Generalized Nash Equilibrium and incomplete energy markets: Market Coupling in the European Power System

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The context: market integration in the European Community

Market coupling as a market design:

Implemented in electricity since 2006 (in discussion for gas these days (e.g. Florence 11 March 2011))

- Day ahead and real time markets:
  1. Market coupling deals with the day-ahead market;
  2. Real time is seen as a deviation management mechanism and agents are incentivised not to resort to it.
- Integration of energy and transmission:
  1. Market coupling partially integrates energy and transmission;
  2. The zonal energy market clears on an ATC (available transmission capacity) representation of the network;
  3. Counter-trading, if necessary, takes care of the real network.
- Counter-trading:
  1. Counter-trading is operated by zonal System Operators;
  2. Without clear indication on how they coordinate.

- Two groups of agents:
  1. Zonal (national) Power Exchanges (PXs) that clear the intra and inter zone energy markets;
  2. Zonal (national) Transmission System Operators (TSOs) that guarantee the security of the transmission system.

Market coupling concentrates on the energy market and is organized as follows:

- TSOs provide the energy market with a simplified representation of the grid (today the ATC);
- PXs jointly clear the energy markets taking into account the ATC received from the TSOs;
- PXs find the equilibrium electricity quantities and prices;
- In presence of saturation of ATCs, electricity prices differ per zone.

THE CONTEXT: A contribution to the never ending debate between zonal and nodal systems:

- first in electricity, resolved in favour of nodal in the US, good arguments for zonal in EU.
- beginning in gas in EU again (point to point transmission rights will be illegal in EU.)
- in economic terms: what is the impact of an incomplete pricing of transmission.

THE TALK: The flows resulting from the PXs' market clearing may not be feasible for the grid:

- TSOs restore feasibility by buying and selling incremental or decremental injections at the different nodes, while maintaining the zonal electricity demand and production levels unchanged. They socialized the cost of that activity. They can do that with different degree of coordination.

Assess the impact of this incomplete pricing of transmission services?

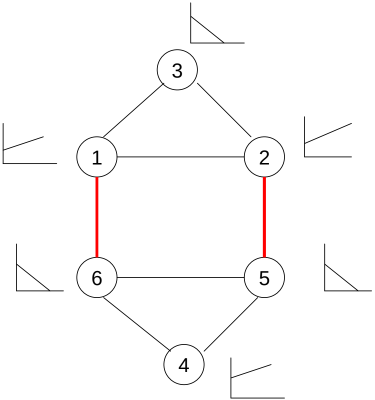
Outline

1. Methodological discussion: Generalized Nash Equilibrium and market incompleteness
2. A prototype case study
3. Conclusion.

Methodological discussion, Generalized Nash Equilibrium and market incompleteness

The illustrative example (1)

Six Node Market



SOURCE: Chao, H.P., S.C. Peck. 1998. Reliability Management in Competitive Electricity Markets. *Journal of Regulatory Economics*, **14**, 198-200.

- **Demand and cost functions**

Node	Function Type	Function
1	Marginal Cost	10+0.05q
2	Marginal Cost	15+0.05q
3	Inverse Demand	37.5-0.05q
4	Marginal Cost	42.5+0.025q
5	Inverse Demand	75-0.1q
6	Inverse Demand	80-0.1q

SOURCE: Chao, H.P., S.C. Peck. 1998. Reliability Management in Competitive Electricity Markets. *Journal of Regulatory Economics*, **14**, 198-200.

- **PTDF Matrix**

Power (1 MW) Injected at Node	**Power flow on link 1 → 6 (MW)**	**Power flow on link 2 → 5 (MW)**
1	0.625	0.375
2	0.5	0.5
3	0.5625	0.4375
4	0.0625	-0.0625
5	0.125	-0.125
6 (hub)	0	0

Capacity link $1 \rightarrow 6 = 200$ MW

Capacity link $2 \rightarrow 5 = 250$ MW

SOURCE: Chao, H.P., S.C. Peck. 1998. Reliability Management in Competitive Electricity Markets. *Journal of Regulatory Economics*, **14**, 198-200.

