Applications of Complementarity-Based Models of Transmission-Constrained Power Markets: B-NL Market Integration & Power-NOx Market Interactions in PJM

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Specific Questions:

- ***What are the benefits of Belgian-Dutch power market integration?***
  - ***Methodology: COMPETES (a LCP Cournot model of transmission-constrained markets)***
  - ***Effect of inefficient transmission & arbitrage***
- ***What strategies might generators use to exploit the interaction of electric power and NO_x markets?***
  - ***Methodology: MPEC Stackelberg model of NOx and power markets (transmission constrained)***
  - ***Demonstrates ability to solve large scale (~20,000 variable) MPECs***

Computational Approach: Direct Solution of Equilibrium Conditions

Producer A

Choose gen & sales to maximize profit

s.t. capacity

$\Rightarrow$ 1st order conditions

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Producer B

Choose gen & sales to maximize profit

s.t. capacity

$\Rightarrow$ 1st order conditions

ISO: Choose Transmission Flows to Max Value of Network

s.t. transmission constraints $\Rightarrow$ 1st order conditions

Consumers: Max Value - Expenditures (Demand Curve)

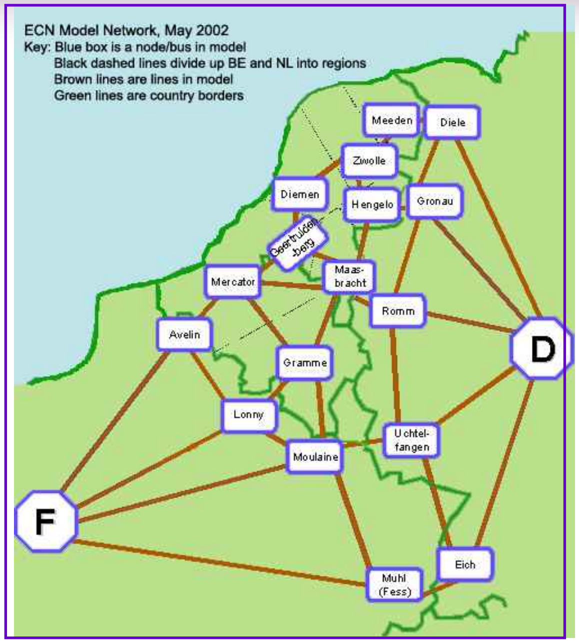
Market Clearing Conditions

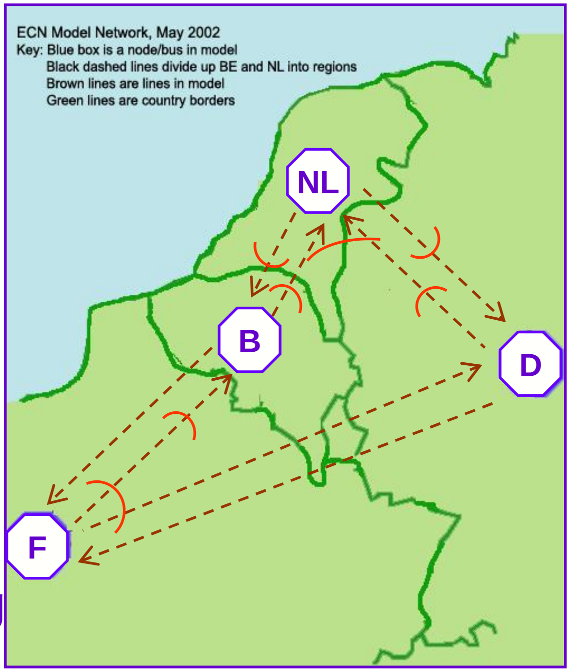
1. Derive first-order conditions for each player
2. Impose market clearing conditions
3. Solve resulting system of conditions (*complementarity problem*) using PATH

B-NL Analysis

COMPETES *Market Structure*

- **Cournot generators compete in bilateral market**
- **Competitive arbitragers in some markets**
- **Two transmission pricing systems:**
  - –Physical network
    - Linearized DC load flow
    - Several nodes per country
  - –Path-based representation
    - One node per country → one market price per country
    - Interfaces defined between countries
    - Crediting for counterflows (netting vs. no-netting





