  - competition on the supply and demand side
  - efficient pricing of transmission
- Short run:
  - Demand functions are given
  - Optimize the use of existing facilities in generation and transmission/distribution
- Long run:
  - Incentives for location of production and consumption
  - Optimal expansion of grid

Why Market Design?

- Objective of Market Design
  - Develop a set of trading rules and procedures so that when all market participants act selfishly so as to maximize profit while following the rules, the market outcome will replicate the results of a benevolent central planner with perfect information, or a perfectly regulated monopoly
- Why do we have to bother?
  - Externalities require coordination
  - Good markets are made, they don’t just happen
  - Design determines your business opportunities

Why has the Nordic market worked so well?

- Successful dilution of market power
- A simple but sound market design
- Strong political support for a market based electricity supply system
- Voluntary, informal commitment to public service by the power industry

Amundsen, Bergman: Why has the Nordic electricyt market worked so well?

Utilities Policy 14 2006 pp 148-157

Congestion Management

- Objective
  - Optimal economic dispatch
    - Max social welfare (consumer benefit – production cost)
    - S.t. thermal and security constraints
  - Gives the value of power in every node
    - Benchmark
- Alternative methods to realize optimal dispatch
  - Nodal prices, Flowgate prices, Optimal redispatch…
- Provide price signals
  - For efficient use of the transmission system
  - For transmission, generation and load upgrades

(1) max $$\sum_{i=1}^{n}\left(\int_0^{q_i^d} p_i^d(q)dq - \int_0^{q_i^s} p_i^s(q)dq\right)$$

(2) s.t. $$q_i^s - q_i^d = \sum_{j\neq i} q_{ij} \qquad i = 1,\dots,n-1$$

(3) $$\sum_{ij\in L_l} q_{ij} = 0 \qquad l = 1,\dots,m-n+1$$

(4) $$\sum_{i=1}^{n}(q_i^s - q_i^d) = 0$$

(5) $$q_{ij} \le C_{ij} \qquad 1 \le i, j \le n$$

(6) $$\begin{cases} p_i^s(q_i^s) = p_{Z_k} \\ p_i^d(q_i^d) = p_{Z_k} \end{cases} \qquad i \in Z_k,\ k = 1,\dots,K$$

(1)-(4): Ubegrenset lastflyt - systempris

(1)-(5): Optimal lastflyt - optimale nodepriser

(1)-(6): Optimale sonepriser gitt soneinndeling

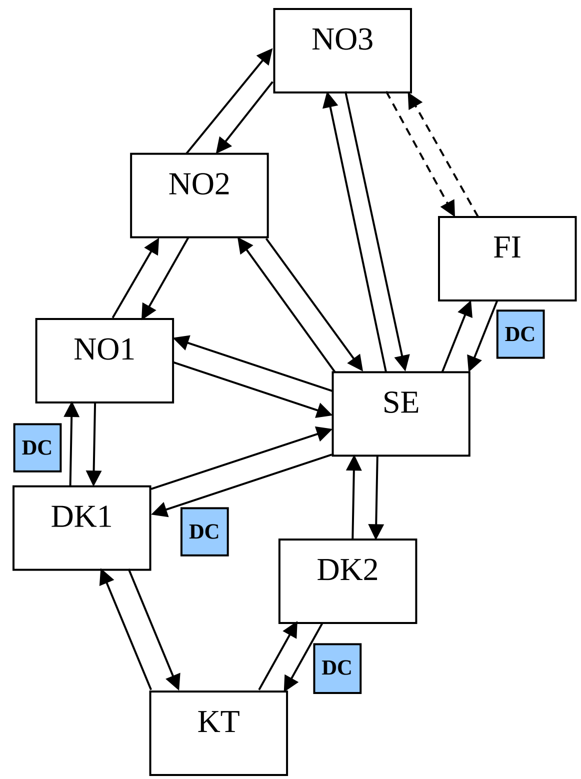
Nord Pool Spot

- Covers
  - Norway, Sweden, Finland, Denmark, Kontek
- Day-ahead
  - Supplemented by balancing / regulation markets
- Voluntary pool
  - Trades between Elspot areas
  - Agents that use Nord Pool Spot in order to determine prices and as a counterpart
- Three kinds of bids
  - Hourly bids – bids for individual hours
  - Block bids – create dependency between hours
  - Flexible hourly bids – sell during hours with highest prices

Network model SESAM

- 8 nodes
- Direction dependent capacities
- AC/DC treated equally
- No loop flow modeling

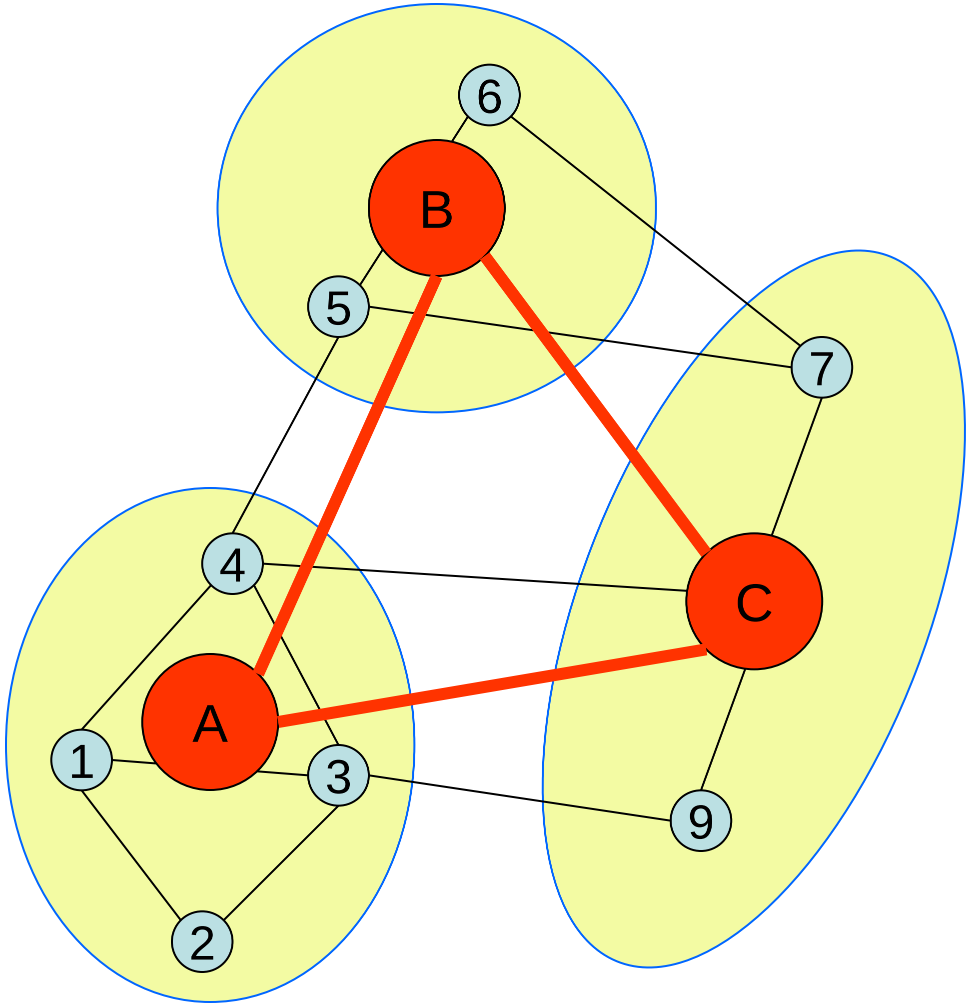
Norway can be split further into more zones if necessary