- **Sets**
  - $l = (1-6), (2-5)$: Set of lines of the transmission grid;
  - $n = 1, ..., 6$: Set of nodes;
  - $i = 1, 2, 4$: Subset of production nodes;
  - $j = 3, 5, 6$: Subset of consumption nodes

- **Variables and Parameters**
  - $\bar{I}$: Imports/export limits among zones;
  - $PTDF_{n,l}$: Power Transfer Distribution Factor matrix of node n on line l;
  - $\bar{F}_l$: Limit of flow through line l;
  - q_n: Power generated or consumed in node n;
  - $c(q_i)$: Cost function of generator located in node i:
  - $w(q_j)$: Inverse demand function of consumer located in node j;
  - I: Imports/exports in the PX's problem;
  - $\lambda_l^{+,-}$: Marginal value of the interconnection line l;
  - $\Delta q_n^{N,S}$: Demand and generation variations (counter-trading services) in node n operated by TSO^N or TSO^S

NOTE: The red lines (1-6) and (2-5) have limited capacity.

1. **Full integration of energy and transmission markets: the reference nodal system (Model 1)**

2. **Imperfect integration of energy and transmission markets: Market Coupling and centralized Counter-Trading (Model 2)**

3. **Imperfect integration of energy and transmission markets: Market Coupling and decentralized Counter-Trading (Model 3)**

The complete market: the nodal model

The reference model:

$$\mathbf{Min_{q_n}} \quad \sum_{i=1,2,4} \int_0^{q_i} c_i(\xi) d\xi - \sum_{j=3,5,6} \int_0^{q_j} w_j(\xi) d\xi$$

s.t.

$$\bar{F}_l - \Big(\sum_{i=1,2,4} PTDF_{i,l} q_i - \sum_{j=3,5,6} PTDF_{j,l} q_j \Big) \geq 0 \qquad (\lambda_l^+)$$

$$\bar{F}_l + \Big(\sum_{i=1,2,4} PTDF_{i,l} q_i - \sum_{j=3,5,6} PTDF_{j,l} q_j \Big) \geq 0 \qquad (\lambda_l^-)$$

where $l = (1-6), (2-5)$

$$\sum_{i=1,2,4} q_i - \sum_{j=3,5,6} q_j = 0 \qquad (\gamma)$$

$$q_n \geq 0 \qquad \forall n \qquad (\nu_n)$$

Results

- **Welfare**

Social welfare: 23,000 €

- **Congested line**

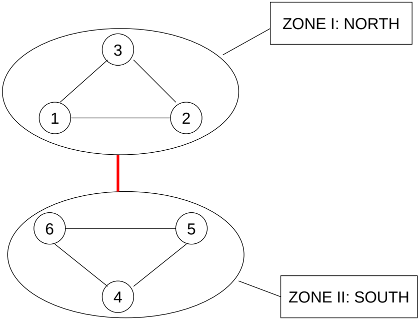
Both lines (1-6) and (2-5) transfer 200 MW of energy.

Line (1-6) is congested and its marginal value is 40 €/MWh.

Market Coupling and counter-trading

Market coupling: defining zones

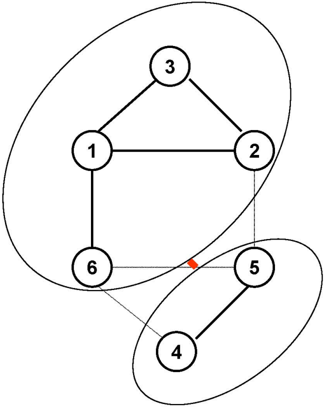
The market is subdivided into two zones (North and South), each controlled by a TSO (here a 3/3 case):



The TSOs compute the ATC between the two zones.

A second example: the 4/2 case

An alternative zonal organization:



Market coupling: clearing the energy market (depends on zonal decomposition)

The PXs solve the following problem for the 3/3 configuration:

$$\mathbf{Min_{q_n}} \quad \sum_{i=1,2,4} \int_0^{q_i} (\alpha + c_i(\xi)) d\xi - \sum_{j=3,5,6} \int_0^{q_j} w_j(\xi) d\xi$$

s.t.

$$q_1 + q_2 - q_3 - I = 0$$

$$q_4 - q_5 - q_6 + I = 0$$

$$q_n \geq 0 \qquad \forall n$$

$$-\overline{I} \leq I \leq \overline{I}$$

Market coupling: results of the clearing of the energy market (1)

- **Welfare before re-dispatching costs**

Welfare: 24,146 € (compared to 23,000 € in the nodal model)

- **Demand and generation**

Total demand is 800 as in the nodal system.