COMPETES

Inputs

- **Demand**
  - **12 periods → 3 seasons, 4 load periods**
  - **Allocated to the nodes**
- **Generation**
  - **15 large power generating companies**
    - **4 NL, 1 B, 2 F, 8 G**
  - **Plus competitive fringe**
  - **5272 generating units**
  - **MC based on heat rate and fuel type**

Congestion management B $\leftrightarrow$ NL

Current Auction System

- **Yearly, monthly, daily**
- **Available capacity for auction *[www.tso-auction.nl]***
  - **B - NL: 1150 MW**
  - **Germany - NL: 2200 MW**
- **Total import capacity to NL $\leq$ 400 MW per party**
- **Price set by lowest accepted bid**
- **Daily auction takes place before APX settles**

Congestion management B $\leftrightarrow$ NL

Proposal for market integration

- **Single market**
  - **One market price**
  - **TSO responsible for re-dispatch**
  - **Payments for constrained-off or -on**
- **Market Coupling (Splitting)**
  - **Similar to the NordPool**
  - **If Congestion: two separate market prices**

Effects of Market Coupling

Differences relative to current situation

1) Increased market access into Belgium
   - For (foreign) Generators and
   - For Traders → Introduce arbitrage

2) Netting of transmission capacity

3) Efficient co-ordination of ‘Auction’ and APX

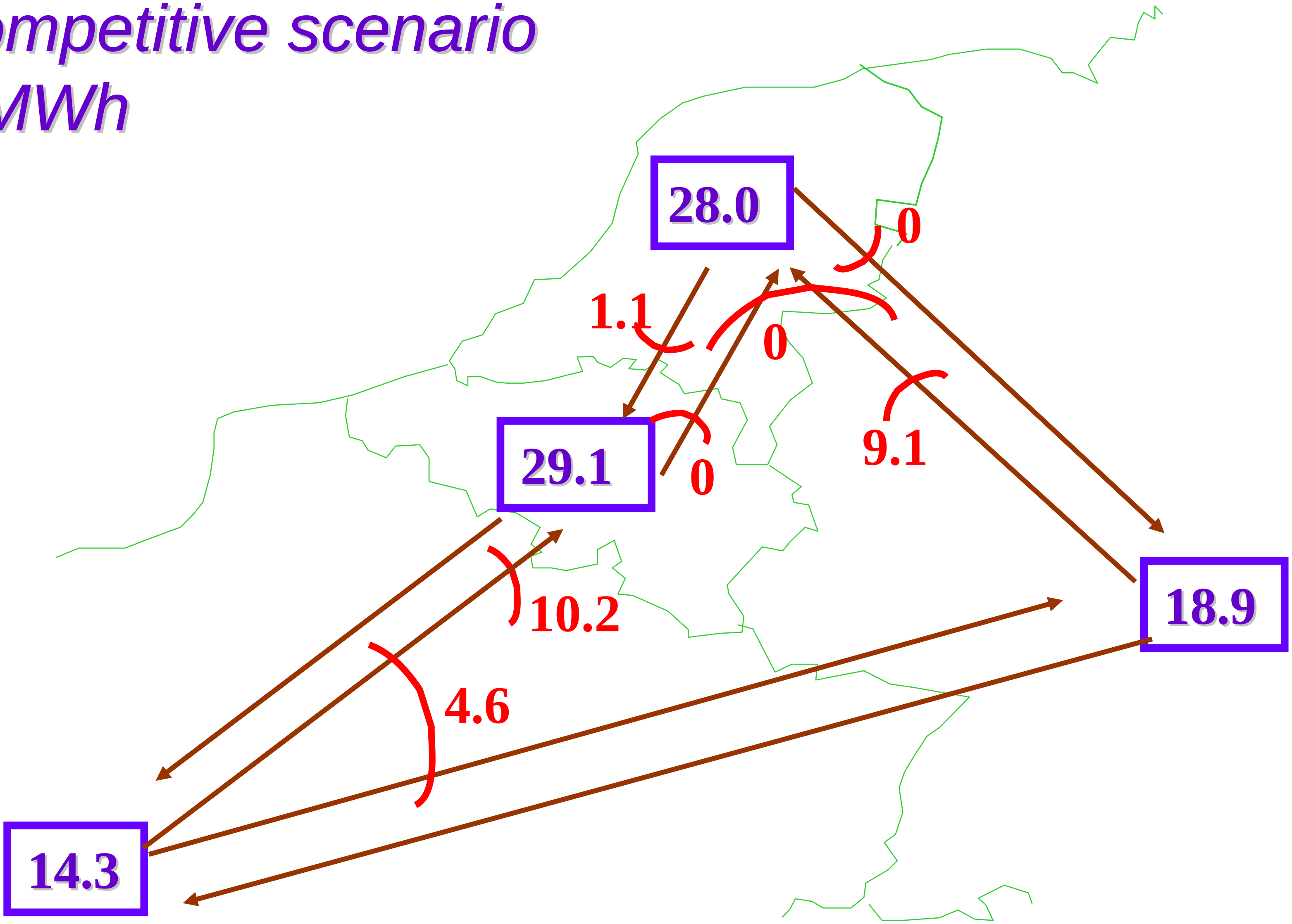
Effects of Market Coupling

Definition of scenarios

		Import cap on firms			Import cap on arbitrageurs			Netting
		B → NL	NL → B	NL → B Electrabel	B → NL	NL → B	G ↔ NL	
Competitive		No limit	No limit	No limit	No limit	No limit	No limit	Yes
C O U R N O T	**Current situation**	**400**	**0**	**950**	**0**	**200**	No limit	**No**
	Market splitting	None*	None*	None*	No limit	No limit	No limit	**B ↔ NL**