Congestion management in the Nordic power market

- Two methods coexist:
- Inter zonal congestion – Zonal pricing / Market splitting
  - Day-ahead market
  - For the largest and long-lasting congestions in Norway and for congestions on the borders of the control areas
- Intra zonal congestion – Counter trading / Redispatching
  - For constraints internal to the price-areas
  - For real-time balancing
    - The regulation market

Aggregation – example



True network
- ”All” nodes included
- ”All” lines represented

Economic aggregation
- ”All” nodes included
- ”All” lines represented
- Zones with uniform prices

Physical aggregation
- Aggregate nodes
- Aggregate lines

Optimal Power Flow - AC/"DC"	I:	Theoretical benchmark: "DC" is an approximation of the full alternate current (AC) power flows
↓ Optimal Zonal Prices	II:	Require the same prices in several nodes: A restriction / More constrained model
↓ Aggregated Nodes (Location of bids unknown)	III:	Intra-zonal constraints are not taken into account: Relaxation / Less restrictive model
↓ Aggregated Lines	IV:	Capacities are added on aggregated lines: Relaxation / Less restrictive model
↓ Without Loop Flow	V:	Characteristics of electrical power flows are not considered: Relaxation / Less restrictive model
↓ Heuristic for Determining Aggregated Capacity	VI:	Restrictions added in order to obtain feasible solution in the original problem
↓ Heuristic for Market Splitting	VII:	The old trading system. SAPRI. computes prices from sequentially splitting the system in two parts SESAM is optimization based and solves this approximation

Physical aggregation in relation to OPF-benchmark

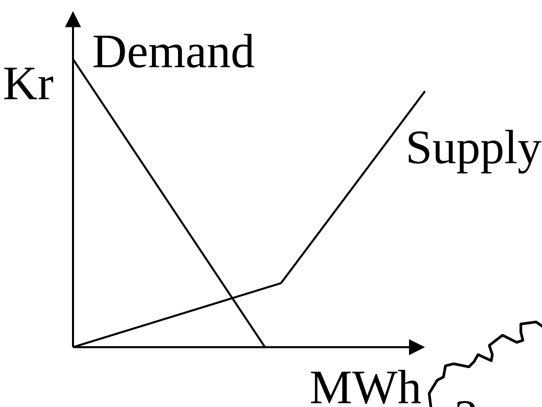
- Issues for evaluating performance
  - The number of zones used
  - The definition of the areas
  - Fixed or flexible zones
  - How to deal with internal constraints
  - Uncertainty about the location of bids within zones
  - How to determine capacity on aggregated lines
  - Aggregate flow model without Kirchhoff's laws
  - Heuristic procedure for market splitting
  - How to deal with block bids and flexible hourly bids