- **Interconnecting line**

The interconnection is saturated. Its marginal value is 18.33 €/MWh and the import/export is 450 MWh from North to South.

$$\mathbf{Min}_{\mathbf{\Delta q_n}} \quad \sum_{i=1,2,4} \int_{q_i}^{q_i+\Delta q_i} c_i(\xi) d\xi - \sum_{j=3,5,6} \int_{q_j}^{q_j+\Delta q_j} w_j(\xi) d\xi$$

s.t.

$$-\overline{F}_l \leq \sum_{i=1,2,4} (PTDF_{i,l}(q_i + \Delta q_i)) - \sum_{j=3,5,6} (PTDF_{j,l}(q_j + \Delta q_j)) \leq \overline{F}_l \qquad (\lambda_l^{\pm})$$

where $l = (1-6), (2-5)$

$$\sum_{i=1,2,4} \Delta q_i + \sum_{j=3,5,6} \Delta q_j = 0 \qquad (\mu^1)$$

$$\sum_{i=1,2,4} \Delta q_i - \sum_{j=3,5,6} \Delta q_j = 0 \qquad (\mu^2)$$

$$q_n + \Delta q_n \geq 0 \qquad \forall n \qquad (\nu_n)$$

Computation of optimized cross-border counter-trading costs

- **Total re-dispatching cost at equilibrium**

The total re-dispatching cost is 1,146 €

- **Average re-dispatching costs**

The average re-dispatching cost is 1.43 €/MWh

- **Net Welfare**

Net welfare is 23,000 €;

- **Welfare loss**

Welfare loss is 0 € w.r.t. to Model 1 (23,000 €)

The average re-dispatching/counter-trading cost α incurred by the TSOs is:

$$\alpha = \frac{\sum_{i=1,2,4} \int_{q_i}^{q_i+\Delta q_i} c_i(\xi) d\xi - \sum_{j=3,5,6} \int_{q_j}^{q_j+\Delta q_j} w_j(\xi) d\xi}{\sum_{i=1,2,4} q_i}$$

This cost is charged to the users of the system. One assumes here that it is paid by the generators selling on the PXs (this is a stylized view of the problem):

Formulation: Suppose that the average counter-dispatching cost adds to the constant term (10, 15 and 42.5) of the marginal cost functions

- The fixed point problem can be solved by looping between the PX and TSO models
- Alternative arrangements can have counter-trading paid by demand nodes or by both demand and supply nodes.
- From here on we only report the results at equilibrium between the PX (market coupling) and the TSO (counter-trading)

Results of optimal cross-border counter-trading (2)

	Configuration 3/3		Configuration 4/2	
	Prod/Cons	**Prod**	**Prod/Cons**	**Prod**
Welfare loss	30	125	8	2,320
TRC	1,146	1,235	5,079	7,065
ARC	1.51	1.63	6.51	9.56
Net welfare	**22,970**	**22,875**	**22,992**	**20,680**
MV line (1-6)	40.00	42.22	40.00	57.05
MV line (2-5)	0.00	0.00	0.00	0.00

NOTATION:

- Welfare loss (€) are computed w.r.t. Model 1 (23,000 €);
- TRC: Total Re-dispatching Costs in €;
- ARC: Average Re-dispatching Costs in €/MWh;
- Net Welfare: welfare value at equilibrium in €;
- MV: marginal value of transmission lines in €/MWh

Market coupling: counter-trading with different degrees of coordination

- **The law (third package) says that TSOs must coordinate**
  - But it does not say how
- **EU documents do not envisage an optimal cross border counter-trading**
  - (e.g. impact assessments of infrastructure document of November 2010)
- **It thus makes sense to make assumptions on lack of optimal cross border counter-trading**
  - National TSOs are not coordinated (Model 3):
    A. National TSOs have full access to all re-dispatching resources: an internal market of counter-trading resources (model 3.1);
    B. National TSOs have only a limited access to all re-dispatching resources: a limited internal market of counter-trading resources (model 3.2)
    C. National TSOs manage only the re-dispatching resources in their control area: national markets of counter-trading resources (model 3.3)

Imperfect counter-trading

Technical note: computation and economics

1. Nodal pricing: optimization;
2. Energy market clearing and optimized cross-border counter-trading: sequence of optimization or complementarity problems;
3. Imperfect coordination of TSOs: Generalized Nash equilibrium problems solved by optimization (Nabetani, Tseng, Fukushima 2009).

Technical note: completing the transmission market

1. Access to counter-trading resources: create an internal market of counter-trading resources (by (close) analogy with discussion on internal market of balancing resources);
2. Create a market of interconnection line capacity (by analogy with PJM MISO interconnection);
3. Merger or coordination contracts between TSOs (as taking place on the market).