Model results

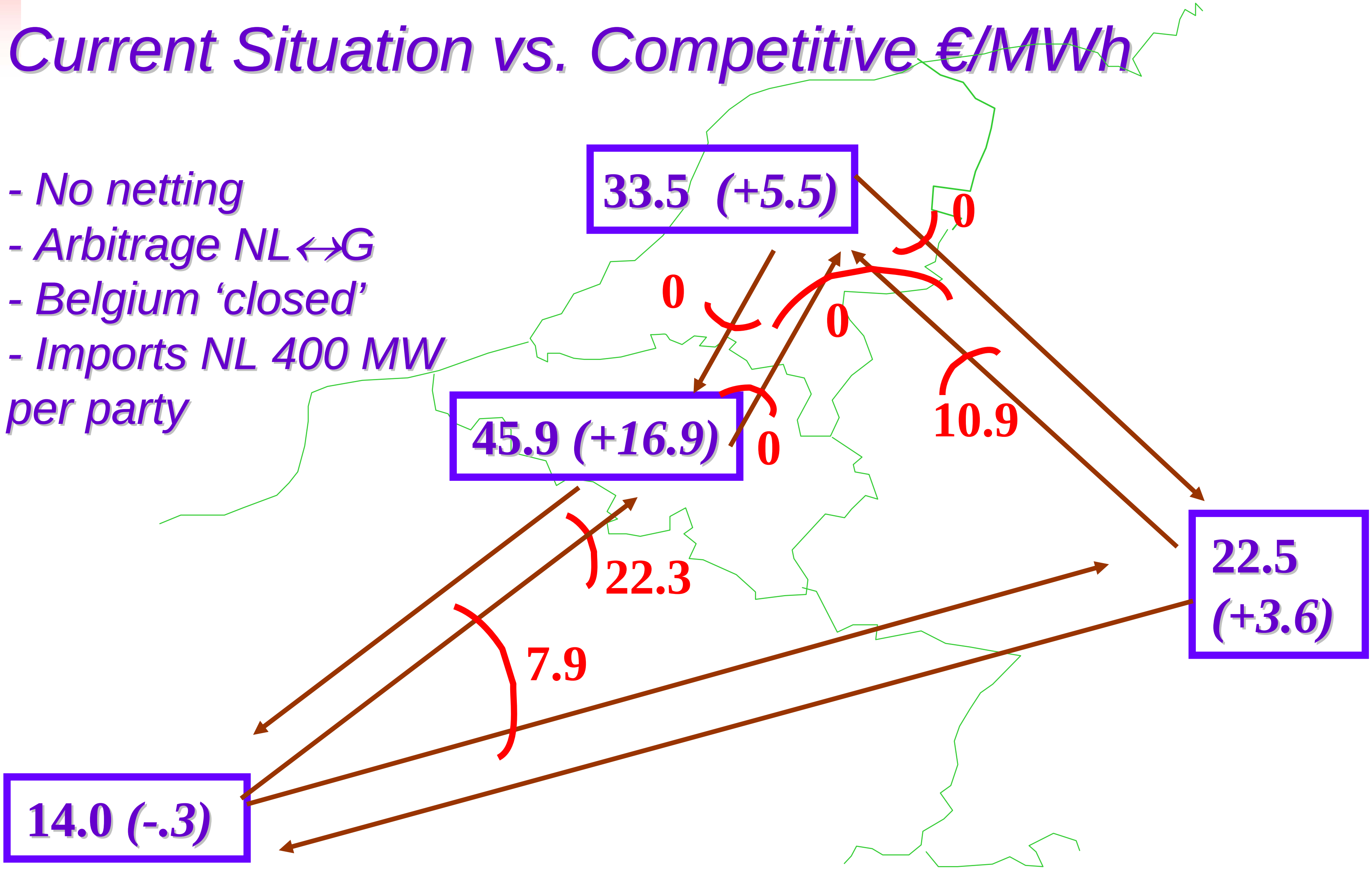
Competitive scenario
€/MWh



Model results

Current Situation vs. Competitive €/MWh

