MODEL-BASED ANALYSIS OF THE EUROPEAN ENERGY SUPPLY SECURITY

MODELING PROCESS AND INTERMEDIATE RESULTS FOR THE SUPPLY SECURITY OF NATURAL GAS

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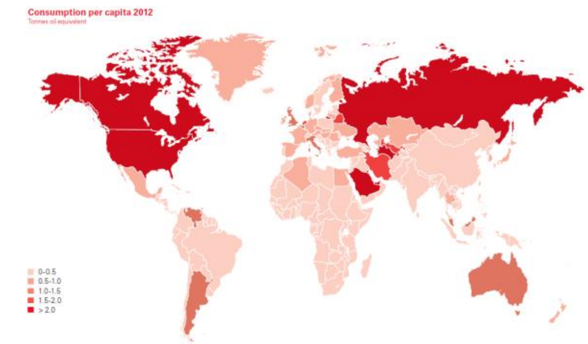
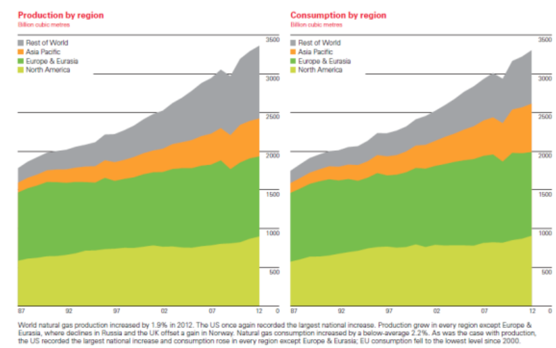
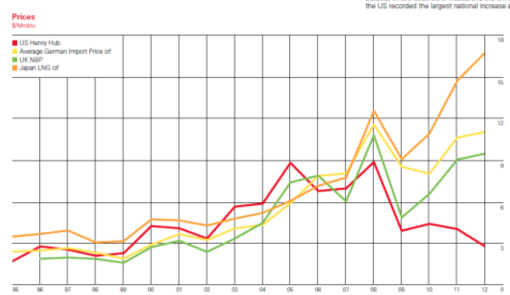


Consumption per capita 2012



Production by region
Consumption by region



Prices

1. INTRODUCTION

PROJECT SCOPE

ANALYSIS OF THE EUROPEAN SUPPLY SECURITY OF ENERGY

- Electricity
- Gas
- Oil

WITH RESPECT TO POTENTIAL THREATS

- Societal (e.g. terroristic attacks)
- Economical (e.g. financial crisis)
- Natural (e.g. landslide)

MEDIUM-TERM PERSPECTIVE

i.e. analysis of the reaction of the energy systems within days to months

Includes, e.g.

- Oil crisis in the 1970'
- Russian-Ukrainian gas conflicts 2006/2009/present
- German nuclear power phase-out 2011

Does not include, e.g.

- Lightning, causing a line outage
- Climate change

REQUIREMENTS & CHOICE OF MODEL TYPE

REQUIREMENTS

Model should be able to represent

- Energy system reaction within days to months to unexpected changes (threats)
- Multiple interacting energy carriers

CHOICE OF MODEL TYPE

Market equilibrium model

- Allows for representation of the coupling between energy prices and their production/consumption
- Energy carriers are coupled via their relative prices and conversion factors
- Allows for comparison of counterfactual situations (market equilibria before and after the threat)
- Does not allow for analysis of transient system behavior

Project decision: start with natural gas

2. BACKGROUND ON NATURAL GAS MARKETS

GAS MARKET STRUCTURE

WORLD-WIDE

- Regional market segmentation as a consequence of capital-intensive infrastructure and high transportation cost
- Development of infrastructure for liquefied natural gas (LNG) shipping leads to converging prices between regions

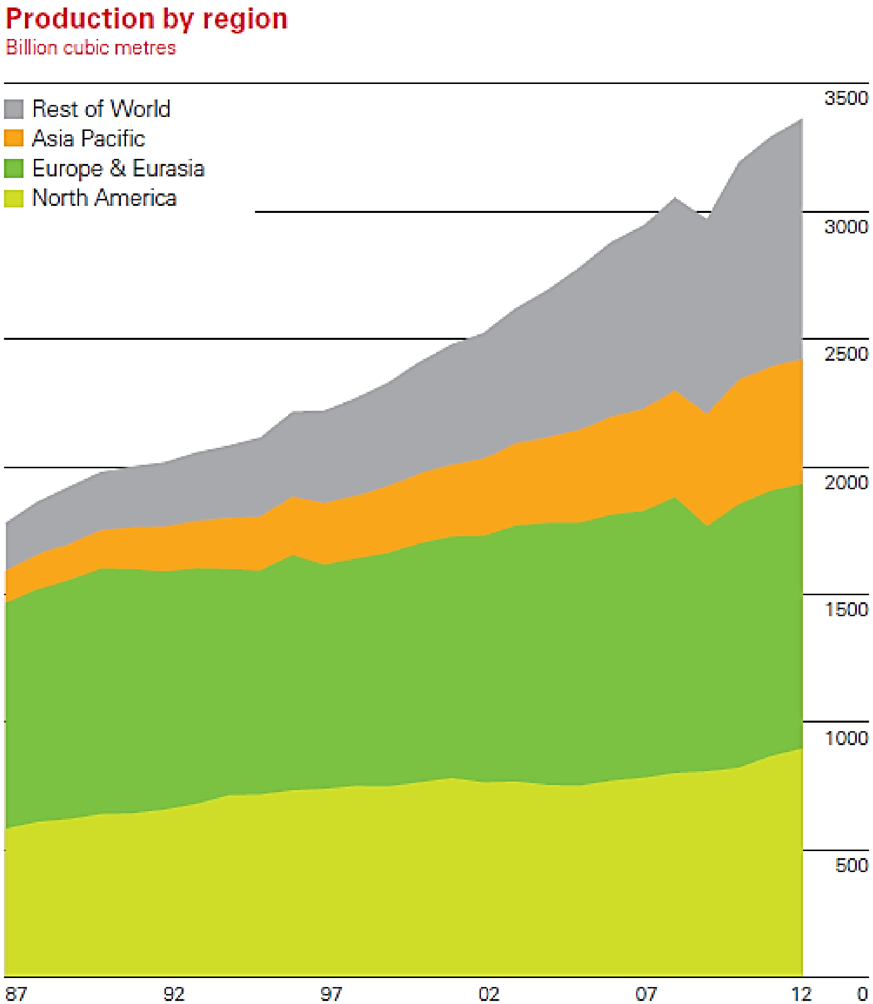
EUROPE

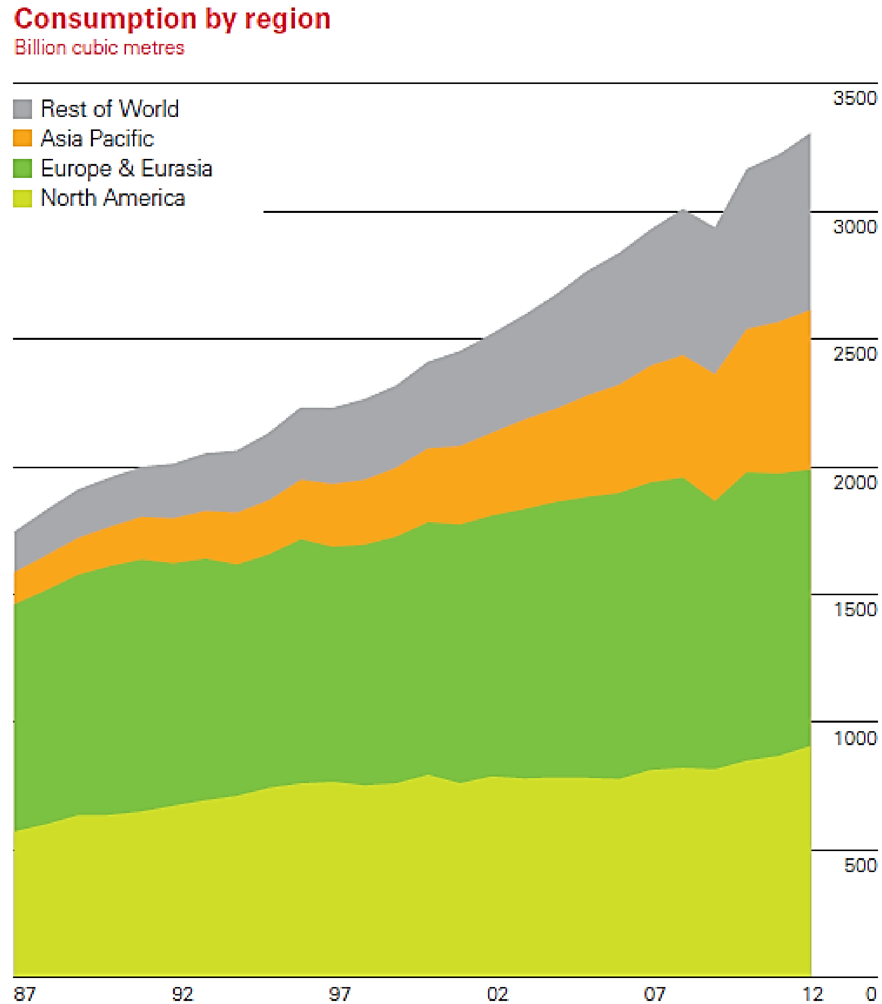
- Traditionally, gas has been traded based on oil-indexed long-term (30y) contracts
- Since 1990s: liberalization and creation of a single EU market
- In 2012: 44% spot-priced volumes (increasing)

SWITZERLAND

- No plans for liberalization, however:
  - large consumers can choose their supplier (since 1964)
  - Swiss gas industry agreed on a common tariff calculation method for 3rd party access