MODEL 3.1 an internal market of counter-trading resources; no market of line capacity (1)

Assume that each TSO can buy counter-trading services in both zones. Note $\Delta q_i^{N,S}$ where $i = 1, 2, .., 6$ these actions of both TSOs.

- **TSO^N (with a similar problem for TSO^S)**

$$\mathbf{Min}_{\mathbf{\Delta q_i^N}} \quad \sum_{i=1,2,4} \int_{q_i+\Delta q_i^S}^{q_i+\Delta q_i^S+\Delta q_i^N} c_i(\xi)d\xi - \sum_{j=3,5,6} \int_{q_j+\Delta q_j^S}^{q_j+\Delta q_j^S+\Delta q_j^N} w_j(\xi)d\xi$$

s.t.

$$\overline{F}_l-(\sum_{i=1,2,4} PTDF_{i,l}(q_i+\Delta q_i^N+\Delta q_i^S)-\sum_{i=3,5,6} PTDF_{i,l}(q_i+\Delta q_i^N+\Delta q_i^S)) \geq 0 \qquad (\lambda_l^{N,+})$$

where $l = (1-6), (2-5)$

$$\sum_{i=1,2,4} \Delta q_i^N + \sum_{j=4,5,6} \Delta q_j^N = 0 \qquad (\mu_l^{N,1})$$

$$\sum_{i=1,2,4} \Delta q_i^N - \sum_{j=4,5,6} \Delta q_j^N = 0 \qquad (\mu_l^{N,2})$$

$$q_n + \Delta q_n^N + \Delta q_n^S \geq 0 \qquad \forall n \qquad (\nu_n^N)$$

MODEL 3.1 An internal market of counter-trading resources; no market of line capacity (2)

Assume that $q_n + \Delta q_n^N + \Delta q_n^S > 0$ for $\forall n$ and define the dual variables $\lambda_l^N = (-\lambda_l^{N,+} + \lambda_l^{N,-})$ for $l = ((1-6),(2-5))$. We obtain the dual conditions:

$$c_i - \sum_l \lambda_l^N \cdot PTDF_{i,l} - \mu^{N,1} + \mu^{N,2} = 0 \qquad i = 1,2,4$$

$$-w_j + \sum_l \lambda_l^N \cdot PTDF_{j,l} - \mu^{N,1} - \mu^{N,2} = 0 \qquad j = 3,5,6$$

Writing the same relations for TSO^S

$$c_i - \sum_l \lambda_l^S \cdot PTDF_{i,l} - \mu^{S,1} + \mu^{S,2} = 0 \qquad i = 1,2,4$$

$$-w_j + \sum_l \lambda_l^S \cdot PTDF_{j,l} - \mu^{S,1} - \mu^{S,2} = 0 \qquad j = 3,5,6$$

we find, if there are enough equalities (here six equalities for four variables), that $\lambda_l^N = \lambda_l^S$.

MODEL 3.1 An internal market of counter-trading resources; no market of line capacity (3)

PROPOSITION: The internal market of counter-trading resources restores the perfect counter-trading: (i) different agents resorting to the same counter-trading resource at the same price induces a price arbitrage that forces the equality of the dual variables of the common constraints (the transmission lines (ii) which has an effect equivalent to a market of line capacity) and hence (iii) leads to a single GNE in counter-trading. (iv) In mathematical terms, the solution set of the QVI is identical to the solution set of the associated VI!!

The Nabetani, Tseng, Fukushima's parametrized approach is as follows:

$$\mathbf{Min}_{\mathbf{\Delta q_n^{N,S}}} \quad \sum_{i=1,2,4} \int_{q_i}^{q_i+\Delta q_i^S+\Delta q_i^N} c_i(\xi)d\xi - \sum_{j=3,5,6} \int_{q_j}^{q_j+\Delta q_j^S+\Delta q_j^N} w_j(\xi)d\xi +$$

$$+\sum_l (\gamma_l^{N,+} - \gamma_l^{N,-}) \cdot (\sum_{i=1,2,4} PTDF_{i,l} \cdot \Delta q_i^N - \sum_{j=3,5,6} PTDF_{j,l} \cdot \Delta q_j^N)$$

$$+\sum_l (\gamma_l^{S,+} - \gamma_l^{S,-}) \cdot (\sum_{i=1,2,4} PTDF_{i,l} \cdot \Delta q_i^S - \sum_{j=3,5,6} PTDF_{j,l} \cdot \Delta q_j^S)$$

s.t.