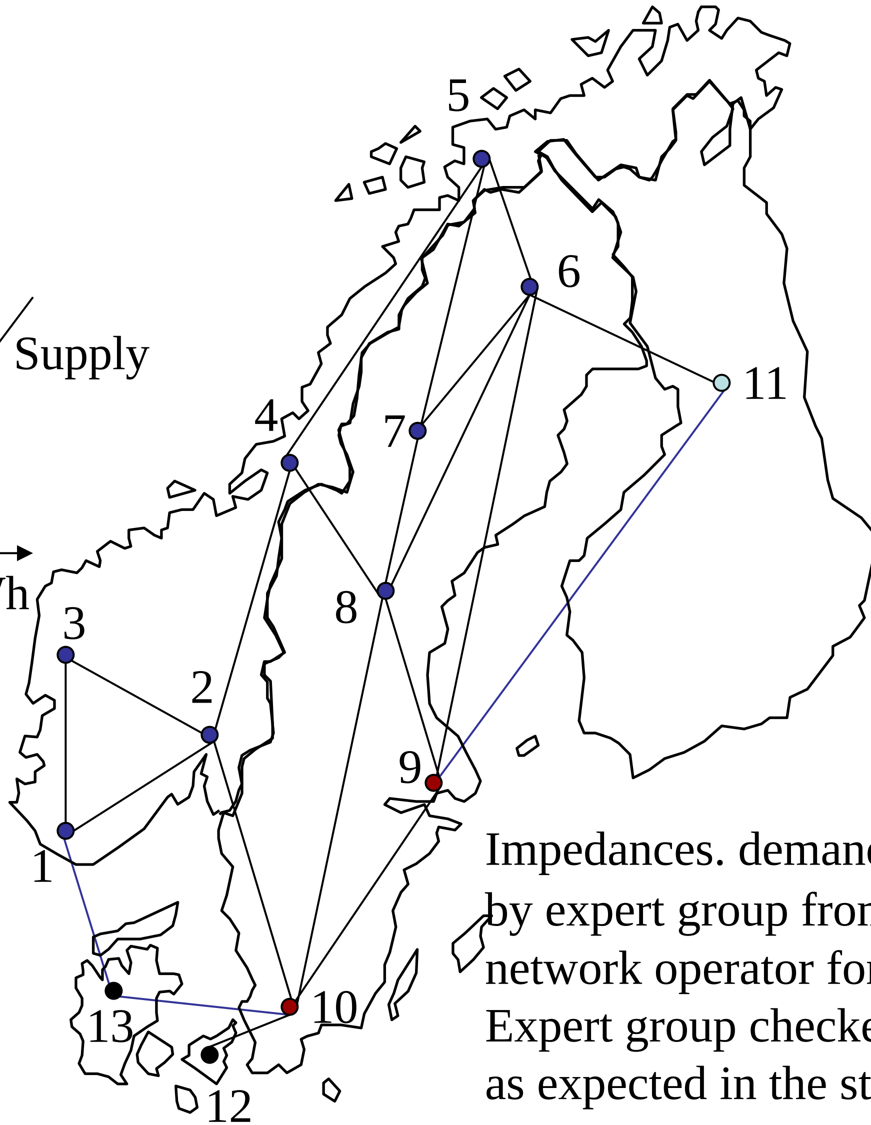
2 Projects

- EBL project 2001
  - What are the potential for cost savings from different zone definitions?
  - What is the cost of moving inter zonal bottlenecks to zonal borders?
- NVE project 2005-2007
  - How is congestion handled at Nord Pool, consequences and alternatives for improvement

Model of the Nordic power system

For every node:





- Hydro
- Mainly nuclear
- Mainly coal based thermal
- Various production tech.

DC

AC ("DC"-approx.)

Impedances. demand and supply generated by expert group from the industry and network operator for various load scenarios. Expert group checked that flows were as expected in the studied load scenarios

Main Results

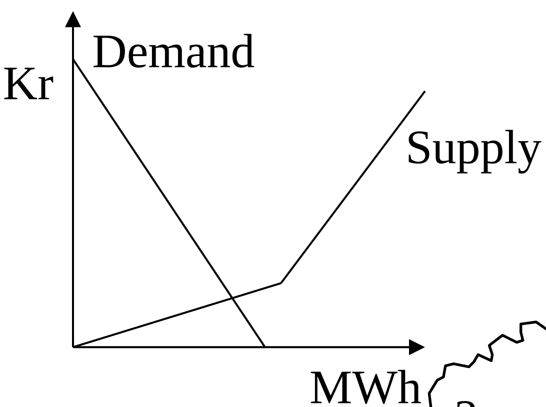
- The differences in congestion costs can be substantial between different zone allocations
  - Optimal handling of capacity limitations can reduce bottleneck costs considerably
- The more zones the better results, but need not always have many zones to reach a near optimal solution
- Without flexible price areas
  - Important to have enough fixed price areas in order to deal with special situations due to inflows and load

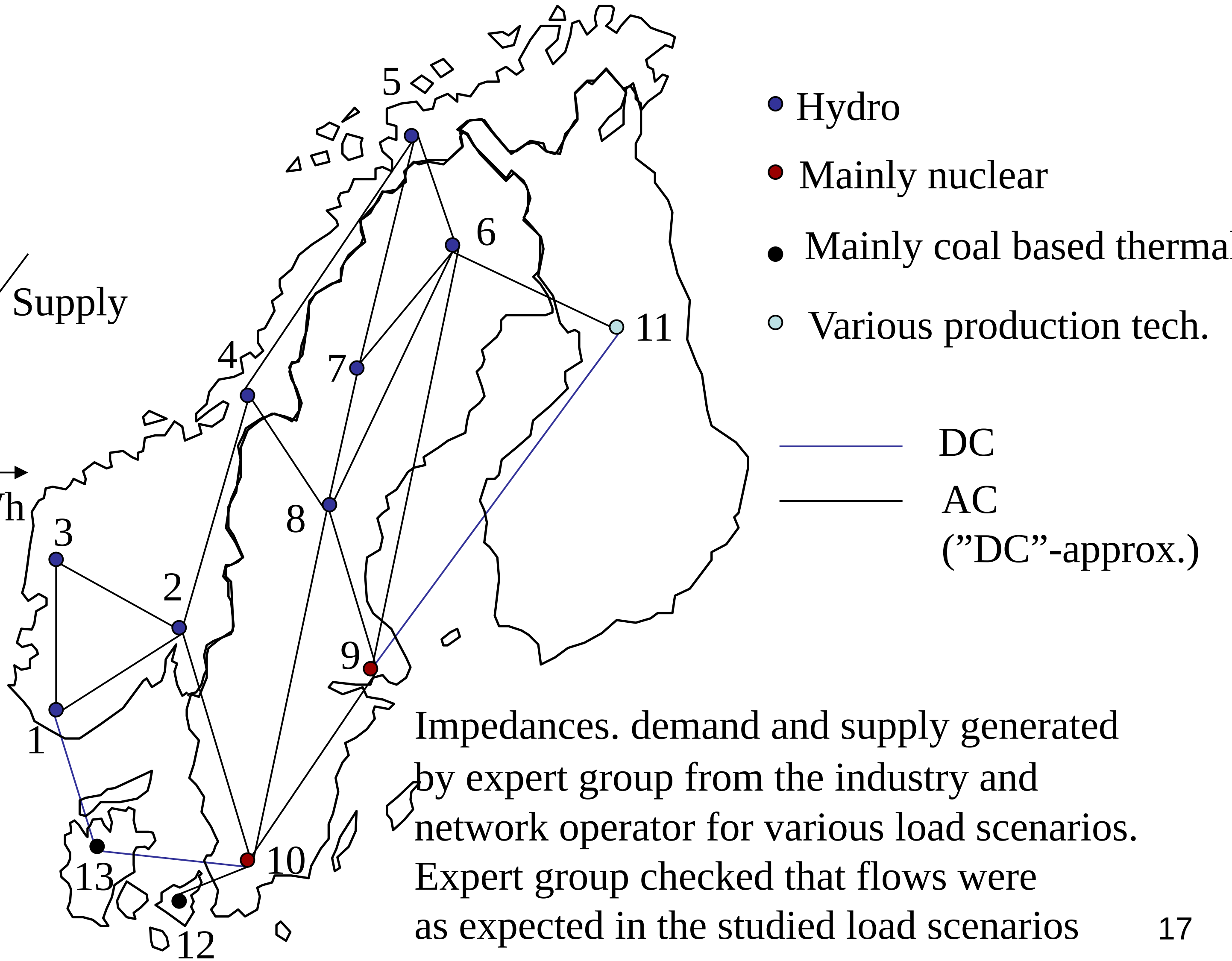
Transfer capacities

- Ref. Nordel July 2006
- Capacity limits are determined by TSOs and communicated to Nord Pool before market clearing
- Limits are based on
  - Forecasts of supply and demand
  - Imports/exports from the Nord Pool area
  - Security constraints
- Sweden cut 2 / Denmark DK1 cut B
  - Proportional allocation to each connection
  - Optimization routine to determine capacity utilization