WORLD-WIDE PRODUCTION AND CONSUMPTION OF GAS



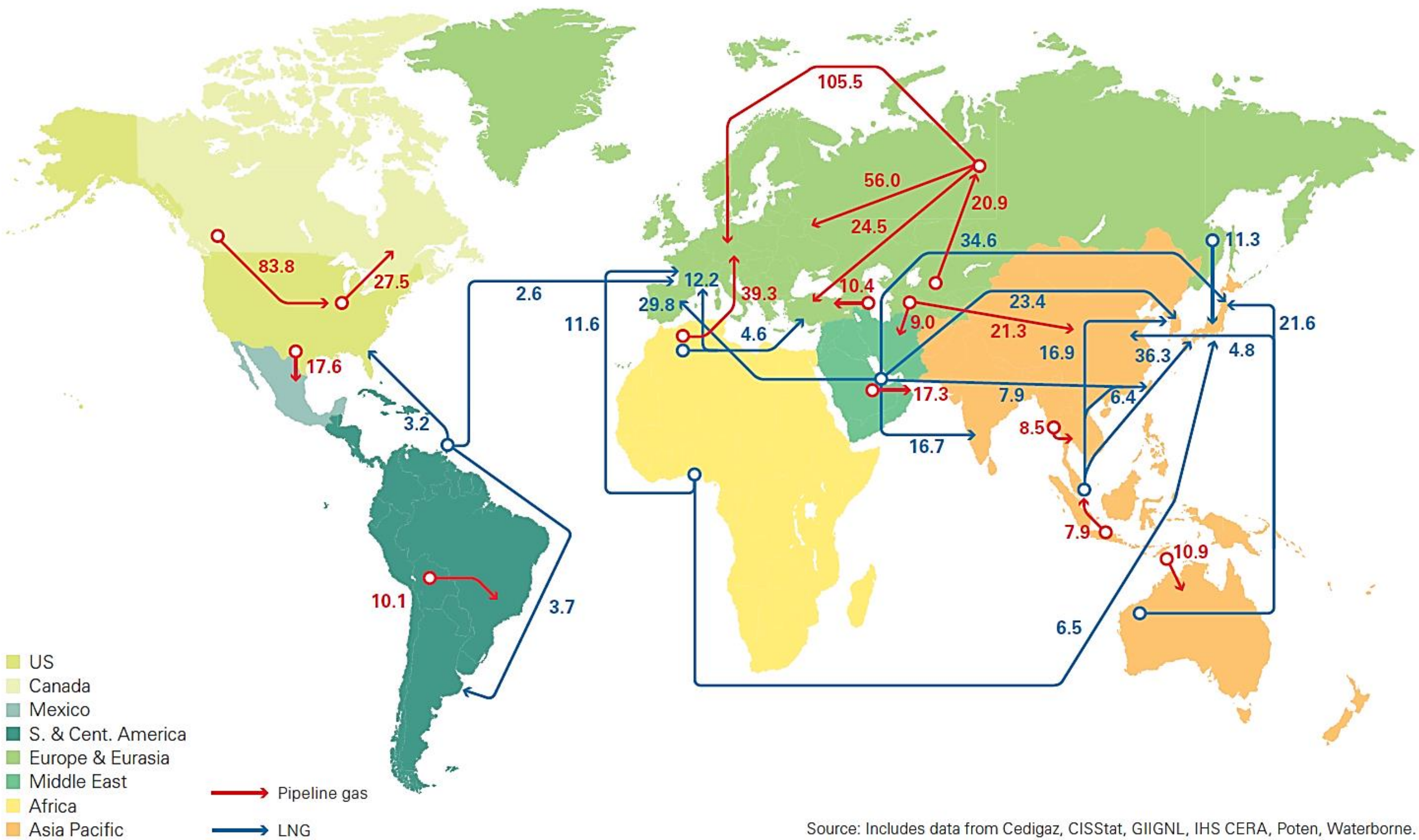


Source: BP

WORLD-WIDE TRADE OF GAS

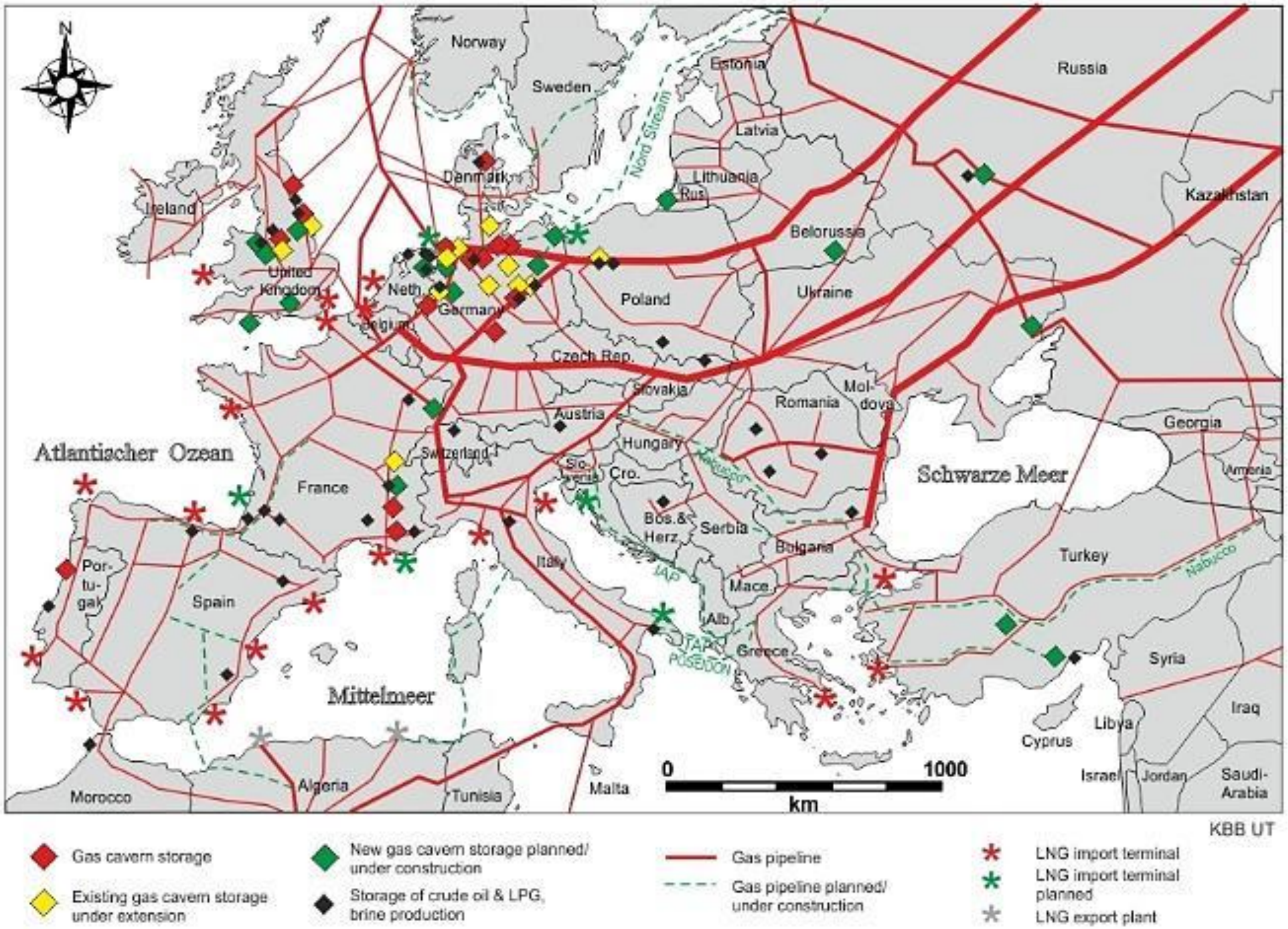
Major trade movements 2012

Trade flows worldwide (billion cubic metres)

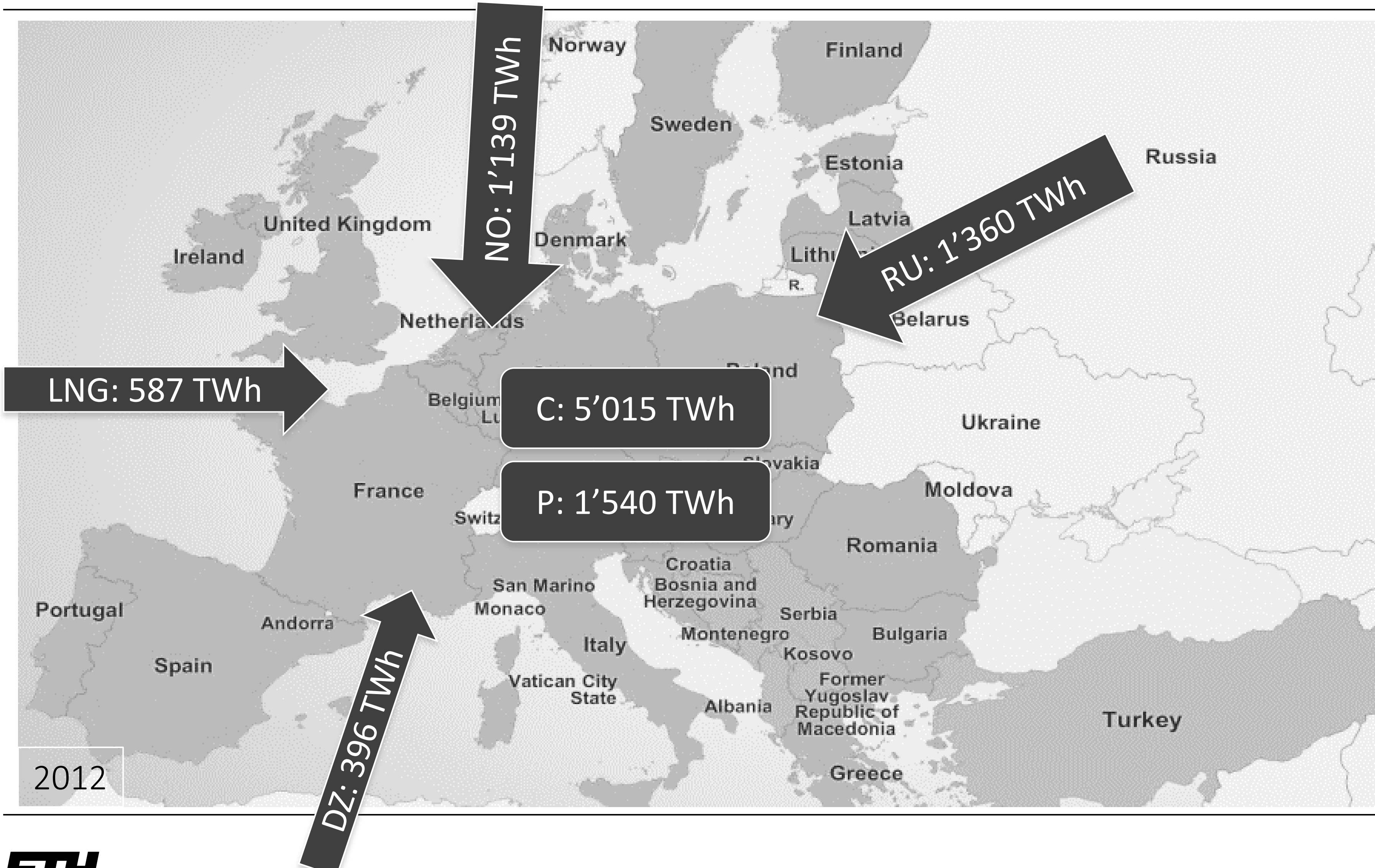


Source: Includes data from Cedigaz, CISStat, GIIGNL, IHS CERA, Poten, Waterborne.