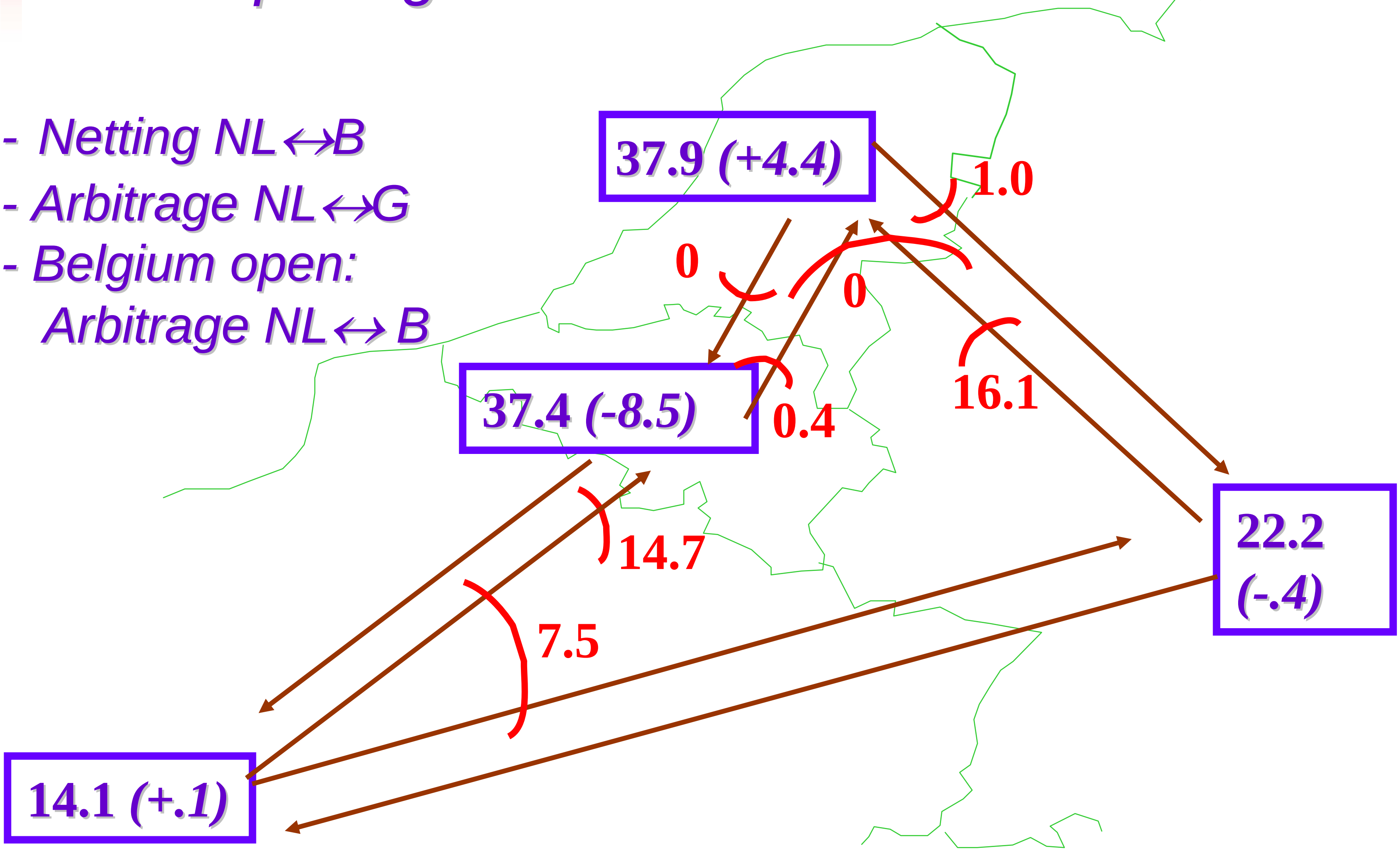
- *No netting*
- *Arbitrage NL↔G*
- *Belgium 'closed'*
- *Imports NL 400 MW per party*