Model of the Nordic power system

For every node:





Impedances. demand and supply generated by expert group from the industry and network operator for various load scenarios. Expert group checked that flows were as expected in the studied load scenarios

Main Results

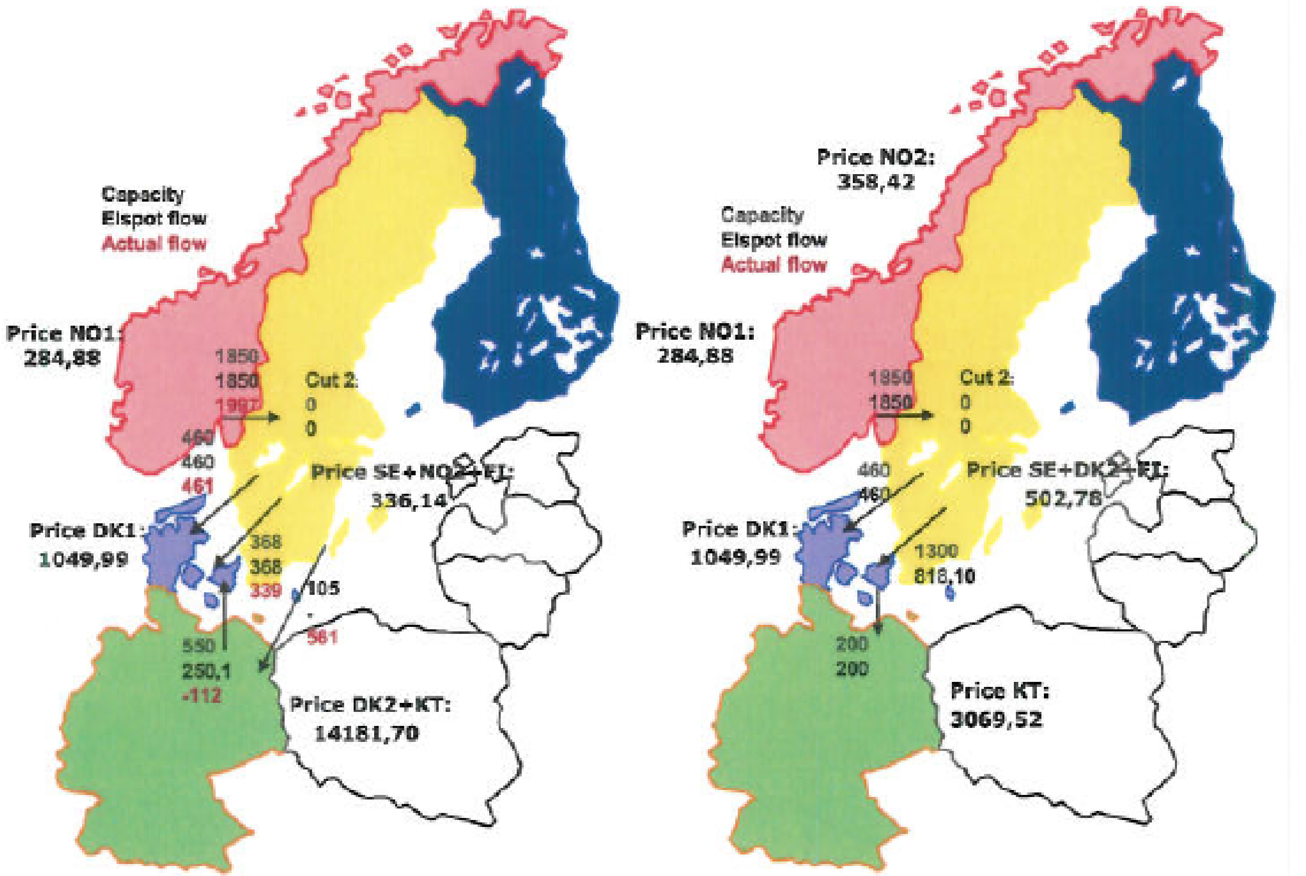
- That two congestion methods are used in the Nordic power market may lead to less efficient capacity usage and larger price differences than necessary
  - ”Moving” an internal bottleneck to a zonal border can be very costly
- Example:
  1) All capacity limitations are considered at their true values, i.e. $C_{2\text{-}3}$ = 2 800 MW and $C_{2\text{-}10}$ = 2 000 MW
  2) The capacity limit on line 2-3 is not considered, instead the capacity on line 2-10 is reduced to 940 MW, which induces flow over line 2-3 to fall below the capacity limit of 2 800 MW

Cost of bottleneck	**ULF**	**OLF**	**SYS**	**NOR2**	**NOR5**	**N2S2**	**NS3**	**N3S3**	**N5**	**N6**
1)	0	162	224	219	186	195	199	170	171	170
2)	0	353	436	435	434	371	390	355	401	355
DIFF		**118 %**	**95 %**	**99 %**	**133 %**	**90 %**	**96 %**	**109 %**	**135 %**	**109 %**

Do bottlenecks ”move”?

- ”The bottleneck from the west towards Oslo is handled through export limitations to Sweden. In Sweden and on Jothland and Sealand counter purchasing is used after a reduction of import/export has been made.” Nordel Maj 2002

Nord Pool Spot har udført en række alternative prisberegninger af time 18 den 28. november 2005. Figur 10 viser effekten af fuldkapacitet på Øresundsforbindelsen.