EUROPEAN GAS INFRASTRUCTURE



EU: CONSUMPTION, PRODUCTION AND IMPORTS

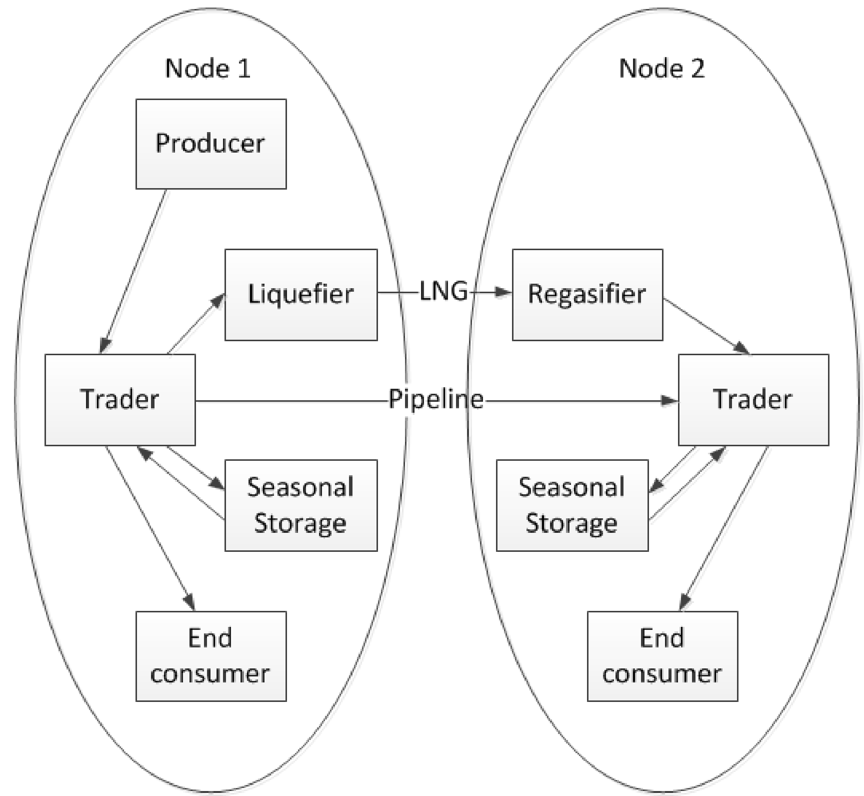


SWITZERLAND: CONSUMPTION AND IMPORTS

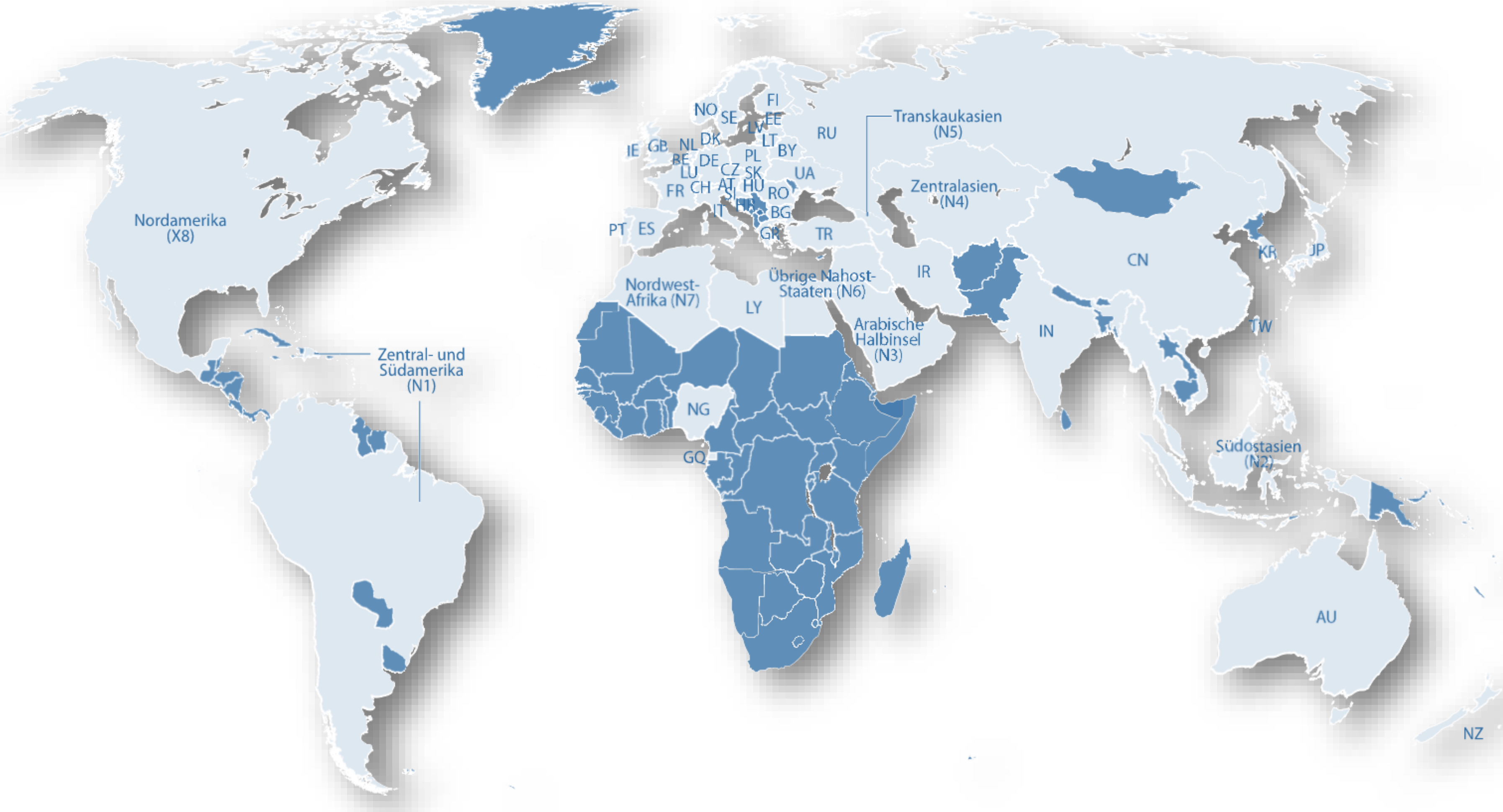
3. ENERGY MARKET MODEL

MARKET REPRESENTATION

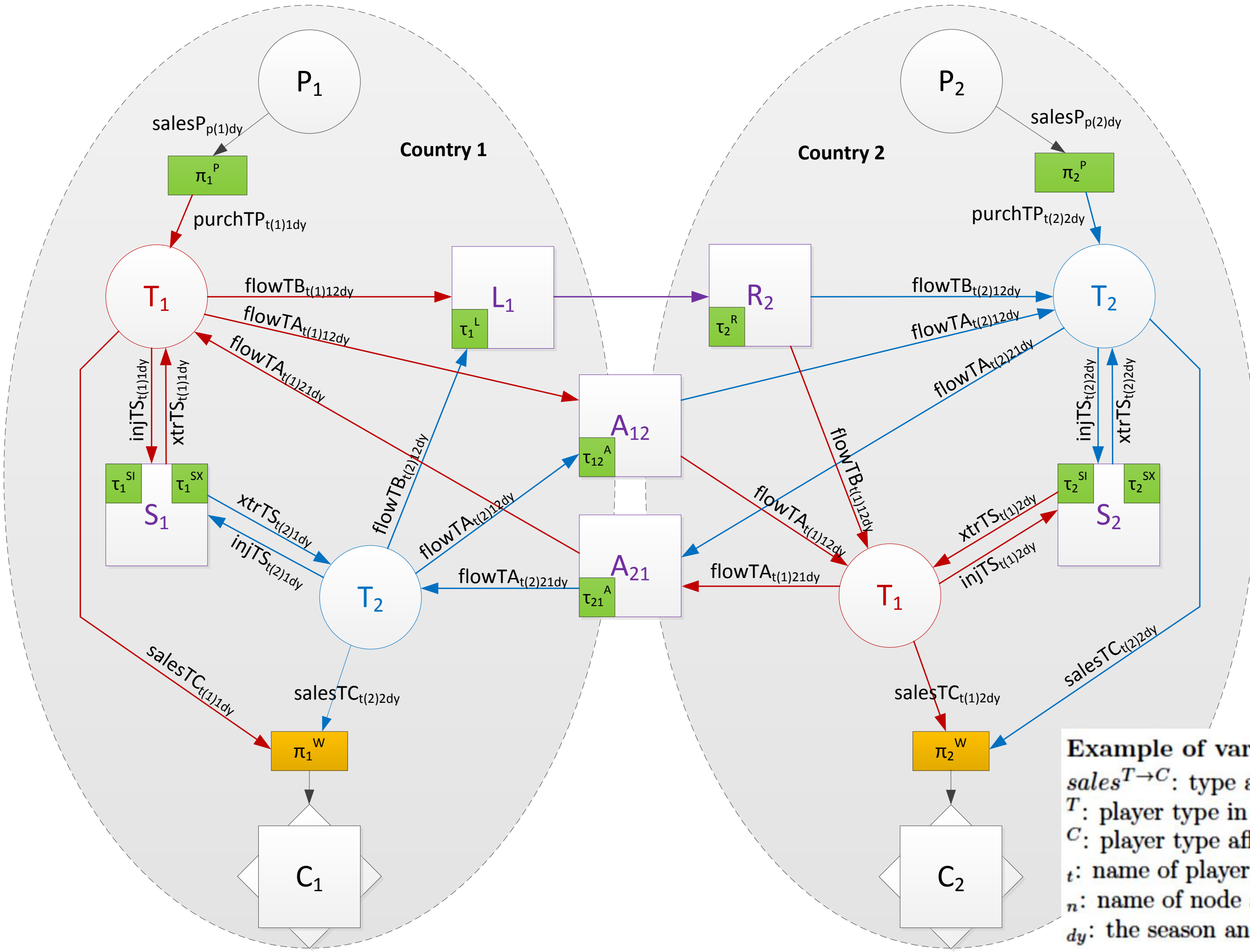
- Each country / group of countries is represented as a node
- Pipelines and LNG transportation is represented as links between nodes
- At each node, several economic actors exchange gas on several markets
- Producers, traders and service providers optimize a quadratic objective function over the time period of one year
- The traders are modelled to have «market power», i.e. they have knowledge about the consumer reaction to changes in supply
- The consumers are divided into 3 sectors (households & commercial consumers, industrial consumers and electricity producers); each sector is modelled by an affine inverse demand curve



GRANULARITY AND COVERAGE



DETAILED MODEL SCHEME AND NOMENCLATURE



Legend

Economic acteurs
P: Producers
T: Traders

System Services
L: Liquefiers
R: Regasifiers
S: Storage operators
C: Consumers
A: Pipelines

Market prices
π^P: Transfer price producer -> trader
π^W: Wholesale price trader -> consumer

Conjestion fees
τ^{SI}: Storage injection
τ^{SX}: Storage extraction
τ^L: Liquefaction
τ^R: Regasification
τ^A: Pipelines

Perfect competition
Cournot market power

Example of variable notation: $sales^{T \to C}_{tndy}$

$sales^{T \to C}$: type and direction of transaction,
^{T}: player type in action,
^{C}: player type affected,
${}_t$: name of player,
${}_n$: name of node at which transaction takes place,
${}_{dy}$: the season and year transaction takes place in.

MODEL EQUATIONS: PRODUCERS

Producers' Objective Function

$$\max_{sales^P_{pdy}} \sum_{y\in Y}\sum_{d\in D} days_d \left(\pi^P_{n(p)dy}\cdot sales^P_{pdy} - c^P_p(sales^P_{pdy})\right) \quad \forall p$$

$$s.t. \quad sales^P_{pdy} \leq \overline{PR}^P_p \quad (\alpha^P_{pdy}) \quad \forall p,d,y,$$

$$\sum_{y\in Y}\sum_{d\in D} days_d \cdot sales^P_{pdy} \leq \overline{PROD}_p \quad (\beta^P_p) \quad \forall p,$$

$$sales^P_{pdy} \geq 0 \quad \forall p,d,y$$

Income - Production cost

Production upper bound

Dual variables

Non-negativity constraints

Producers' KKT conditions

$$0 \leq days_d\left(-\pi^P_{n(p)dy} + \frac{dc^P_p(sales^P_{pdy})}{dsales^P_{pdy}}\right) + \alpha^P_{pdy} + days_d\cdot\beta^P_p \perp sales^P_{pdy} \geq 0 \quad \forall p,d,y$$

$$0 \leq \overline{PR}^P_p - sales^P_{pdy} \perp \alpha^P_{pdy} \geq 0 \quad \forall p,d,y$$

$$0 \leq \overline{PROD}_p - \sum_{y\in Y}\sum_{d\in D} days_d\cdot sales^P_{pdy} \perp \beta^P_p \geq 0 \quad \forall p$$

Allows for representation as linear complementarity problem

Production Cost Function

$$c^P_p(sales^P_{pdy}) = k + a^P_p\cdot sales^P_{pdy} + b^P_p\cdot(sales^P_{pdy})^2$$

$$\frac{dc^P_p(sales^P_{pdy})}{dsales^P_{pdy}} = a^P_p + 2b^P_p\cdot sales^P_{pdy}$$

MODEL EQUATIONS: TRADERS

Traders' Objective Function

$$\max_{\substack{sales^{T\to C}_{tndy}\\ flow^{TA}_{tnmdy}\\ flow^{TB}_{tnmdy}\\ inj^{TS}_{tndy}\\ xtr^{TS}_{tndy}\\ purch^{T\leftarrow P}_{tndy}}} \sum_{y\in Y}\sum_{d\in D} days_d \Bigg[\sum_{n\in N(t)} \Big[\Big(\delta^C_{tndy}\cdot \Pi^{W(T)}_{ndy}(\cdot) + (1-\delta^C_{tndy})\cdot \pi^W_{ndy}\Big)\cdot sales^{T\to C}_{tndy} - \pi^P_{ndy}\cdot purch^{T\leftarrow P}_{tndy}\Big] - \sum_{n\in S(t)} \Big(\big(\tau^{SI,reg}_{sdy} + \tau^{SI}_{sdy}\big)\cdot inj^{TS}_{tndy} + \tau^{SX}_{sdy}\cdot xtr^{TS}_{tndy}\Big) - \sum_{(n,m)\in A(t)} \big(\tau^A_{nmdy} + \tau^{A,reg}_{nmdy}\big)\cdot flow^{TA}_{tnmdy} - \sum_{(n,m)\in B(t)} \big(\tau^L_{ndy} + \tau^{L,reg}_{ndy}\big)\cdot flow^{TB}_{tnmdy} - \sum_{(n,m)\in B(t)} \tau^{B,reg}_{nmdy}\cdot (1-loss^L_n) flow^{TB}_{tnmdy} - \sum_{(n,m)\in B(t)} \big(\tau^R_{mdy} + \tau^{R,reg}_{mdy}\big)\cdot (1-loss^L_n)(1-loss^B_{nm}) flow^{TB}_{tnmdy} \Bigg] \quad \forall t$$