$$\overline{F}_l - (\sum_{i=1,2,4} PTDF_{i,l}(q_i+\Delta q_i^N+\Delta q_i^S) - \sum_{j=3,5,6} PTDF_{j,l}(q_j+\Delta q_j^N+\Delta q_j^S)) \geq 0 \qquad (\lambda_l^+)$$

$$\sum_{i=1,2,4} \Delta q_i^Z + \sum_{j=3,5,6} \Delta q_j^Z = 0 \qquad Z = N, S \qquad (\mu_l^{Z,1})$$

$$\sum_{i=1,2,4} \Delta q_i^Z + \sum_{j=3,5,6} \Delta q_j^Z = 0 \qquad Z = N, S \qquad (\mu_l^{Z,2})$$

$$q_n + \Delta q_n^N + \Delta q_n^S \geq 0 \qquad \forall n \qquad (\nu_n^Z) \qquad Z = N, S$$

MODEL 3.2: A restricted internal market of counter-trading resources (1)

Each TSO can buy counter-trading services in both zones, but purchase in other zone is limited.

- **TSO^N (with a similar problem for TSO^S)**

$$\mathbf{Min}_{\mathbf{q_n^N}} \quad \sum_{i=1,2,4} \int_{q_i+\Delta q_i^S}^{q_i+\Delta q_i^N+\Delta q_i^S} c_i(\xi)d\xi - \sum_{j=3,5,6} \int_{q_j+\Delta q_j^S}^{q_j+\Delta q_j^N+\Delta q_j^S} w_j(\xi)d\xi \quad s.t.$$

$$\overline{F}_l - (\sum_{i=1,2,4} PTDF_{i,l}(q_i+\Delta q_i^N+\Delta q_i^S) - \sum_{j=3,5,6} PTDF_{j,l}(q_j+\Delta q_j^N+\Delta q_j^S)) \geq 0 \qquad (\lambda_l^{N,+})$$

where $l = (1-6), (2-5)$

$$\sum_{i=1,2,4} \Delta q_i^N + \sum_{j=3,5,6} \Delta q_j^N = 0 \qquad (\mu_l^{N,1})$$

$$\sum_{i=1,2,4} \Delta q_i^N - \sum_{j=3,5,6} \Delta q_j^N = 0 = 0 \qquad (\mu_l^{N,2})$$

$$q_n + \Delta q_n^N + \Delta q_n^S \geq 0 \qquad \forall n \qquad (\nu_n^N)$$

$$-\overline{\Delta q_n^N} \leq \Delta q_n^N \leq \overline{\Delta q_n^N} \qquad n = 4,5,6 \qquad (\eta_n^{N,\pm})$$

MODEL 3.2: A restricted internal market of counter-trading resources (2)

A FIRST RESULT: The implicit market of interconnection line capacity is lost when TSOs have limited access to counter-trading resources in other zones. This introduces inefficiencies; these can be more or less important depending on whether one does or does not introduce a market for transmission.

MAIN QUESTION: How far can one go in deteriorating the efficiency of counter-trading and hence the overall efficiency of market coupling?

Results of Model 3.2 (1)

Market configuration 3/3 with a market of interconnection capacity

Trading interconnection capacities among TSOs (setting $\gamma_l^{N/S,\pm} = 0$) under the following counter-trading resource restrictions, counter-trading remains relatively efficient:

$\overline{\Delta} q_1^S$	$\overline{\Delta} q_2^S$	$\overline{\Delta} q_3^S$	$\overline{\Delta} q_4^N$	$\overline{\Delta} q_5^N$	$\overline{\Delta} q_6^N$
33.33	16.67	8.33	16.67	8.33	16.67

	Configuration 3/3	
	Prod/Cons	**Prod**
Welfare loss	30	125
TRC	1,146	1,235
ARC	1.51	1.63
Net welfare	**22,970**	**22,875**
MV line (1-6)	40.00	42.22
MV line (2-5)	0.00	0.00
$\gamma_l^{N/S,\pm}$	0.00	0.00

Eliminating trade of transmission capacities (setting $\gamma^{N,+}_{(1-6)} = 60$ and $\gamma^{S,+}_{(1-6)} = 0$) and keeping the same limits on counter-trading resources, restrictions degrades the efficiency of counter-trading:

	Configuration 3/3	
	Prod/Cons	**Prod**
Welfare loss	396	494
TRC	1,490	1,580
ARC	2	2.13
Net welfare	**22,604**	**22,506**
MV line (1-6)	22.67	27.68
MV line (2-5)	0.00	0.00
$\gamma^{N,+}_{(1-6)}$	60.00	60.00
$\gamma^{S,+}_{(1-6)}$	0.00	0.00