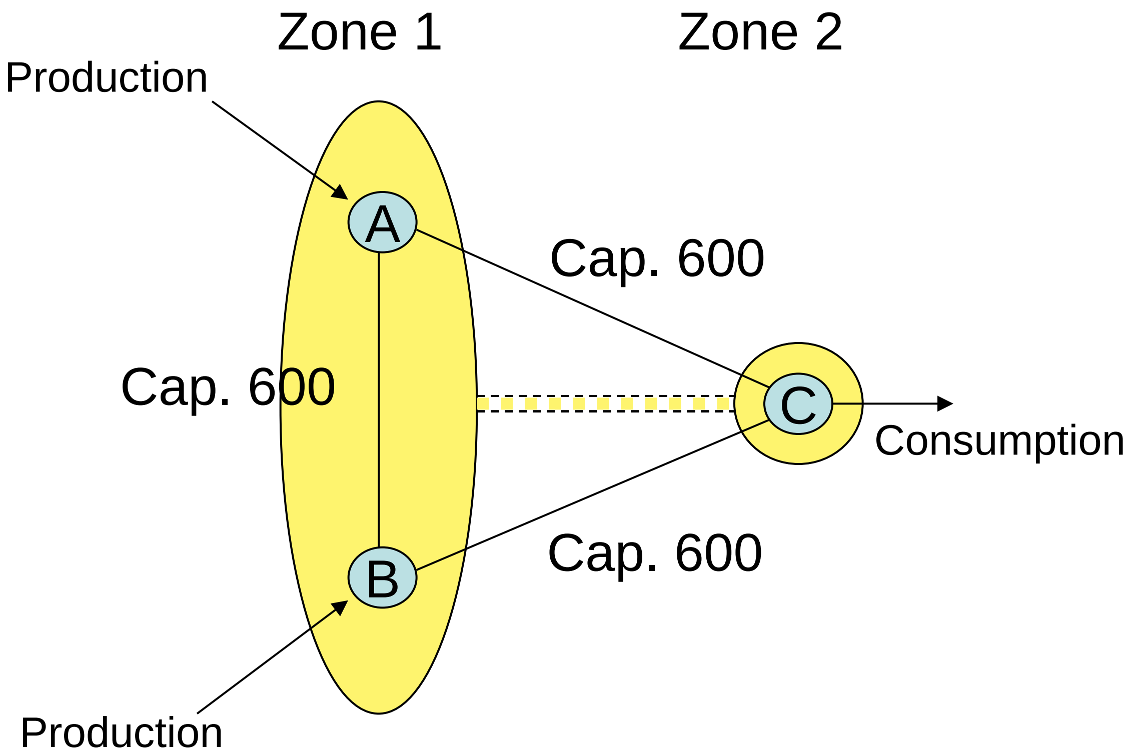
Area	Price Change
NO2	+20
SE+FI	+170
DK2	-13 500
KT	-11 000

Figur 10: Venstre figur: Realiserede spotpriser og flow time 18, 28. november 2005. Højre figur: Elspot simulerede spotpriser med fuld kapacitet på Øresundsforbindelsen. Priser er i NOK/MWh Note: forskellen i Elspot flow og Actual flow i venstre figur på Kontek-forbindelsen, skyldes Energi E2s gamle aftale om at sende 350 MWh i sydgående retning.

Other issues

- Is it necessary to model ”loop flow”?
  - Does it depend on the level of aggregation?
- How is the capacity of an aggregated line to be determined?
  - A cut may consist of many simple lines
  - Flows in opposite directions
- How important is it to get bids on nodal level?
  - Uncertainty about the location of bids within zones
  - Inexact capacity determination and -control as a result of that
  - Need to hedge for ”worst case” location of bids?

Example



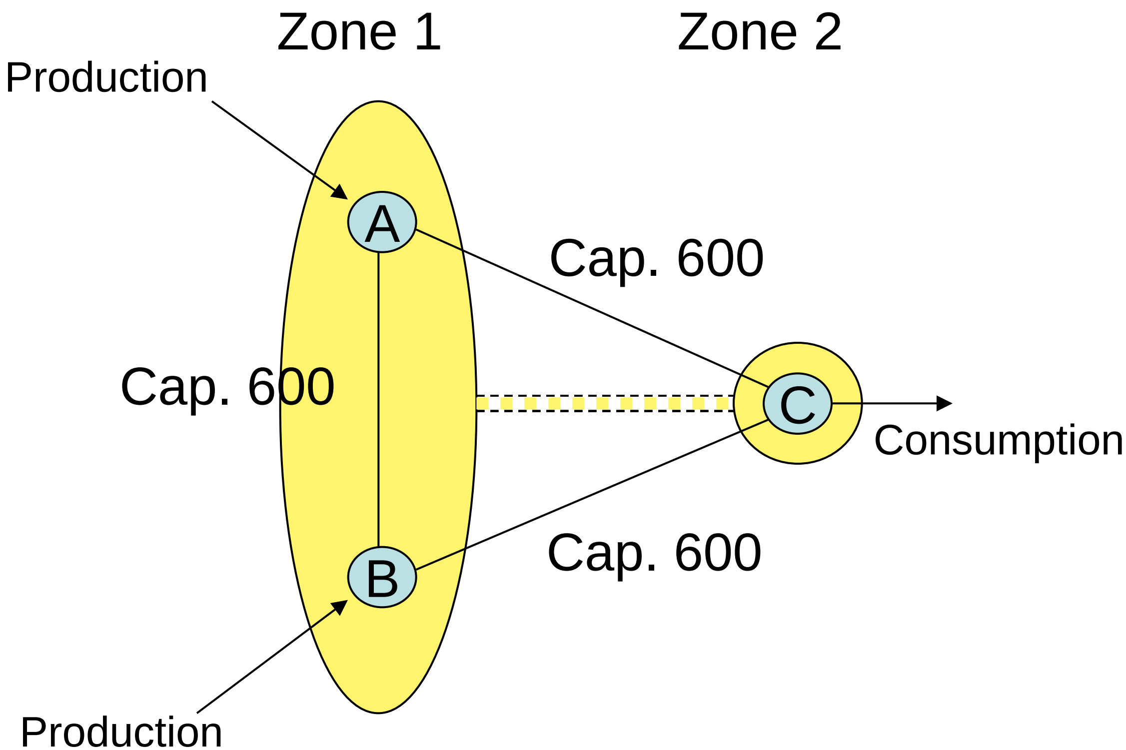
$f_{AC} = 2/3\ q_A + 1/3\ q_B$

$f_{BC} = 1/3\ q_A + 2/3 q_B$

$f_{AB} = 1/3\ q_A – 1/3\ q_B$

Which capacity to choose for the aggregated link between zone 1 and zone 2?