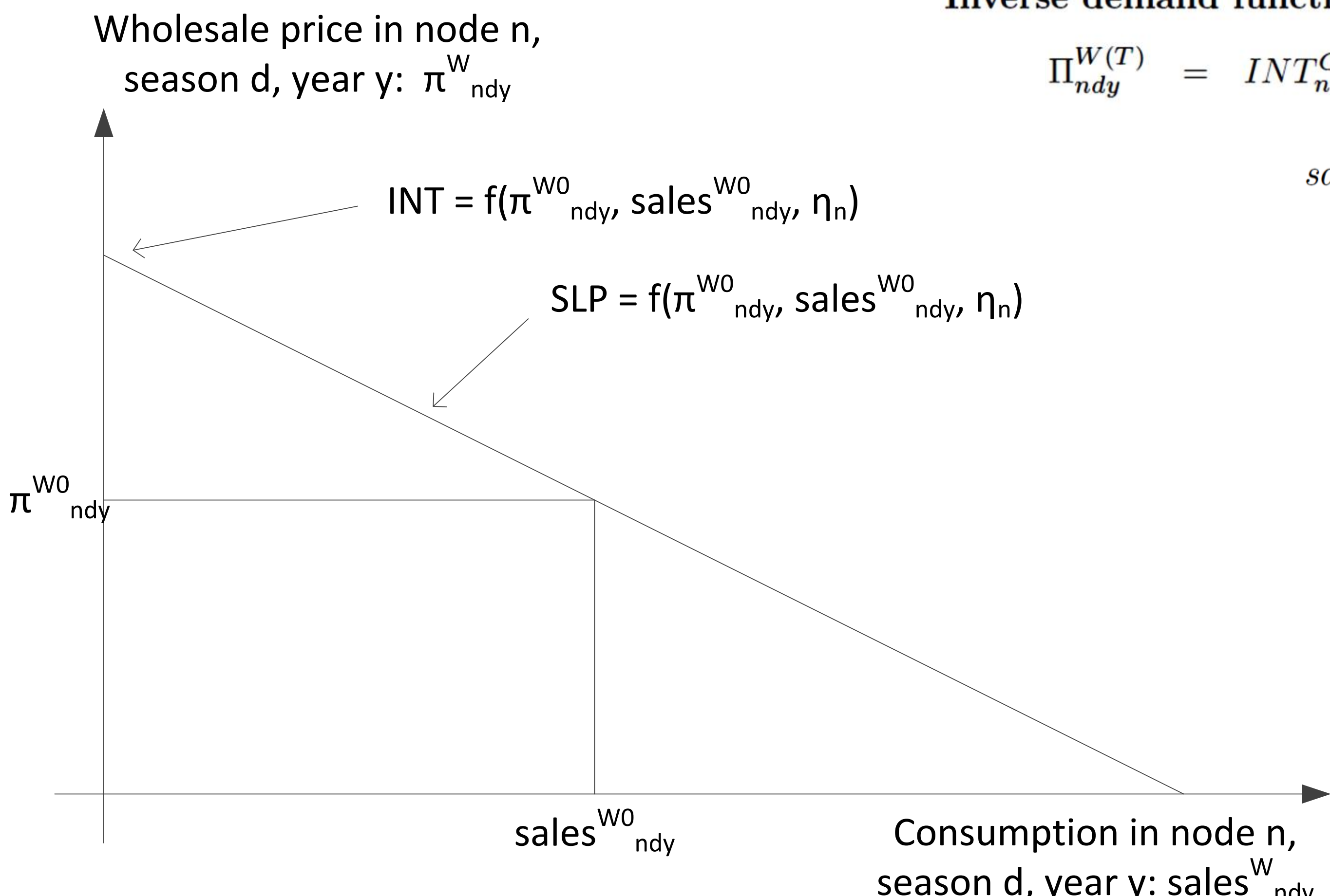
Income - Purchasing cost

- Storage cost
- Pipeline transportation cost
- Liquefaction cost
- Shipping cost
- Regasification cost

Inverse demand function

$$\Pi^{W(T)}_{ndy} = INT^C_{ndy} - SLP^C_{ndy} \sum_{t\in T(n)} \cdot sales^{T\to C}_{tndy}$$

MODEL EQUATIONS: INVERSE DEMAND FUNCTION



Inverse demand function

$$\Pi^{W(T)}_{ndy} = INT^{C}_{ndy} - SLP^{C}_{ndy} \sum_{t \in T(n)} sales^{T \to C}_{tndy}$$

$$sales^{W}_{ndy} := \sum_{t \in T(n)} sales^{T \to C}_{tndy}$$

Price sensitivity η_n= -0.75 … -0.25

MODEL EQUATIONS: TRADERS

$$
\begin{aligned}
s.t.\quad & purch_{tndy}^{T\leftarrow P} + \sum_{m\in N_s(A(n))} (1-loss_{mn}^{A})\cdot flow_{tmndy}^{TA} \\
& + \sum_{m\in N_s(B(n))} (1-loss_{m}^{L})(1-loss_{mn}^{B})(1-loss_{n}^{R}) flow_{tmndy}^{TB} + xtr_{tndy}^{T\rightarrow S} = \\
& sales_{tndy}^{T\rightarrow C} + \sum_{m\in N_e(A(n))} flow_{tnmdy}^{TA} + \sum_{m\in N_e(B(n))} flow_{tnmdy}^{TB} + inj_{tndy}^{T\rightarrow S} \quad (\phi_{tndy}^{T}) \quad \forall n\in N(t), d, y, \\
& sales_{tndy}^{T\rightarrow C} \geq \underline{obl}_{tndy}^{TC} \quad (\epsilon_{tndy}^{TC}) \quad \forall\{t; n(c)\}, d, y, \\
& sales_{tndy}^{T\rightarrow C} \leq \overline{res}_{tndy}^{TC} \quad (\alpha_{tndy}^{TC}) \quad \forall\{t; n(c)\}, d, y, \\
& purch_{tndy}^{T\leftarrow P} \geq 0 \quad \forall\{t; n(p(t))\}, d, y, \\
& flow_{tnmdy}^{TA} \geq 0 \quad \forall\{t; a(t)\}, d, y \\
& flow_{tnmdy}^{TB} \geq 0 \quad \forall\{t; b(t)\}, d, y \\
& inj_{tdy}^{T\rightarrow S} \geq 0 \quad \forall\{t; s(t)\}, d, y \\
& xtr_{tdy}^{T\rightarrow S} \geq 0 \quad \forall\{t; s(t)\}, d, y
\end{aligned}
$$

Mass balance

Lower & upper bounds

MODEL EQUATIONS: STORAGE OPERATORS

Storage Operators' Objective Function

$$\max_{sales^{SI}_{sdy},\ sales^{SX}_{sdy}} \sum_{y \in Y} \sum_{d \in D} days_d \cdot \left[\tau^{SI}_{sdy} \cdot sales^{SI}_{sdy} + \tau^{SX}_{sdy} \cdot sales^{SX}_{sdy}\right] \quad \forall s$$

$$\begin{aligned}
s.t. \quad & sales^{SI}_{sdy} \le \overline{CAP}^{SI}_{s} \quad (\alpha^{SI}_{sdy}) \quad \forall s, d, y \\
& sales^{SX}_{sdy} \le \overline{CAP}^{SX}_{s} \quad (\alpha^{SX}_{sdy}) \quad \forall s, d, y \\
& \sum_{d \in D} days_d \cdot sales^{SX}_{sdy} \le \overline{WG}^{S}_{s} \quad (\alpha^{SW}_{sy}) \quad \forall s, y \\
& sales^{SI}_{sdy} \ge 0 \quad \forall s, d, y \\
& sales^{SX}_{sdy} \ge 0 \quad \forall s, d, y
\end{aligned}$$

MODEL EQUATIONS: TRANSMISSION SYSTEM OPERATORS

TSO's Objective Function

$$\max_{sales^A_{nmdy},\, sales^L_{ndy},\, sales^R_{mdy}} \sum_{y \in Y} \sum_{d \in D} days_d \left[\sum_{(n,m) \in A} \tau^A_{nmdy} \cdot sales^A_{nmdy} + \sum_{n \in N_s(B)} \tau^L_{ndy} \cdot sales^L_{ndy} + \sum_{n \in N_e(B)} \tau^R_{ndy} \cdot sales^R_{ndy} \right]$$

$$\begin{aligned}
s.t. \quad & sales^A_{nmdy} \leq \overline{CAP}^A_{nmy} \quad (\alpha^A_{nmdy}) \quad \forall (n,m) \in A, d, y, \\
& sales^L_{ndy} \leq \frac{\overline{CAP}^{L,in}_{ny}}{1 - loss^L_n} \quad (\alpha^L_{ndy}) \quad \forall n \in N_s(B), d, y, \\
& sales^R_{ndy} \leq \frac{\overline{CAP}^{R,in}_{ny}}{1 - loss^R_n} \quad (\alpha^R_{ndy}) \quad \forall n \in N_e(B), d, y, \\
& sales^A_{nmdy} \geq 0 \quad \forall (n,m) \in A, d, y, \\
& sales^L_{ndy} \geq 0 \quad \forall n \in N_s(B), d, y, \\
& sales^R_{ndy} \geq 0 \quad \forall n \in N_e(B), d, y
\end{aligned}$$

MODEL EQUATIONS: MARKET CLEARING CONDITIONS

$$0 = \sum_{p \in P(n)} \left(sales^{P}_{pdy} - purch^{T \leftarrow P}_{t(p)ndy} \right), \quad \pi^{P}_{ndy}(\text{free}) \quad \forall n \in N(P), d, y \tag{12}$$

$$0 = sales^{A}_{nmdy} - \sum_{t \in T(n,m)} flow^{TA}_{tnmdy}, \quad \tau^{A}_{nmdy}(\text{free}) \quad \forall (n,m) \in A, d, y \tag{13}$$

$$0 = sales^{L}_{ndy} - \sum_{t \in T(n,m)} \sum_{m \in N_e(B)} flow^{TB}_{tnmdy}, \quad \tau^{L}_{ndy}(\text{free}) \quad \forall n \in N_s(B), d, y \tag{14}$$

$$0 = sales^{R}_{mdy} - \sum_{t \in T(n,m)} \sum_{n \in N_s(B)} flow^{TB}_{tnmdy} \cdot (1 - loss^{L}_{n})(1 - loss^{B}_{nm}), \quad \tau^{R}_{mdy}(\text{free}) \quad \forall m \in N_e(B), d, y \tag{15}$$

$$0 = sales^{SI}_{sdy} - \sum_{t \in T(N(s))} inj^{TS}_{tsdy}, \quad \tau^{SI}_{sdy}(\text{free}) \quad \forall s, d, y \tag{16}$$

$$0 = sales^{SX}_{sdy} - \sum_{t \in T(N(s))} xtr^{TS}_{tsdy}, \quad \tau^{SX}_{sdy}(\text{free}) \quad \forall s, d, y \tag{17}$$

$$0 = \pi^{W}_{ndy} - \left(INT^{C}_{ndy} - SLP^{C}_{ndy} \cdot \sum_{t \in T(n)} sales^{T \rightarrow C}_{tndy} \right), \quad \pi^{W}_{ndy}(\text{free}) \quad \forall n \in N(C), d, y \tag{18}$$

MATHEMATICAL FORMULATIONS

LINEAR COMPLEMENTARITY PROBLEM

$$\mathbf{0} \leq \boldsymbol{Mx} + \boldsymbol{q} \perp \boldsymbol{x} \geq \mathbf{0}$$

$$M = \begin{pmatrix} \boldsymbol{A} & -\boldsymbol{B}^{\boldsymbol{T}} & -\boldsymbol{C}^{\boldsymbol{T}} \\ \boldsymbol{B} & \mathbf{0} & \mathbf{0} \\ \boldsymbol{C} & \mathbf{0} & \boldsymbol{D} \end{pmatrix}$$

A: diagonal, psd

D: diagonal, pd

EQUIVALENT QP FORMULATION

min $\boldsymbol{x}^{\boldsymbol{T}}\boldsymbol{Q}\boldsymbol{x} + \boldsymbol{q}^{\boldsymbol{T}}\boldsymbol{x}$

s.t. $\boldsymbol{Mx} + \boldsymbol{q} \geq \mathbf{0}$

$\boldsymbol{x} \geq \mathbf{0}$

$$Q = \begin{pmatrix} \boldsymbol{A} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \boldsymbol{D} \end{pmatrix}$$

Q: diagonal, psd

LCP feasible if $\min \boldsymbol{x}^{\boldsymbol{T}}\boldsymbol{Q}\boldsymbol{x} + \boldsymbol{q}^{\boldsymbol{T}}\boldsymbol{x} = 0$

4. CALIBRATION

MODEL CALIBRATION

CALIBRATION VARIABLES

- Base case wholesale price: π^{W0}_{ndy} ➔ $\pi^{W,M}_{ndy}$
- (Base case consumption: $sales^{W0}_{ndy}$ ➔ $sales^{W,M}_{ndy}$)
- Node-specific market power: δ^{C}_{ndy} ➔ [0…1]

  [The trader-specific market power is fixed beforehand, and the overall market power is $\delta^{C}_{tndy} = f(\delta^{C}_{t}, \delta^{C}_{ndy})$]

CALIBRATION PROCEDURE

- For now: by iteration
- In future: formulate optimization problem
  - leads to an MPEC (Mathematical Problem with Equilibrium Constraints)