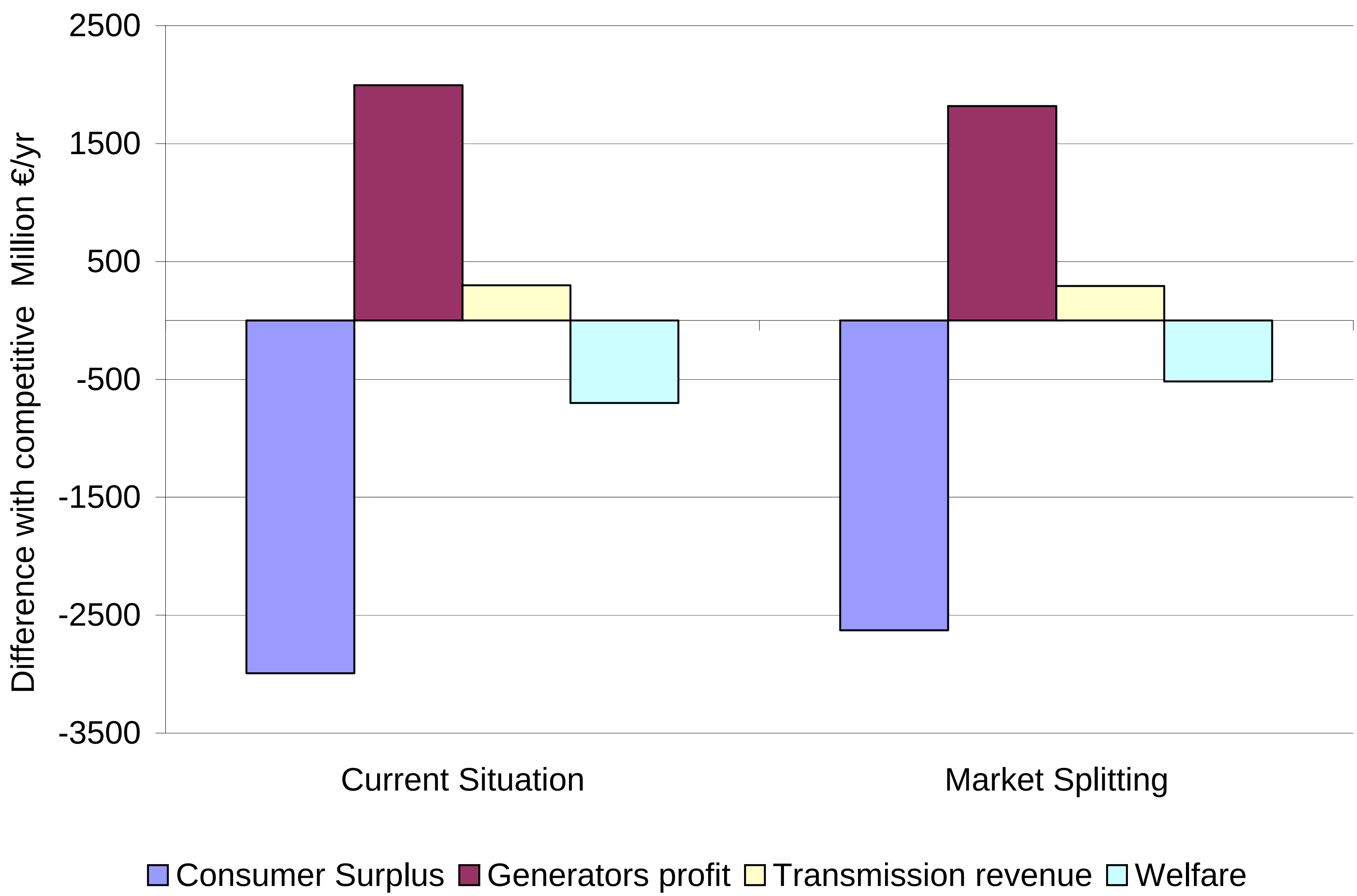
Model results

Market Splitting vs. Current Situation €/MWh

- *Netting NL↔B*
- *Arbitrage NL↔G*
- *Belgium open:*
  Arbitrage NL↔ B



Welfare Compared to Perfect Competition



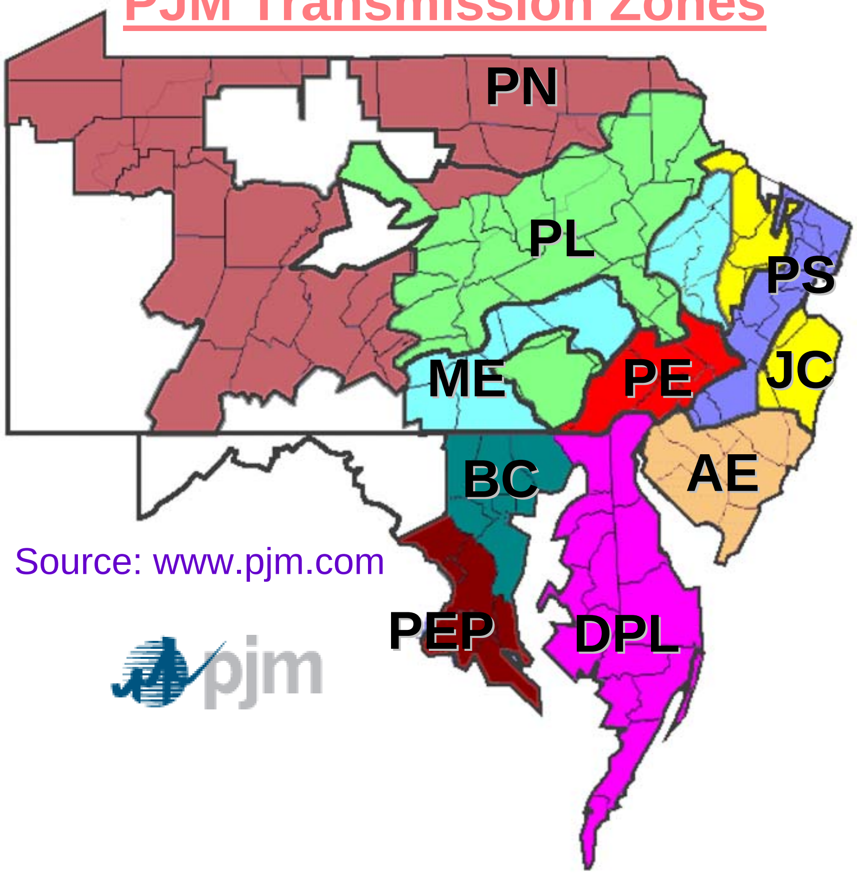
Effects of Market Coupling

- Market Coupling affects prices, increases welfare (+ 182 M€/yr more than current)
  - Induced by lower prices in Belgium
  - Increased welfare is mainly in Belgium

- What is “in it” for the Netherlands?
  - Profits Dutch generators increase
  - But consumer surplus decreases more

PJM Power Market & USEPA NO_x Program Analysis

PJM Transmission Zones



Source: www.pjm.com

Can the NOx market be profitably manipulated by a large generator who is long on allowances?