Example



$f_{AC} = 2/3\ q_A + 1/3\ q_B$

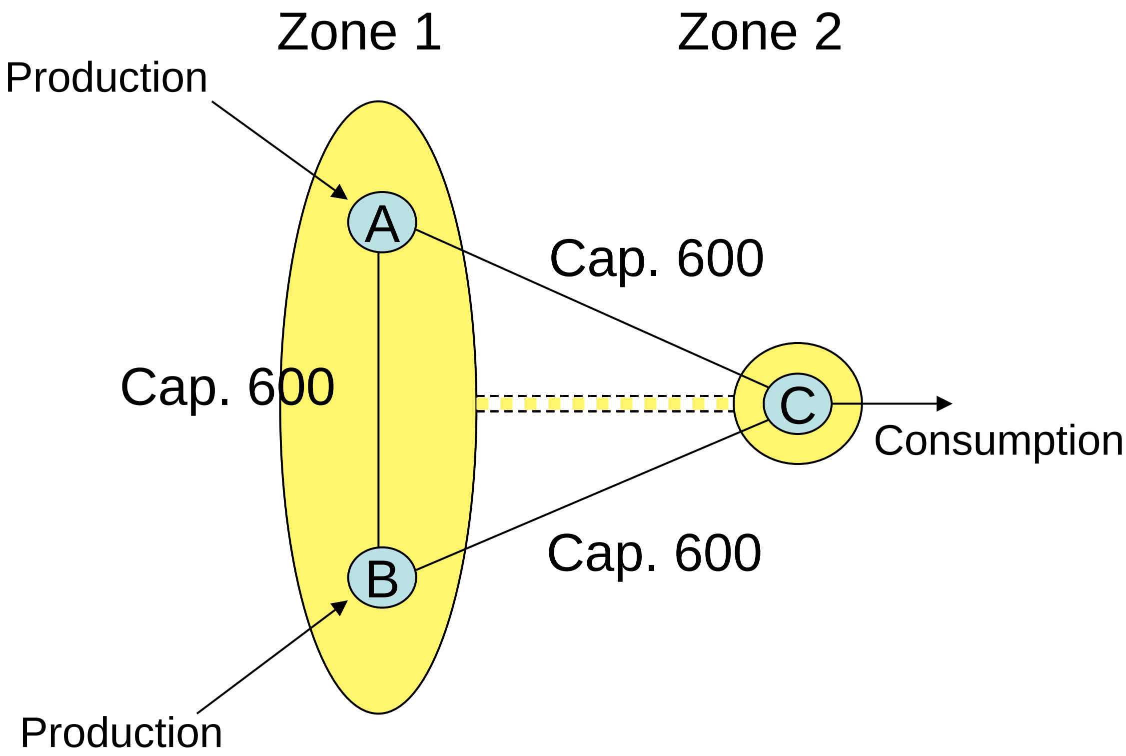
$f_{BC} = 1/3\ q_A + 2/3 q_B$

$f_{AB} = 1/3\ q_A - 1/3\ q_B$

Which capacity to choose for the aggregated link between zone 1 and zone 2?

	qa	qb		
	600	600		
	Injection in A	Injection in B	Flows	AC+BC
Link AC	0,67	0,33	600	1200
Link BC	0,33	0,67	600	
Link AB	0,33	-0,33	0	

Example



$f_{AC} = 2/3\ q_A + 1/3\ q_B$

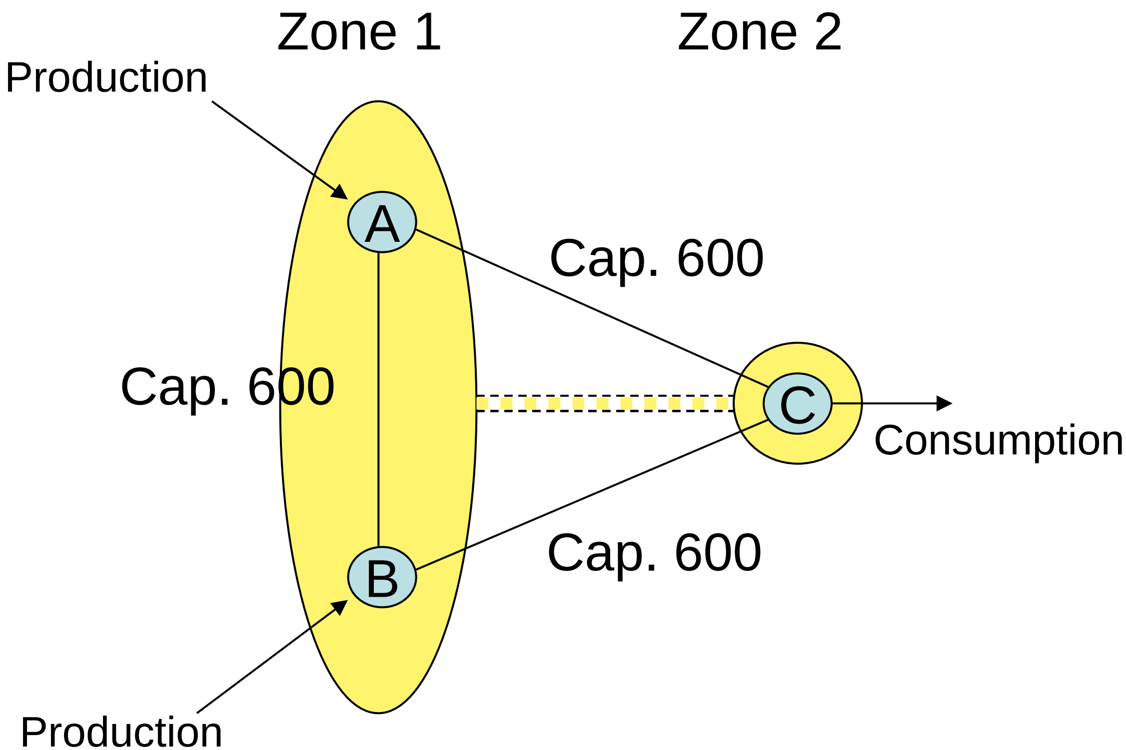
$f_{BC} = 1/3\ q_A + 2/3 q_B$

$f_{AB} = 1/3\ q_A – 1/3\ q_B$

Which capacity to choose for the aggregated link between zone 1 and zone 2?