CALIBRATION FORMULAS

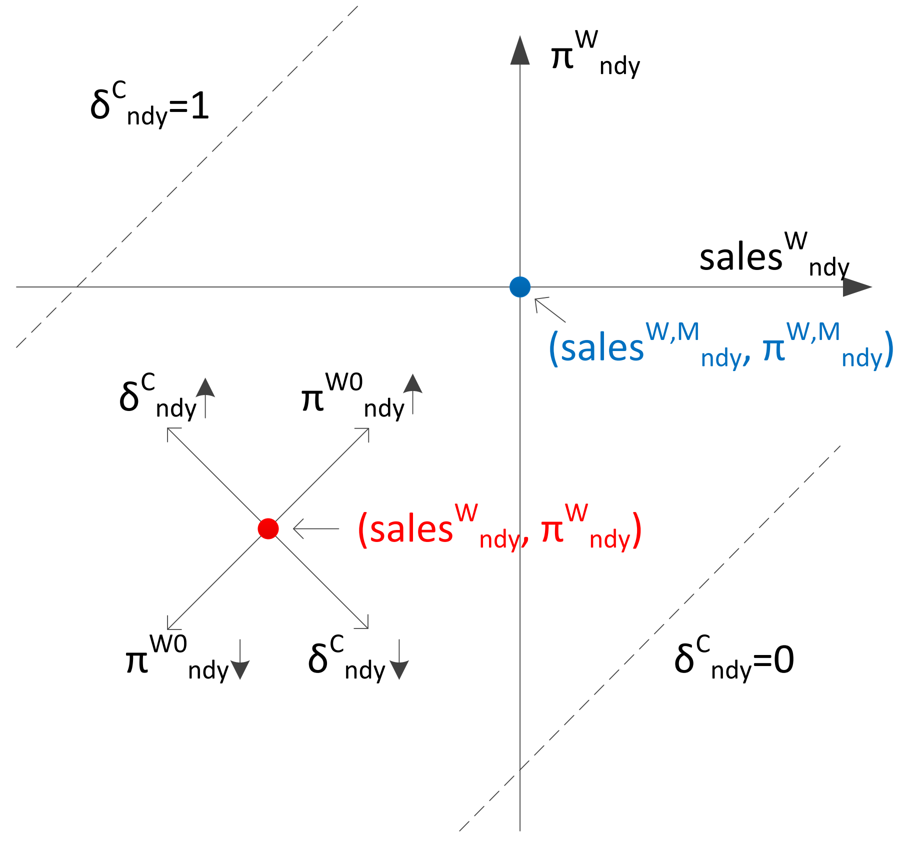
$$\delta^{C}_{ndy}(k+1) = \delta^{C}_{ndy}(k) + \gamma_{\delta^{C}_{ndy}} \cdot \left(-\frac{\pi^{W}_{ndy}(k)}{\pi^{W,M}_{ndy}} + \frac{sales^{W}_{ndy}(k)}{sales^{W,M}_{ndy}}\right)$$

$$\pi^{W0}_{ndy}(k+1) = \pi^{W0}_{ndy}(k) + \gamma_{\pi^{W0}_{ndy}} \cdot \left(-\frac{sales^{W}_{ndy}(k)}{sales^{W,M}_{ndy}}\right)$$

TERMINATION CRITERIA

$|sales^{W}_{ndy}(k) / sales^{W,M}_{ndy} - 1| < TOL$ AND

$|\pi^{W0}_{ndy}(k) / \pi^{W,M}_{ndy} - 1| < TOL$ OR δ^{C}_{ndy}, π^{W0}_{ndy} don't change anymore



Note: calibrated parameters are not unique

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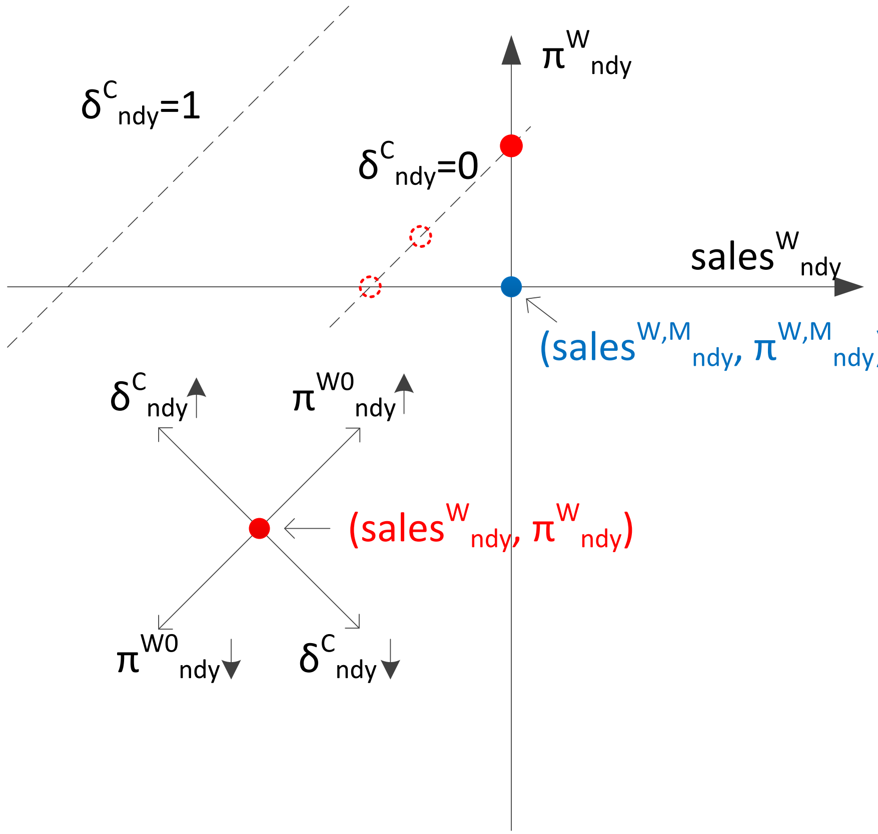
$$\pi^{W0}_{ndy}(k+1) = \pi^{W0}_{ndy}(k) + \gamma_{\pi^{W0}_{ndy}} \cdot \left(-\frac{sales^{W}_{ndy}(k)}{sales^{W,M}_{ndy}}\right)$$

TERMINATION CRITERIA

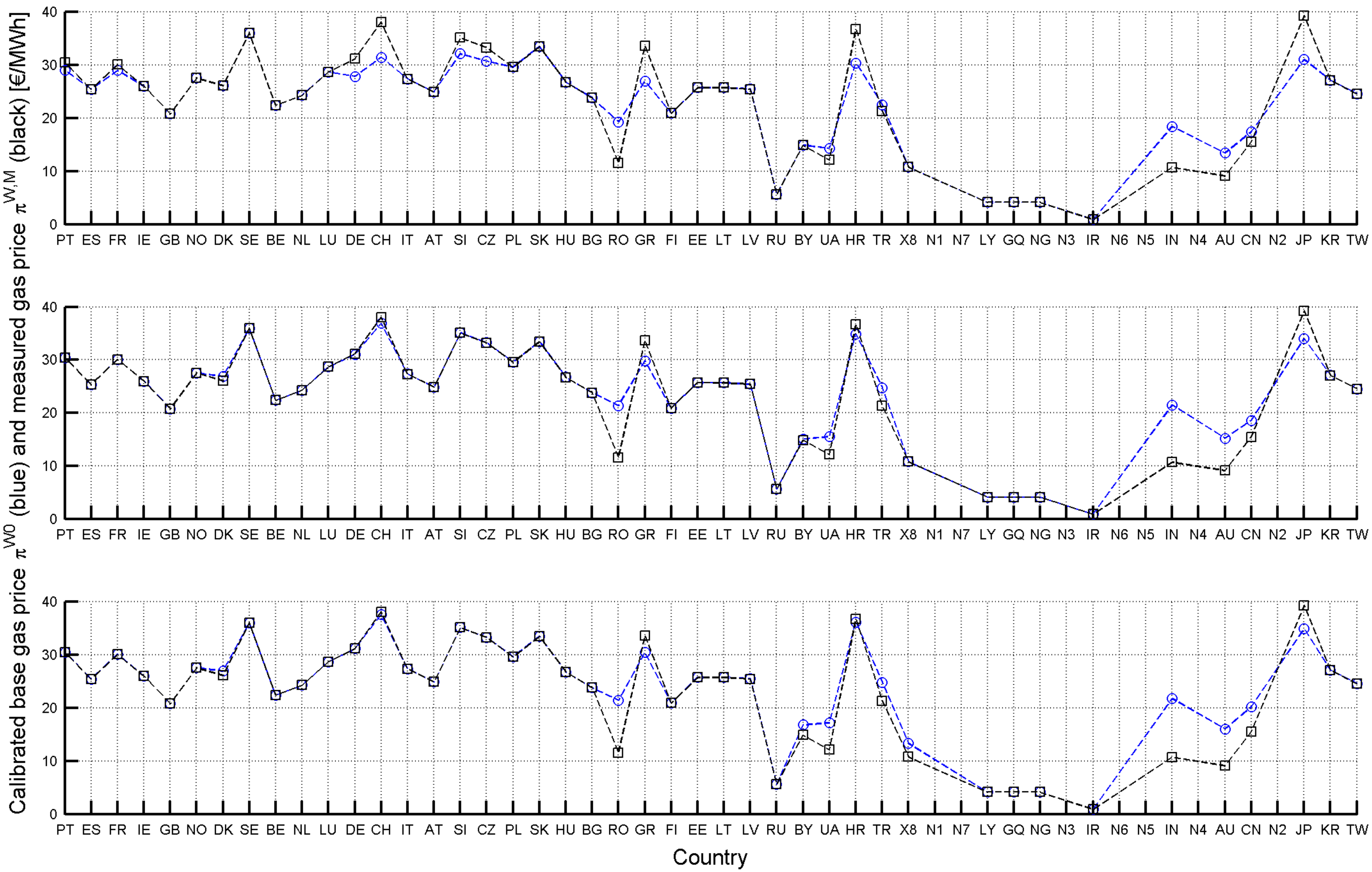
$|sales^{W}_{ndy}(k) / sales^{W,M}_{ndy} - 1| < TOL$ AND

$|\pi^{W0}_{ndy}(k) / \pi^{W,M}_{ndy} - 1| < TOL$ OR δ^{C}_{ndy}, π^{W0}_{ndy} don't change anymore



Note: calibrated parameters are not unique

CALIBRATION RESULTS: MEASURED AND CALIBRATED PRICES



5. SENSITIVITY ANALYSIS

SETUP & RESULTS

VARIATION OF MOST UNCERTAIN PARAMETERS

Base case wholesale price π^{W0}_{ndy}

- [-50%, -10%, +10%, +50%]

Node-specific market power δ^{C}_{ndy}

- [-0.5, -0.1, +0.1, +0.5]

Price sensitivity η_{n}

- [-0.2, -0.1, +0.1, +0.2]

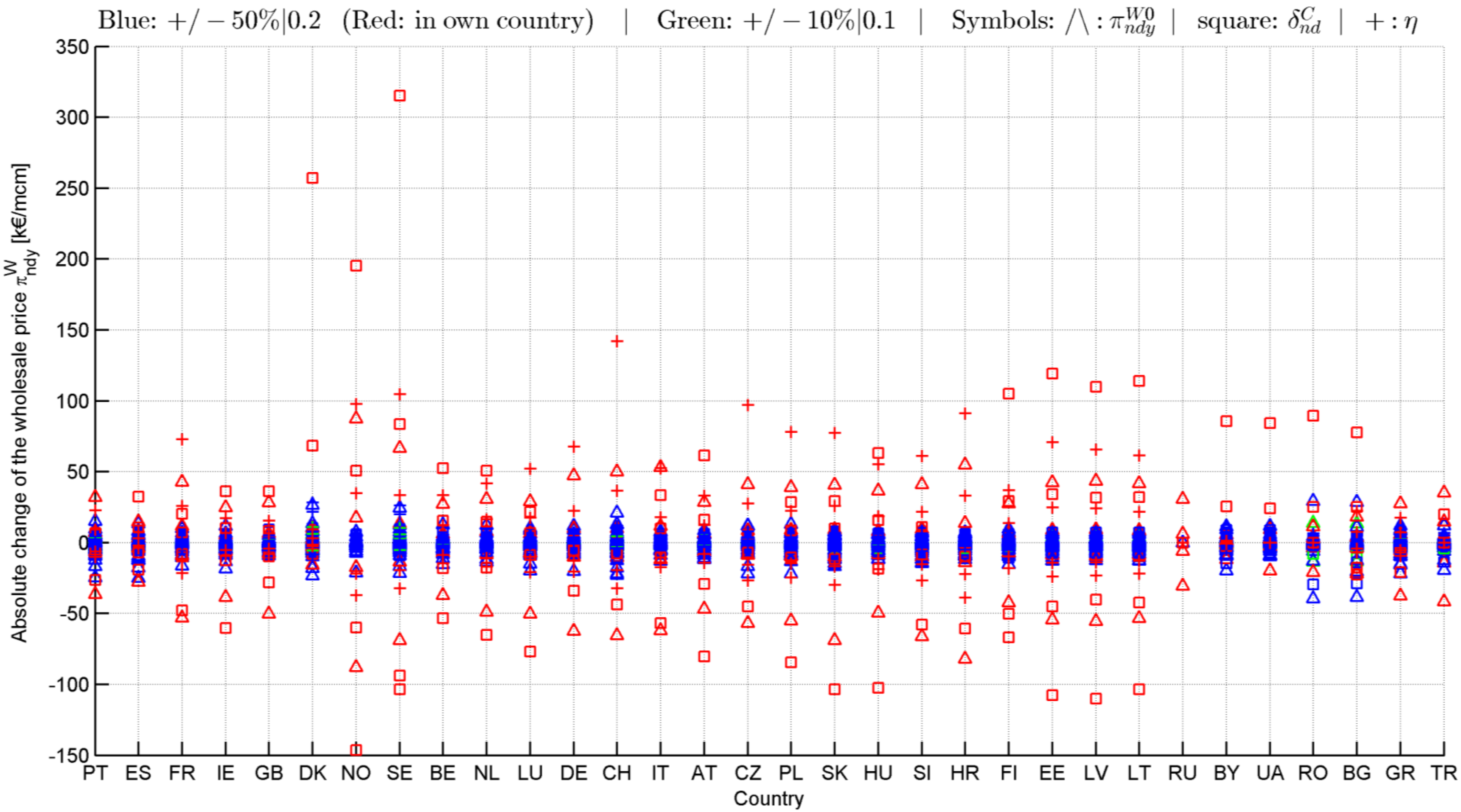
RESULTS

Overall satisfying:

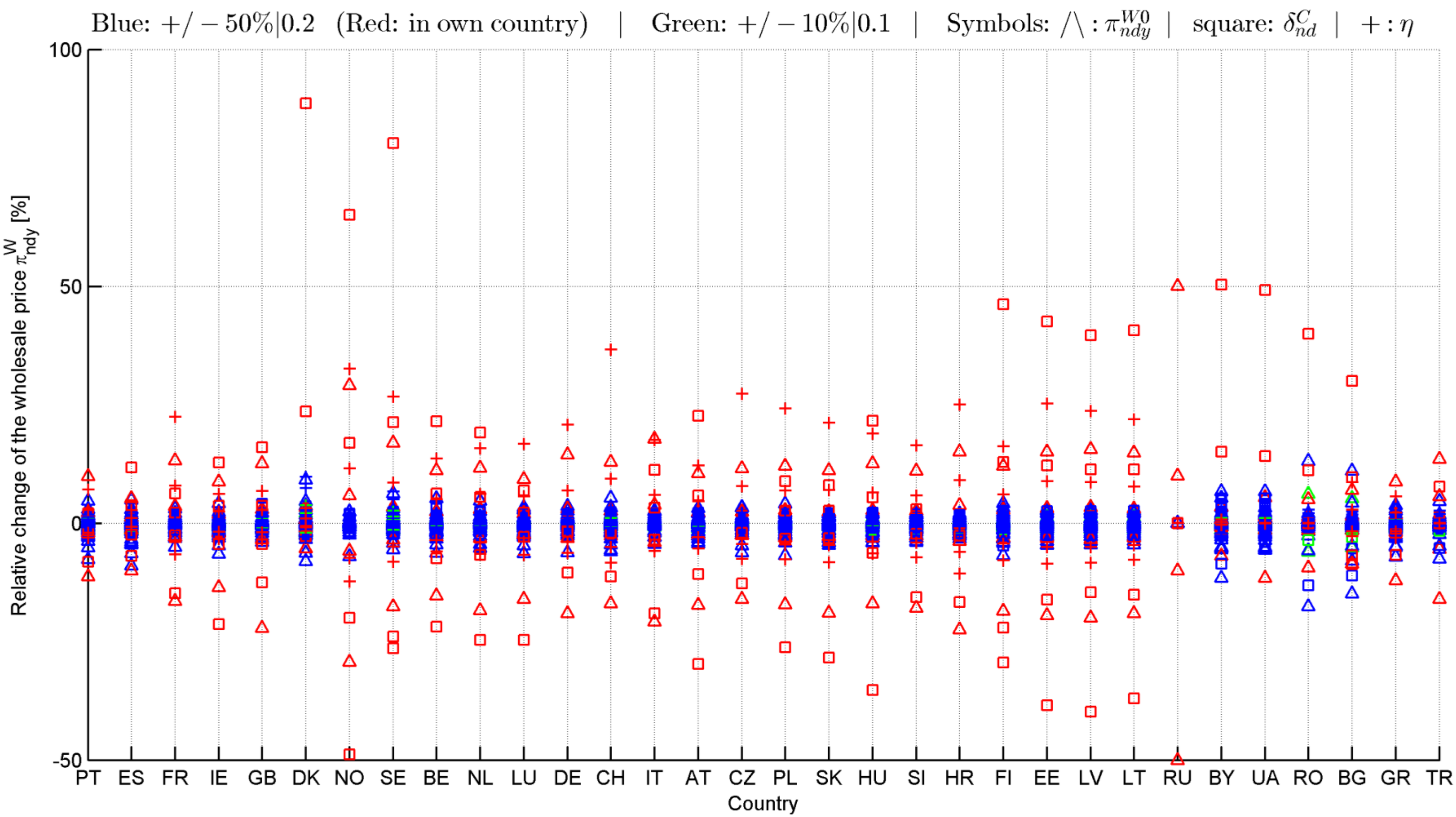
- Country, in which the parameter is changed, is affected the most (red symbols)
  - Especially high change of $sales^{W}_{ndy}$ if π^{W0}_{ndy} is varied
- In all other countries, π^{W}_{ndy} and $sales^{W}_{ndy}$ only change moderately (blue symbols)
  - $|\pi^{W}_{ndy} - \pi^{W0}_{ndy}| < 20\%$
  - $|\, sales^{W}_{ndy} - sales^{W0}_{ndy} \,| < 8\%$

➔ the cases, which lead to particularly high changes can be dealt with separately if required

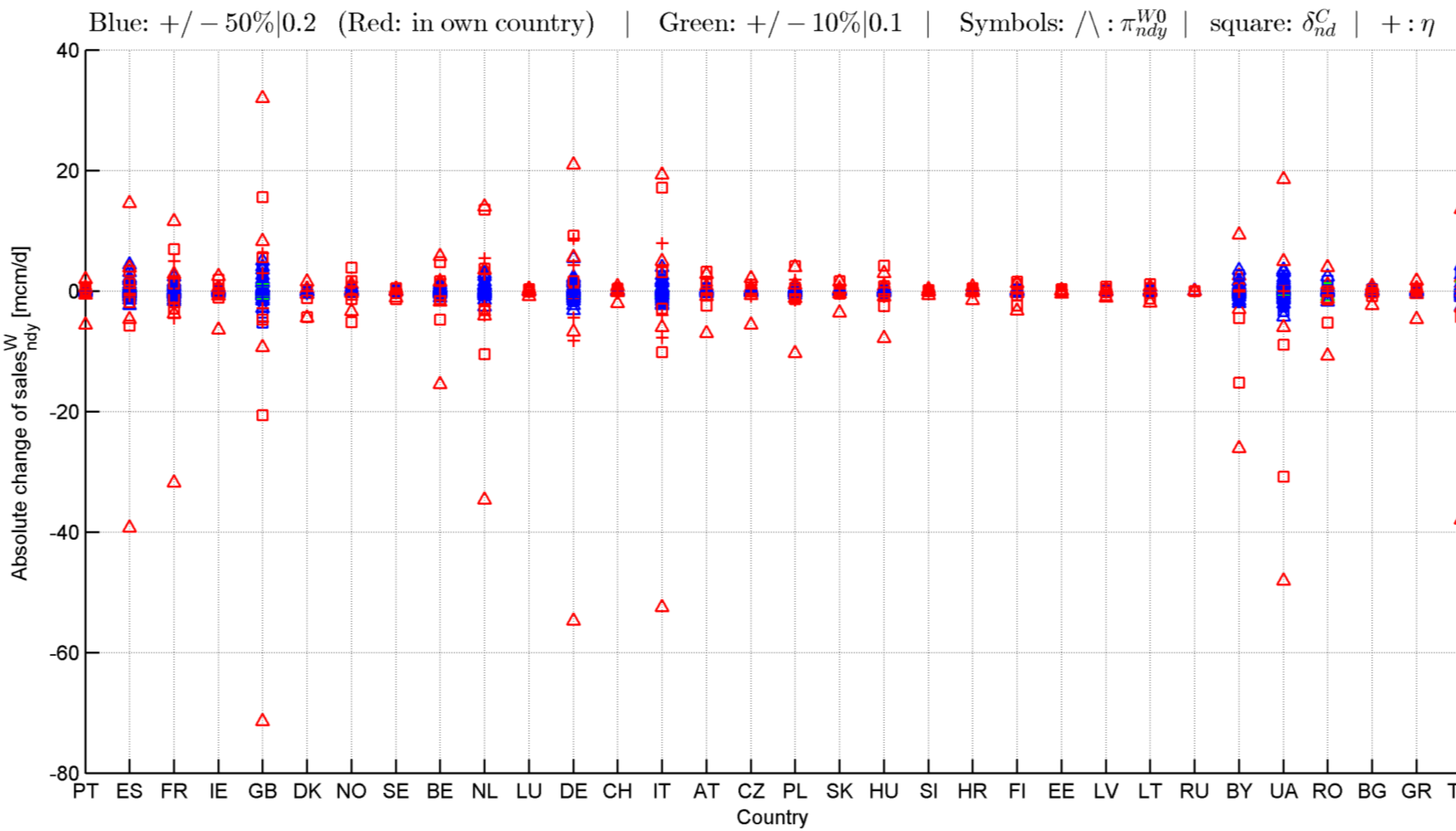
ABSOLUTE PRICE CHANGE



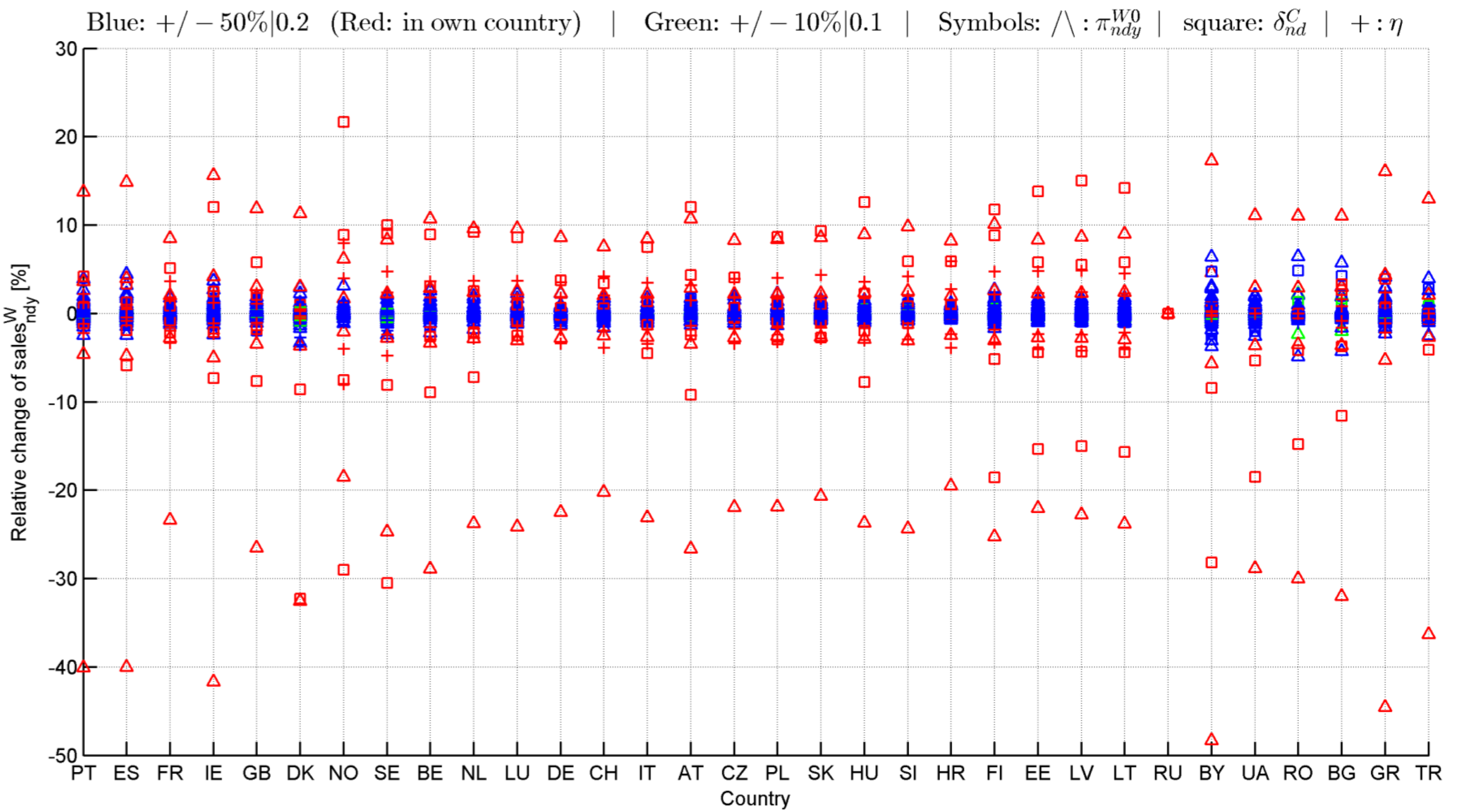
RELATIVE PRICE CHANGE



ABSOLUTE CONSUMPTION CHANGE



RELATIVE CONSUMPTION CHANGE



6. INTERMEDIATE RESULTS AND OUTLOOK

PLANNED CASE STUDIES

CONSEQUENCES FROM CUTBACKS IN

- Production
- Pipeline capacities
- Liquefaction and Regasification capacities

CONSEQUENCES OF THE EXPANSION OF

- Pipeline capacities
- Liquefaction and Regasification capacities
- Possibly coupled to a future gas market setting