PJM Market

- *Peak Load 50,000 MW*
- *Average Load-weighted Price - 30.7 $/MWh*

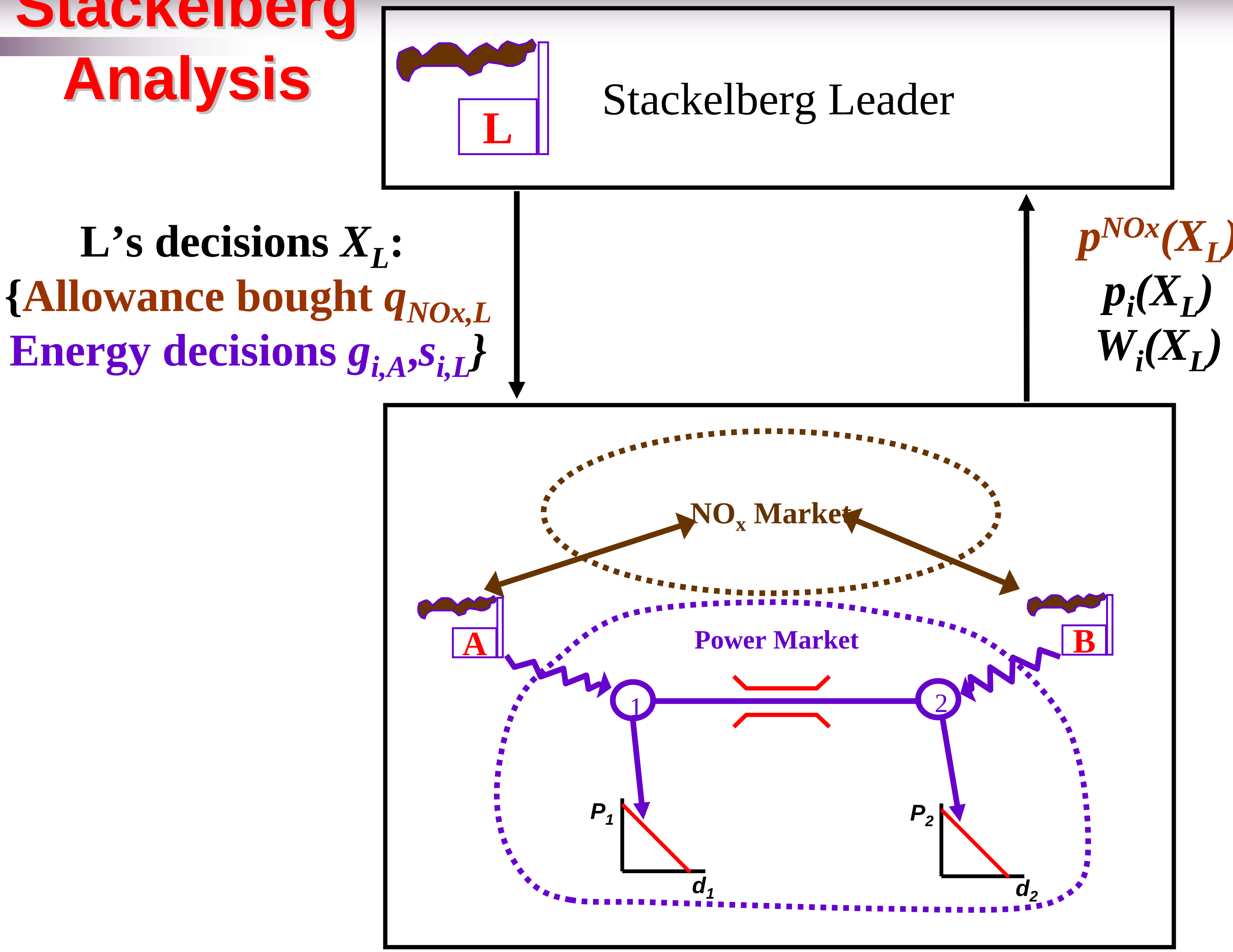
USEPA *NO_x* Program

- *Cap-and-Trade*
- *9 states participated in 2000*
- *Total Allowances: 195,401 tons*

Model Assumptions

- **Market structure**
  - *Generators compete to sign bilateral contracts*
  - *ISO provides transmission services between nodes*
- **Network**
  - *500 kV network: 14 nodes, 18 arcs, no transmission losses*
  - *Linearized "DC" load flow approximation: Power Transfer Distribution Factors (PTDFs)*
- **Producers**
  - *791 generation units*
  - *6 largest producers (capacity share: 4% to 18%)*
    - *Largest is Stackelberg leader*
    - *Others:*
      - *Cournot strategy in electricity market*
      - *Price taking in NO_x market*
  - *Remaining producers are price takers (3 producers)*
- **Consumers**
  - *Linear demand at each node*
  - *5 demand periods in ozone season*
- **ISO allocates transmission capacity to highest value**