	qa	qb		
	1200	0		
	Injection in A	Injection in B	Flows	AC+BC
Link AC	0,67	0,33	800	1200
Link BC	0,33	0,67	400	
Link AB	0,33	-0,33	400	

Example



$f_{AC} = 2/3\ q_A + 1/3\ q_B$

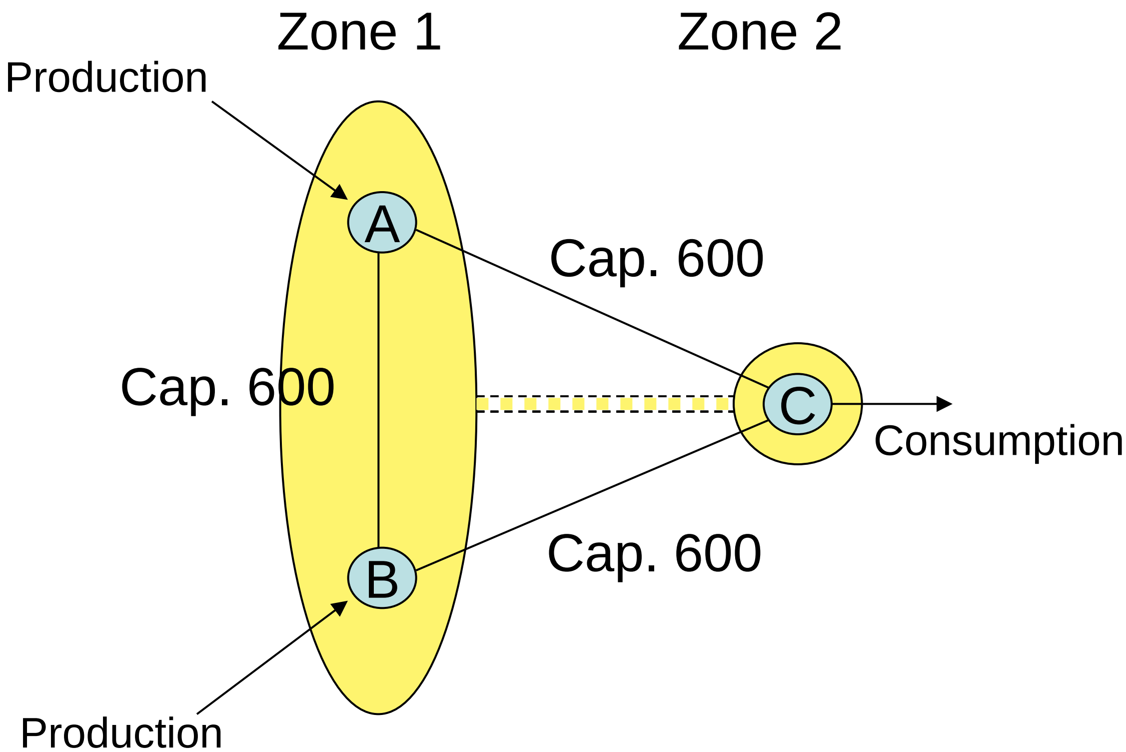
$f_{BC} = 1/3\ q_A + 2/3 q_B$

$f_{AB} = 1/3\ q_A – 1/3\ q_B$

Which capacity to choose for the aggregated link between zone 1 and zone 2?

	qa	qb		
	900	0		
	Injection in A	Injection in B	Flows	AC+BC
Link AC	0,67	0,33	600	900
Link BC	0,33	0,67	300	
Link AB	0,33	-0,33	300	

Example



$f_{AC} = 2/3\ q_A + 1/3\ q_B$

$f_{BC} = 1/3\ q_A + 2/3 q_B$

$f_{AB} = 1/3\ q_A - 1/3\ q_B$

Which capacity to choose for the aggregated link between zone 1 and zone 2?

	qa	qb		
	850	100		
	Injection in A	Injection in B	Flows	AC+BC
Link AC	0,67	0,33	600	950
Link BC	0,33	0,67	350	
Link AB	0,33	-0,33	250	

Block Bids

- Block bids yields a combinatorial exchange
- Hourly market clearing prices might not exist
- Differences between the American and European approach to deregulated electricity markets

Example

.Block bid 100 in each period if average price above 40

	Capacity of hourly bidder	Minimum Price of hourly bidder	Fixed Demand
Period 1	50	10	100
Period 2	70	60	150
Period 3	60	30	140

Solution

Objective function value 16200

Block bid 100 in each period

Complemented with flexible bid in period 2 producing 50 and flexible bid in period 3 producing 40