ANALYZE EUROPEAN MARKET DYNAMICS

- Which countries are affected/can profit the most by which cutbacks/network expansions
- How can these burdens/gains be shared efficiently
- Is a top-down regulation necessary, or can the EU member states implement efficient measures by their own

FUTURE WORK (REQUIRES SUBSTANTIAL MODEL EXTENSION):

COUPLE TO OTHER ENERGY CARRIERS

- Couple gas, electricity, coal & oil markets
- Estimate price changes for the consumer taking the overall energy system into account, e.g.,
  - If a shock occurs in one market
  - If taxes are raised on certain carriers
  - …

LINK CUTBACKS MORE SPECIFICALLY TO THREATS

- Co-work with a risk-management specialist

EXAMPLE CASE STUDIES

RUSSIAN EMBARGO OF EUROPE

EU DIVERSIFICATION STRATEGY

- Expansion of regasification capacities (in all countries, proportional to existing capacity)

EU AND N-AMERICAN JOINT ACTION

- Expansion of EU regasification capacities
- Simultaneous increase of N-American liquefaction capacities

EU AND N-AMERICAN JOINT ACTION <-> ROBUSTNESS IN CASE OF A RUSSIAN EMBARGO

- Increase of EU R-capacity
- Increase of N-American L-capacity
- Russian embargo of EU

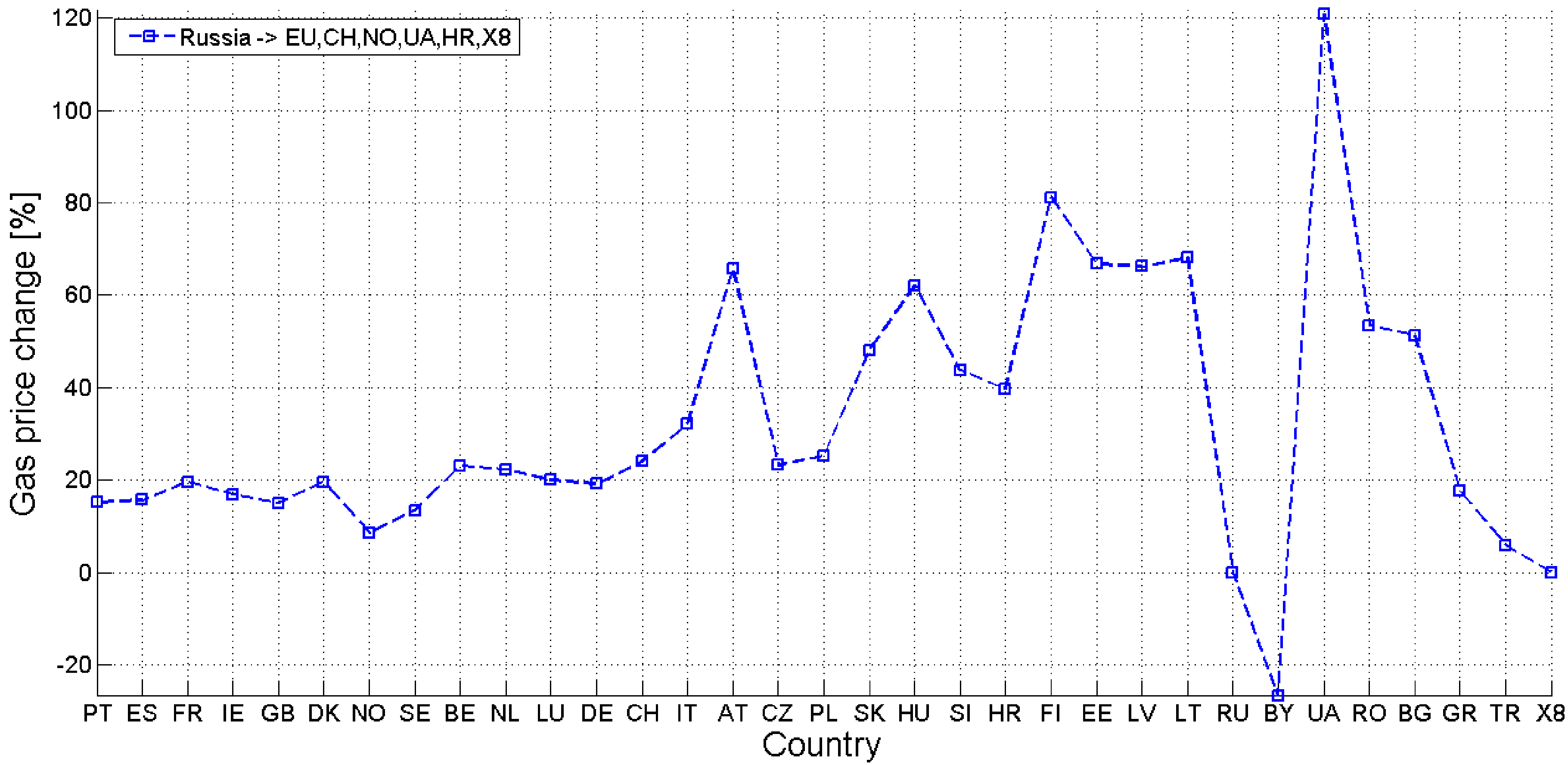
GUIDING QUESTIONS:

- Which countries benefit? Which ones loose?
- Which countries pay for the benefits (of others)?

THE RESULTS IN CONTEXT:

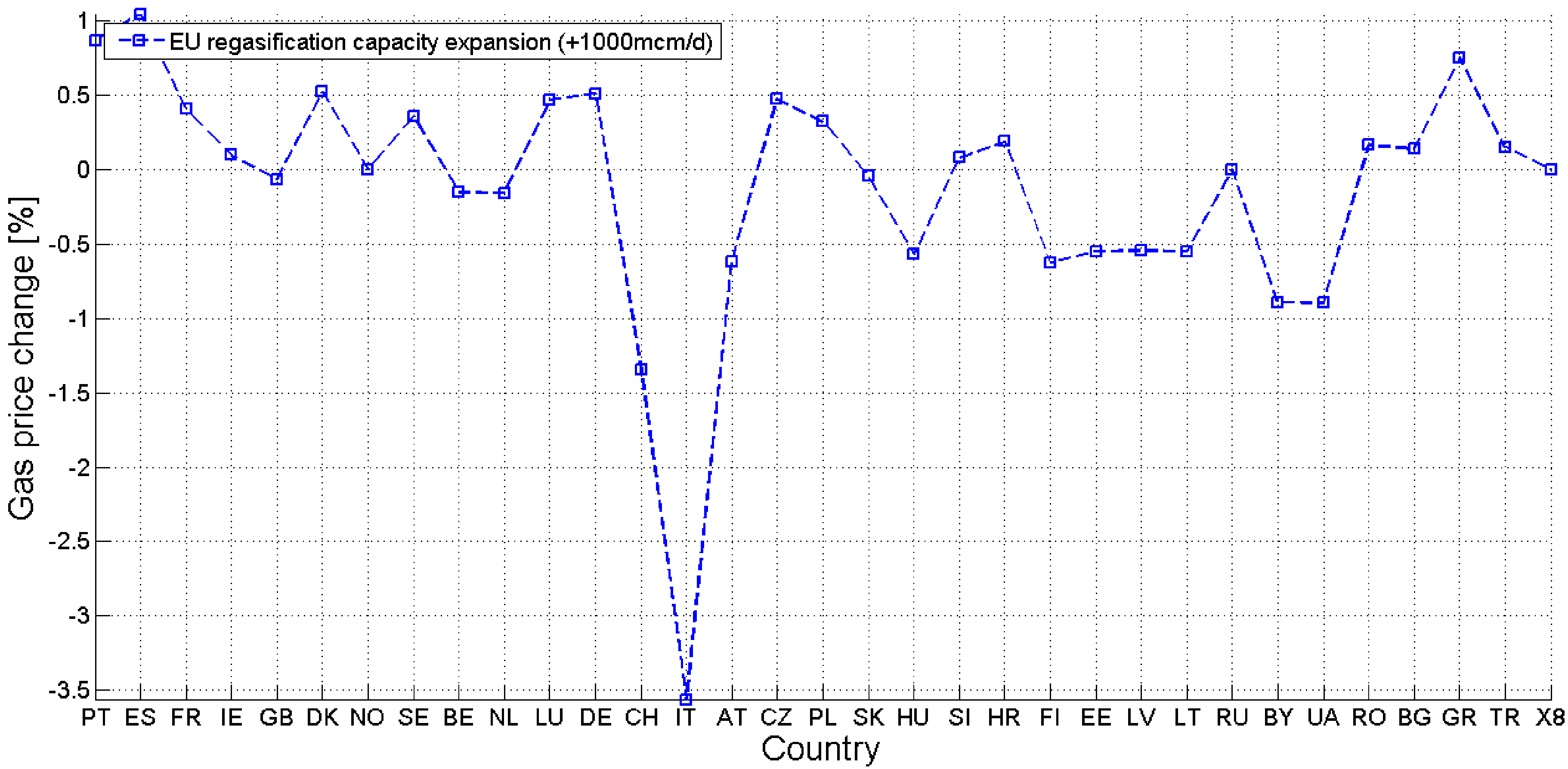
- Which scenarios are likely?
- Accuracy of results
  - Cf. sensitivity analysis
  - Interferences with other (not modeled) energy systems?
  - e.g.: electricity, coal markets, expansion of renewable capacities