Results of Model 3.2 (3)

Market configuration 4/2 with a market of line capacity

Setting $\gamma_l^{N/S,\pm} = 0$ under the following counter-trading resource restrictions, the result can be very bad depending on how one organizes counter-trading, even in presence of a transmission market:

$\overline{\Delta} q_1^S$	$\overline{\Delta} q_2^S$	$\overline{\Delta} q_3^S$	$\overline{\Delta} q_4^N$	$\overline{\Delta} q_5^N$	$\overline{\Delta} q_6^S$
72.48	22.48	94.96	94.96	34.98	59.98

	Configuration 4/2	
	Prod/Cons	**Prod**
Welfare loss	8	infeasible
TRC	5,079	infeasible
ARC	6.51	infeasible
Net welfare	**22,992**	infeasible
MV line (1-6)	40.00	infeasible
MV line (2-5)	0.00	infeasible
$\gamma_l^{N/S,\pm}$	0.00	0.00

Setting $\gamma_{(1-6)}^{N,+} = 60$ and $\gamma_{(1-6)}^{S,+} = 0$ and keeping the same limits on counter-trading resources restrictions, one has for configuration 4/2:

	Configuration 4/2	
	Prod/Cons	**Prod**
Welfare loss	2,472	infeasible
TRC	7,191	infeasible
ARC	9.76	infeasible
Net welfare	**20,528**	infeasible
MV line (1-6)	18.16	infeasible
MV line (2-5)	0.00	infeasible
$\gamma_{(1-6)}^{N,+}$	60.00	60.00
$\gamma_{(1-6)}^{S,+}$	0.00	0.00

A SECOND RESULT: Not only the implicit coordination is lost when TSOs have limited access to counter-trading resources in other zones, but counter-trading can become impossible in some zonal markets (in this case example 4/2) (as encountered in the single zone Sweden).

A THIRD RESULT: Even when counter-trading is possible (examples 3/3 and 4/2) it can become extremely inefficient in the absence of a market for transmission capacities (different γ).

MODEL 3.3: Domestic counter-trading resources (1)

Assume that each TSO can only buy counter-trading services in its zone.

- **TSO^N (similar problem for the TSO^S)**

$$\mathbf{Min}_{\boldsymbol{\Delta} \mathbf{q_n^N}} \quad \sum_{i=1,2} \int_{q_i}^{q_i+\Delta q_i^N} c_i(\xi) d\xi - \int_{q_3}^{q_3+\Delta q_3^N} w_3(\xi) d\xi$$

s.t.

$$\overline{F}_l - (\sum_{i=1,2} PTDF_{i,l}(q_i + \Delta q_i^N) + PTDF_{4,l}(q_4 + \Delta q_4^S) +$$

$$-PTDF_{3,l}(q_3 + \Delta q_3^N) - \sum_{j=5,6} PTDF_{j,l}(q_j + \Delta q_j^S)) \geq 0 \qquad (\lambda_l^+)$$

where $l = (1-6), (2-5)$

$$\Delta q_1^N + \Delta q_2^N + \Delta q_3^N = 0 \qquad (\mu_l^{N,1})$$

$$\Delta q_3^N - \Delta q_1^N - \Delta q_2^N = 0 \qquad (\mu_l^{N,2})$$

$$q_n + \Delta q_n^N \geq 0 \qquad n = 1, 2, 3$$

Results of Model 3.3 (1)

Only imposing that each TSO remains in balance, even when assuming a transmission market (setting all the weight $\gamma_l^{N/S,\pm} = 0$) can make the situation difficult:

	Configuration 3/3		Configuration 4/2	
	Prod/Cons	**Prod***	**Prod/Cons***	**Prod**
Welfare loss	1,454	3,096	3,009	infeasible
TRC	2,442	3,781	7,629	infeasible
ARC	3.45	5.88	10.50	infeasible
Net welfare	**21,546**	**19,904**	**19,991**	**infeasible**
MV line (1-6)	146.67	220.00	82.30	infeasible
MV line (2-5)	0.00	0.00	0.00	infeasible
$\gamma_{N/S,\pm}$	0.00	0.00	0.00	infeasible

∗ These scenarios admit always the same solution whatever γ considered.