NO hourly prices support this solution

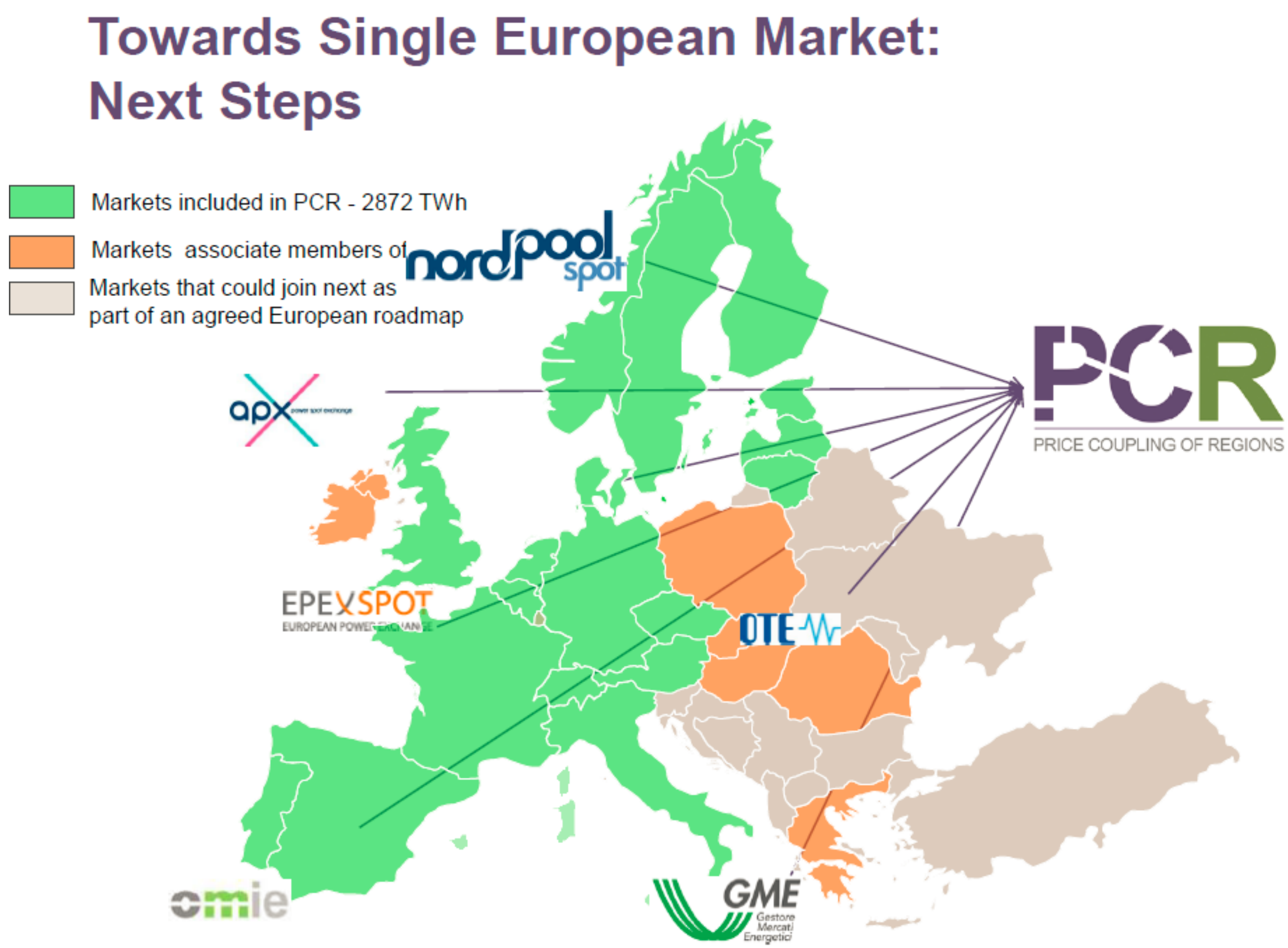
Euphemia

ALGORITHM EUPHEMIA

- EUPHEMIA is an algorithm that solves optimally the market coupling problem.
  - EUPHEMIA means: Pan-European Hybrid Electricity Market Integration Algorithm.
  - Hybrid: It is hybrid because it supports both ATC-based and flow-based network models, both standalone and in combination.

- It maximizes the welfare of the solution

Integrated European Market



New order formats in Euphemia

COMPLEX ORDERS. MIC ORDERS

MIC Orders are Stepwise Hourly Orders under an economical condition defined by two terms:

- Tf: Fixed Term in Euros which shows the fixed costs of the whole amount of energy traded in the order.
- Tv: Variable Term in Euros per accepted MWh which shows the variable costs of the whole amount of energy traded in the order.

The same acceptance rules for Stepwise Hourly Orders are applied to MIC Orders plus the acceptance of the economic condition which is defined mathematically as:

$$Tf + Tv \cdot (\Sigma_h \Sigma_{o \in h} [q_o \cdot x_o]) \leq \Sigma_h (MCP_h \cdot (\Sigma_{o \in h} [q_o \cdot x_o]))$$

New order formats in Euphemia

LOAD GRADIENT ORDER

The load gradient condition limits the variation between the accepted volume of an order in a period and the accepted volume of the same order in the adjacent periods.

A Load Gradient Order (LG) is defined by the next terms:

- ***Increase Gradient:*** Maximum increase gradient in MWh.
- ***Decrease Gradient:*** Maximum decrease gradient in MWh.

LG Orders must fulfill the following gradient condition:

$$(\Sigma_{o \in h+1} [q_o \cdot x_o]) \leq (\Sigma_{o \in h} [q_o \cdot x_o]) + \text{Increase Gradient}$$

$$(\Sigma_{o \in h+1} [q_o \cdot x_o]) \geq (\Sigma_{o \in h} [q_o \cdot x_o]) - \text{Decrease Gradient}$$

NEW CONDITION!!

Handeling of Block orders

MATCHING BLOCK ORDERS

- EUPHEMIA provides solutions where
  - Block orders that are accepted are in-the-money, i.e. there are no paradoxically accepted blocks (PAB)
    - Weighted average of the *published* MCPs is above limit price for a supply block
    - Weighted average of the *published* MCPs is below limit price for a demand block
  - Block orders that are rejected might sometimes happen to be in-the-money
    - Those are called paradoxically rejected (PRB)

Euphemia algorithm

EUPHEMIA MAIN IDEA

- For a fixed selection of blocks, the PCR Market Coupling Problem **can be written as a LP** (or QP if linear orders)
  - Solving this problem yields volumes and prices satisfying the Market Rules
  - If there is no Paradoxically Accepted Block with respect to those prices, the block selection and the prices form a feasible solution to the MCP
- The optimal solution between those is the one with the highest welfare

Euphemia price calculation

- Check if the solution obtained by algorithm is supported by a linear price system.
- If yes accept and prices are determined
- If No cur away current solution and move to second best. Check if this solution is supported by a linear price system
- Continue

PJMs pricing alternative

- Use shadow prices from continuous relaxation
- Leads to the missing money problem

Conclusions

- Show potential for improving the methods for congestion management in the Nord Pool area
- Possible to move in direction of optimal zonal prices
  - More zones / improved power flow model
  - Prices based on better information of bids and capacities
  - More market based management of internal and external bottlenecks
  - Possible to implement without major changes in pricing algorithm

One main message to remember

- Aggregation
  - Economic
  - Physical
- Need not to be identical
  - Bids can be nodal based
  - Capacities can be set on ”simple lines”
  - Prices can be computed on zonal level
    - Takes internal constraints directly into account
    - Are based on real limitations in the system

Challenges

- Hourly prices in a market where the number of block bids increase
- Zone definition: flexible or fixed,
- Different congestion management regimes in the various market areas