Stackelberg Analysis



Stackelberg Leader's Problem

- *The firm with a longest position in NOx market and greatest power sales is designated as the leader:*

  q^w = *Stackelberg's NO_x withholding variable [tons]*

  $\overline{q}_f^{NO_x}$ = *Firm's available NO_x allowances [tons]*

$$MAX_{s_{if}, g_{if}, q^w} \sum_i \{[p_i(s_{if} + \sum_{g \neq f} s_{ig}) - W_i] s_{if} - [C_{if}(g_{if}) - W_i g_{if}]$$

$$- p^{NO_x}[E_f^{NO_x} - (\overline{q}_f^{NO_x} - q^w)]\}$$

s.t.: $g_{if} \leq CAP_{if}, \forall i$

$$\sum_i s_{if} = \sum_i g_{if}$$

$$s_{if}, g_{if} \geq 0, \forall i$$

$$0 \leq q^W \leq \overline{q}_f^{NO_x}$$

$$0 \leq p^{NO_x} \perp \sum_f (E_f^{NO_x} - \overline{q}_f^{NO_x}) + q^w \leq 0$$

- *Other Producer Complementarity Equilibrium Conditions*
- *Market Clearing Conditions*

ISO Optimization Problem Quadratic Loss Functions

- **ISO's decision variables:**
  - y_i = transmission service from hub to *i*
  - q_i^{Losses} = generation purchases from node *i* (to make up losses)
  - t_{ij} = positive flow from *i* to *j*
- **ISO's maximizes the "value of services" :**

$$MAX \quad \pi_{ISO}(t_{ij}, y_i, q_i^{Losses}) = \sum_i (W_i y_i - p_i q_i^{Losses})$$

$$s.t.: y_i - q_i^{Losses} + \sum_{j \in J(i)} (t_{ij} - (1 - L_{ji} t_{ji}) t_{ji}) \leq 0, \quad \forall i \qquad \textit{Kirchhoff's Current Law}$$

$$\sum_{(i,j) \in v(k)} R_{ij}(t_{ij} - t_{ji}) = 0, \quad \forall k, (i,j) \in v(k) \qquad \textit{Kirchhoff's Voltage Law}$$

$$\sum_i y_i = 0 \qquad \textit{Services Balance}$$

$$0 \leq t_{ij} \leq T_{ij}, \quad \forall i, j \qquad T_{ij} = \textit{capacity of line (i,j)}$$

$$q_i^{Losses} \geq 0, \quad \forall i$$

  - **Solution allocates transmission capacity to most valuable transactions**
- **Define the model's KKTs (complementarity conditions), one per variable $\underline{x}_{ISO}$**

Model Statistics

- 18,618 variables; 9739 constraints
  - Order of magnitude larger than test problems in R. Fletcher and S. Leyffer, “Numerical Experience with Solving MPECs as NLPs,” Univ. of Dundee, 2002
- Solved by PATH and SQP (SNOPT, FILTER) (Thanks to Todd Munson & Sven Leyffer!)
- 9,536 seconds (1.8 MHz Pentium 4)
  - Other MPECs took much less time

Stackelberg Results

Compared to the Cournot Case:

- ***Stackelberg leader:***
  - *withholds 5,536 tons of allowances (7.2% of total)*
  - *… increasing NO_x price from 0 to 1,173 [$/ton]*
- ***Output:***
  - *other producers shrink their power sales (87.4→83.5 x10^6 MWh) due to increased NO_x price*
  - *… while the leader expands its output (24.6→28.7 x10^6 MWh)*
- ***Profit:***
  - *Stackelberg leader earns more profit (893 → 970 M$)*
  - *… at the expense of other producers (2394 → 2273 M$)*
- ***Consumers:***
  - *are only marginally better off with a gain of 14 [M$] in consumer surplus, as power prices almost unchanged*

Conclusions

- *Detailed market representations make possible:*
  - *a variety of welfare and efficiency analyses,*
  - *insights on player strategies,*
  - *detailed distributions of impacts of policy*
- *B-NL analysis shows how models can quantify benefits of improving market efficiency*
- *Large scale Stackelberg models can be solved*
  - *Nonlinear (lossy) DC load flow*
  - *Leader maximizes subject to Cournot/fringe market equilibrium*
  - *Manipulating allowances market is profitable*