Results of Model 3.3 (2)

When setting $\gamma^{N,+}_{(1-6)} = 60$ and $\gamma^{S,+}_{(1-6)} = 0$ (eliminating the transmission market), the situation becomes dramatic:

	Configuration 3/3		Configuration 4/2	
	Prod/Cons	**Prod**	**Prod/Cons**	**Prod**
Welfare loss	1,555	3,096	3,009	infeasible
TRC	2,529	3,781	7,629	infeasible
ARC	3.60	5.88	10.50	infeasible
Net welfare	**21,445**	**19,904**	**19,991**	**infeasible**
MV line (1-6)	106.67	160.00	82.30	infeasible
MV line (2-5)	0.00	0.00	0.00	infeasible
$\gamma^{N,+}_{(1-6)}$	60.00	60.00	60.00	60.00
$\gamma^{S,+}_{(1-6)}$	0.00	0.00	0.00	0.00

A GENERAL OBSERVATION: Counter-trading efficiency further and dramatically deteriorates when one completely segments the counter-trading resources market.

AN ADDITIONAL RESULT: Even when counter-trading is possible (example 3/3) it can become extremely inefficient in the absence of a market for transmission capacities (different γ).

Summing up on this example and barring incentives to game counter-trading

Nodal pricing is, as expected, the best system.

Integrating counter-trading services and TSOs does well.

Integrating counter-trading resources, even without a transmission market does as well (but requires drastic harmonization of market design between zones).

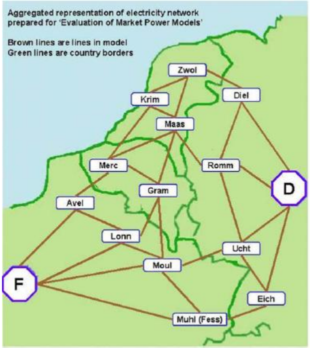
Partially segmenting the counter-trading resources, with or without a transmission market can serious degrade efficiency and even make counter-trading impossible.

Totally segmenting counter-trading resources, with or without a transmission market further deteriorates efficiency.

Case Study

A toy model of Central Western European (CWE) Market:

Market coupling is currently operated among Belgium, France and the Netherlands and Germany.



Flowgate	Reactance	Max Capacity [MW]
AVEL_LONN	22,2	2762
D_DIEL	45,9	20000
D_EICH	45,9	20000
D_ROMM	45,9	20000
D_UCHT	45,9	20000
DIEL_ROMM	69,2	1842
DIEL_ZWOL	12,2	2971
EICH_UCHT	41,3	3329
F_AVEL	45,9	20000
F_LONN	45,9	20000
F_MOUL	45,9	20000
F_MUHL	45,9	20000
GRAM_LONN	45,2	1207
GRAM_MOUL	156,5	267
KRIM_MERC	34,2	936
LONN_MOUL	27,1	1842
MAAS_GRAM	41,8	641
MAAS_KRIM	29,1	1842
MAAS_MERC	61,0	641
MERC_AVEL	55,4	898
MERC_GRAM	31,1	1842
MOUL_MUHL	38,2	3329
MUHL_EICH	11,5	1282
ROMM_MAAS	28,3	896
ROMM_UCHT	43,0	1842
UCHT_MOUL	25,4	1326
ZWOL_KRIM	33,1	1842
ZWOL_MAAS	50,0	1842

SOURCE: Energy research Centre of the Netherlands (ECN) website

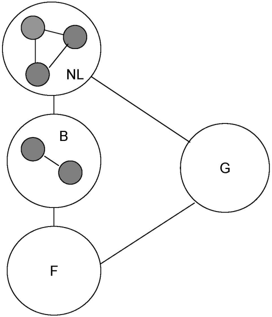
MAIN RESULTS

Considering different demand scenarios of the nodal model, we obtain the following results:

Demand level	**Social Welfare (M€)**
Reference	267,124
Increase 5%	279,254
Increase 10%	291,080
Increase 20%	313,592

Table: Welfare of different nodal model scenarios

PXs solve a welfare maximization problem while taking into account the following stylized representation of the transmission network:



The social welfare resulting from the clearing of the energy market, before removing violations of line constraints, amounts to 267,571 M€.

MAIN RESULTS

All TSOs coordinate counter-trading. Results for different demand scenarios:

Demand level	**Total Re-dispatching costs (M€)**	**Average Re-dispatching costs (€/MWh)**	**Welfare (PX) (M€)**
Reference	450	0.37	267,120
Increase 5%	431	0.35	279,249
Increase 10%	550	0.43	291,066
Increase 20%	322	0.24	313,590

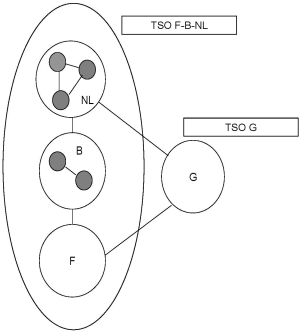
Table: Welfare and re-dispatching costs

Welfare losses respectively amount to 4, 5, 14 and 2 million €/year w.r.t. the values obtained in Models 1.

Model 3.1: Model A Trilateral TSO (1)

Uncoordinated Counter-Trading

Only one TSO operates in the market. This coordinates the re-dispatching activities inside and on the interconnections of France, Belgium and the Netherlands. This market organization is depicted as follows:



MAIN RESULTS

Total Re-dispatching costs (M€)	Average Re-dispatching costs (€/MWh)	Welfare (PX) (M€)
455	0.38	267,116

Table: Welfare and re-dispatching costs

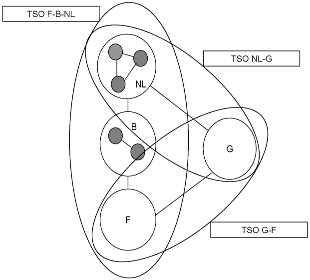
Welfare losses amount to 4 and 8 million €/year w.r.t. the reference values obtained in Models 1 and 2 respectively.

Multilateral Arrangement: Model 3.2 (1)

Uncoordinated Counter-Trading

Three TSOs operate in the market:

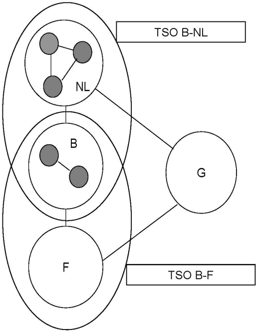
- (F-B-NL) TSO manages the re-dispatching activities in France, Belgium and the Netherlands;
- (G-NL) TSO manages the re-dispatching activities in Germany and in the Netherlands;
- (G-F) TSO manages the re-dispatching activities in Germany and in France



MAIN RESULT: one restores the efficiency of an integrated counter-trading

This model creates arbitrage possibilities between TSOs that have un-discriminatory access to common counter-trading resources. This assumption allows TSOs to implicitly coordinate their action: we fall back on the results of Model 2 where we consider an explicit coordination.

Two TSOs operate in the market. They manage congestion on the interconnection lines between France and Belgium (note as is the case between RTE (F) and Elia (B)) and Belgium and the Netherlands (as is not the case between Elia (B) and TenneT (NL)). One is the (F-B) TSO and the other is the (B-NL) TSO. They share counter-trading resources in Belgium as illustrated in the following picture:



MAIN RESULTS

Variation limits for (B-NL) TSO	Total Re-dispatching cost (M€)	Average Re-dispatching costs (€/MWh)	Welfare (PX) (M€)
936	455	0.38	267,116
936*0.5	455	0.38	267,116
936*0.1	460	0.38	267,111

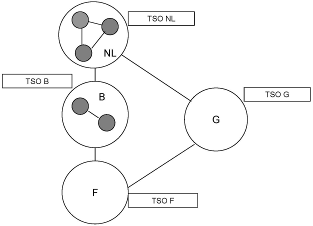
Table: (B-NL) has limited action in Belgium: degradation with respect to Model 2

Variation limits for (F-B) TSO	Total Re-dispatching cost (M€)	Average Re-dispatching costs (€/MWh)	Welfare (PX) (M€)
898	455	0.38	267,116
898*0.5	455	0.38	267,116
898*0.1	656	0.55	266,914

Table: (F-B) has limited action in Belgium: degradation with respect to Model 2

Welfare losses amount to 5 and 202 million € for the cases "936*0.1" and

There are four TSOs: one per each national market. None of the TSOs controls the interconnection lines:



This problem is infeasible, but feasibility can be restored with a significant investment in the grid (in practice by reducing ATC for the PXs).

An Uncoordinated Counter-Trading with Four TSOs: Model 3.4 (2)

MAIN RESULTS

This segmentation of the TSOs' action implies market inefficiencies as results show:

- Welfare amounts to 264,182 € (loss of 2.9 billion €/year w.r.t. the welfare of Model 1);
- High average re-dispatching costs in Belgium (4.32 €/MWh) and in the Netherlands (35.67 €/MWh);
- No re-dispatching costs in France and in Germany

Conclusions

Conclusions

1. Counter-trading can be costly: this has indeed been observed in practice e.g. ERCOT;
2. As expected the less coordination, the more costly it can be;
3. Counter-trading can even be impossible (also observed in practice (e.g. PECO, Sweden))