RUSSIAN EMBARGO OF EUROPE



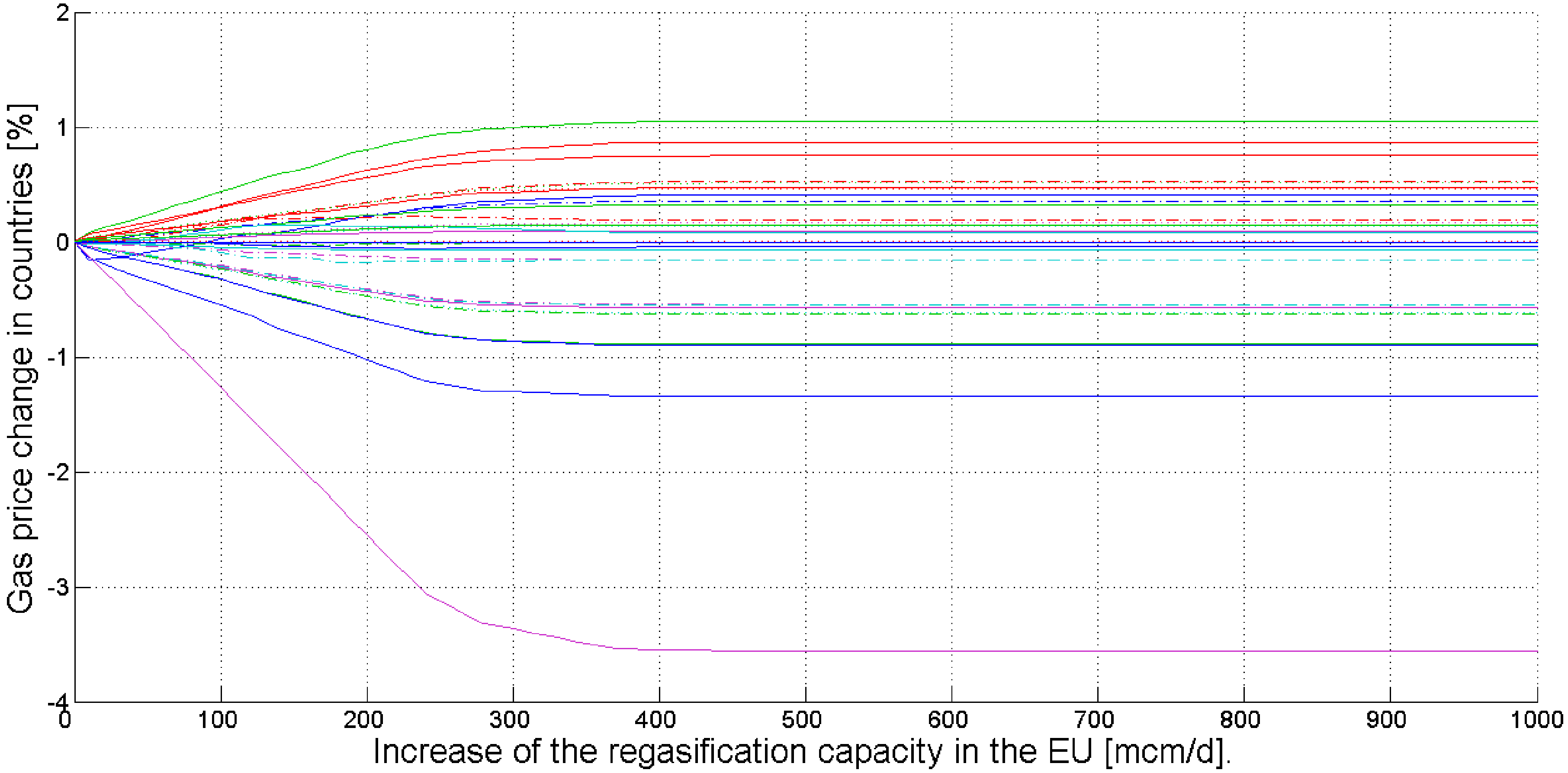
X8: N-America

EU DIVERSIFICATION STRATEGY

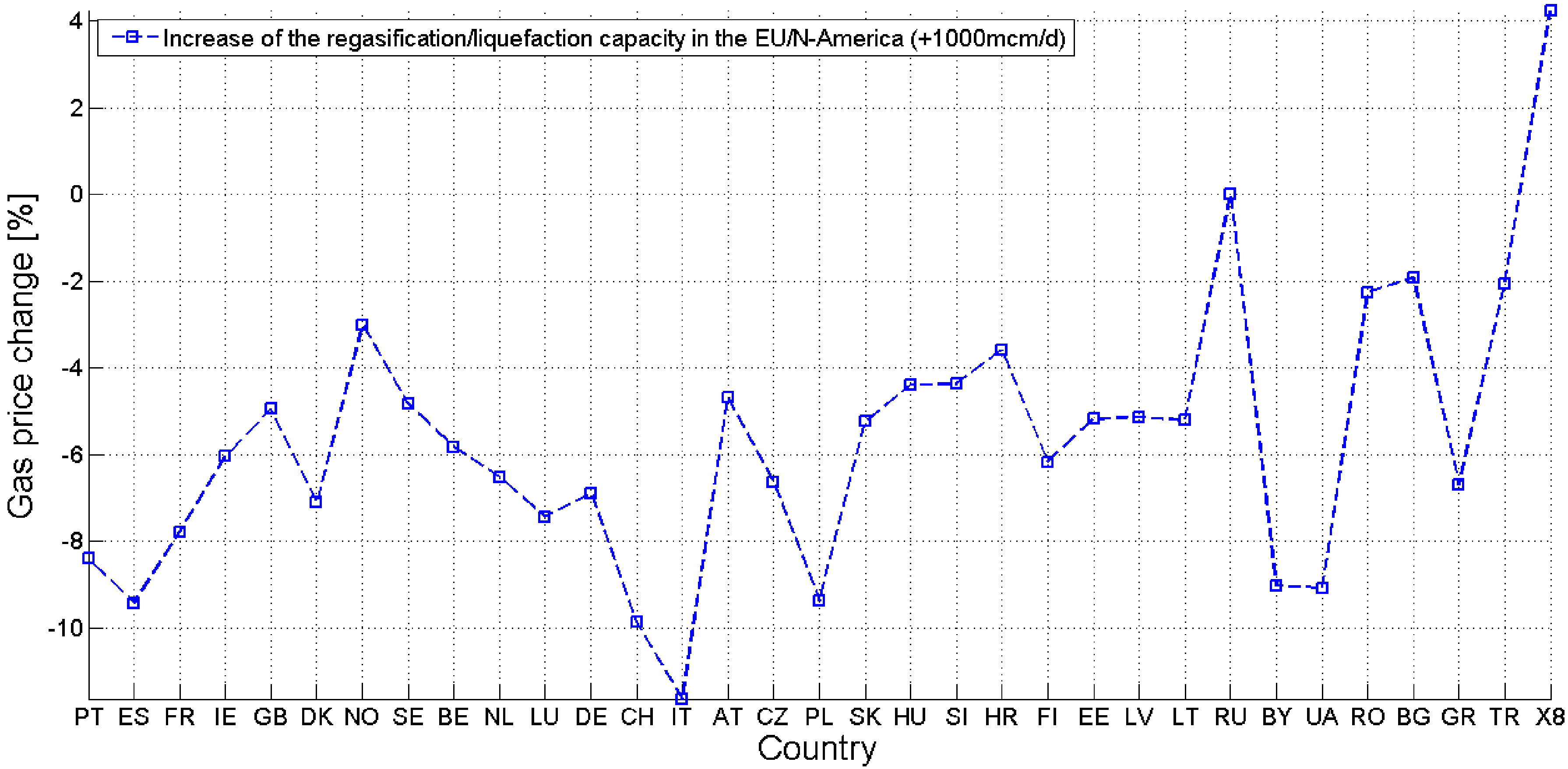


X8: N-America

EU DIVERSIFICATION STRATEGY

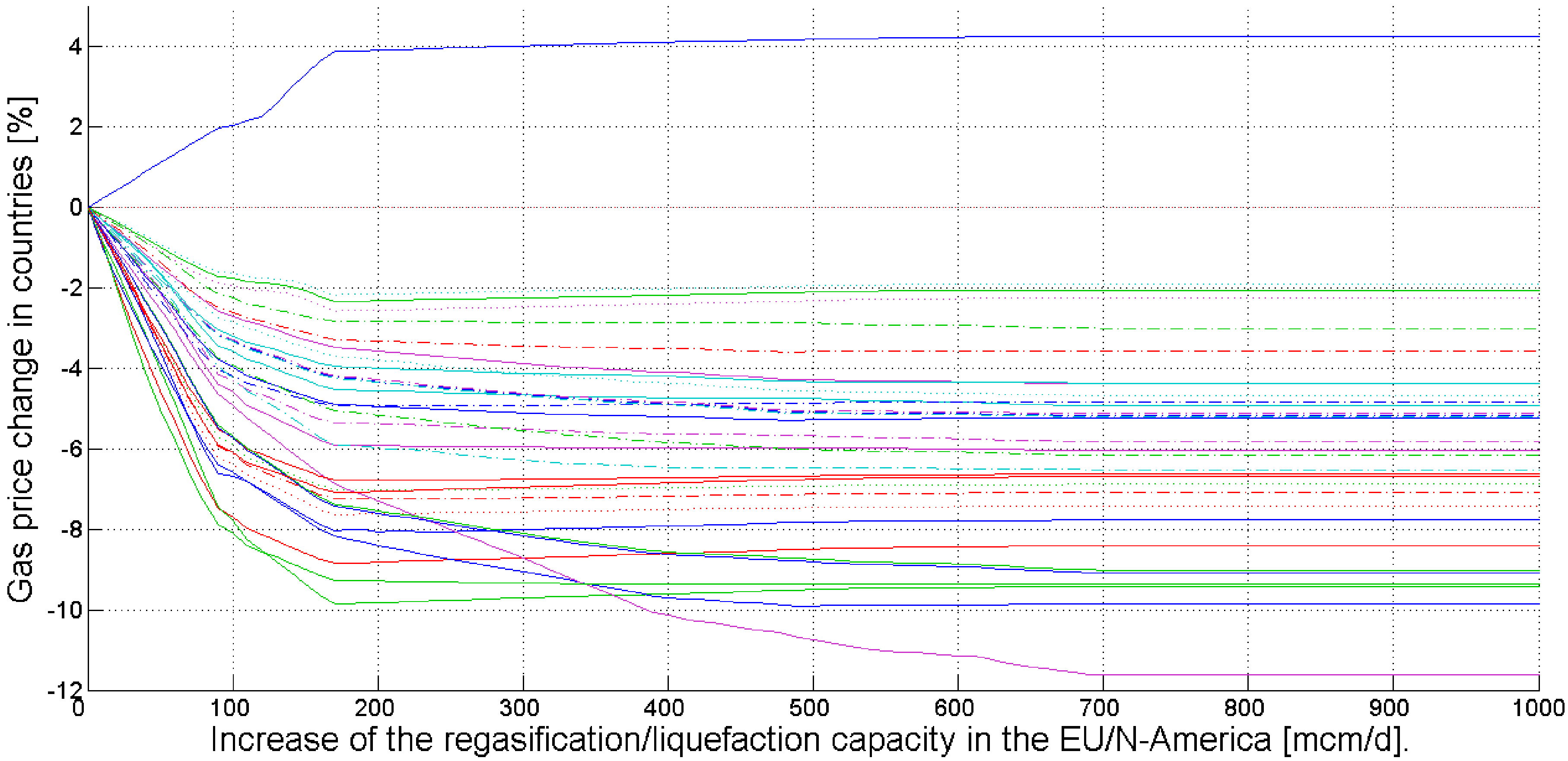


EU AND N-AMERICAN JOINT ACTION

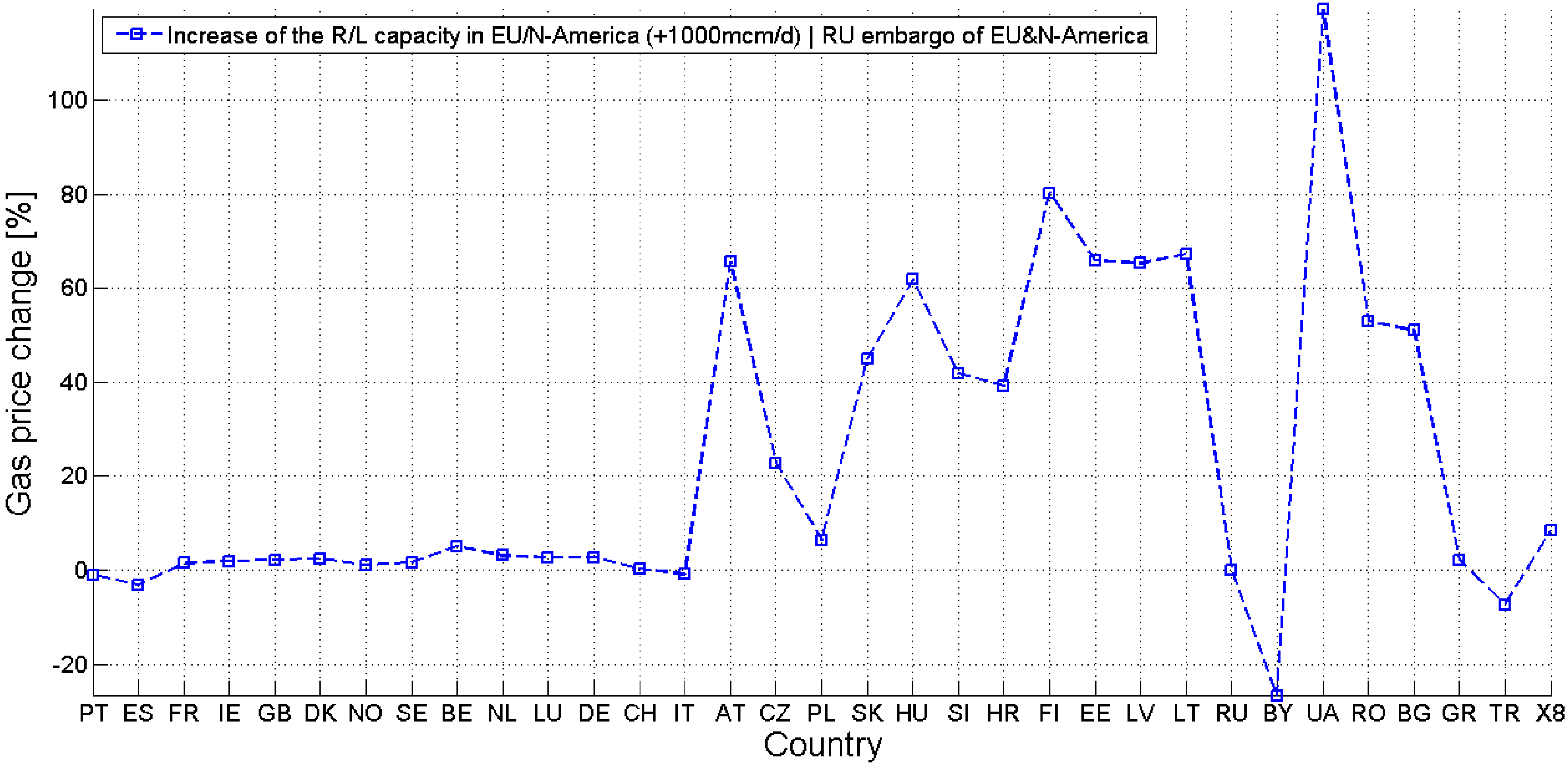


X8: N-America

EU AND N-AMERICAN JOINT ACTION

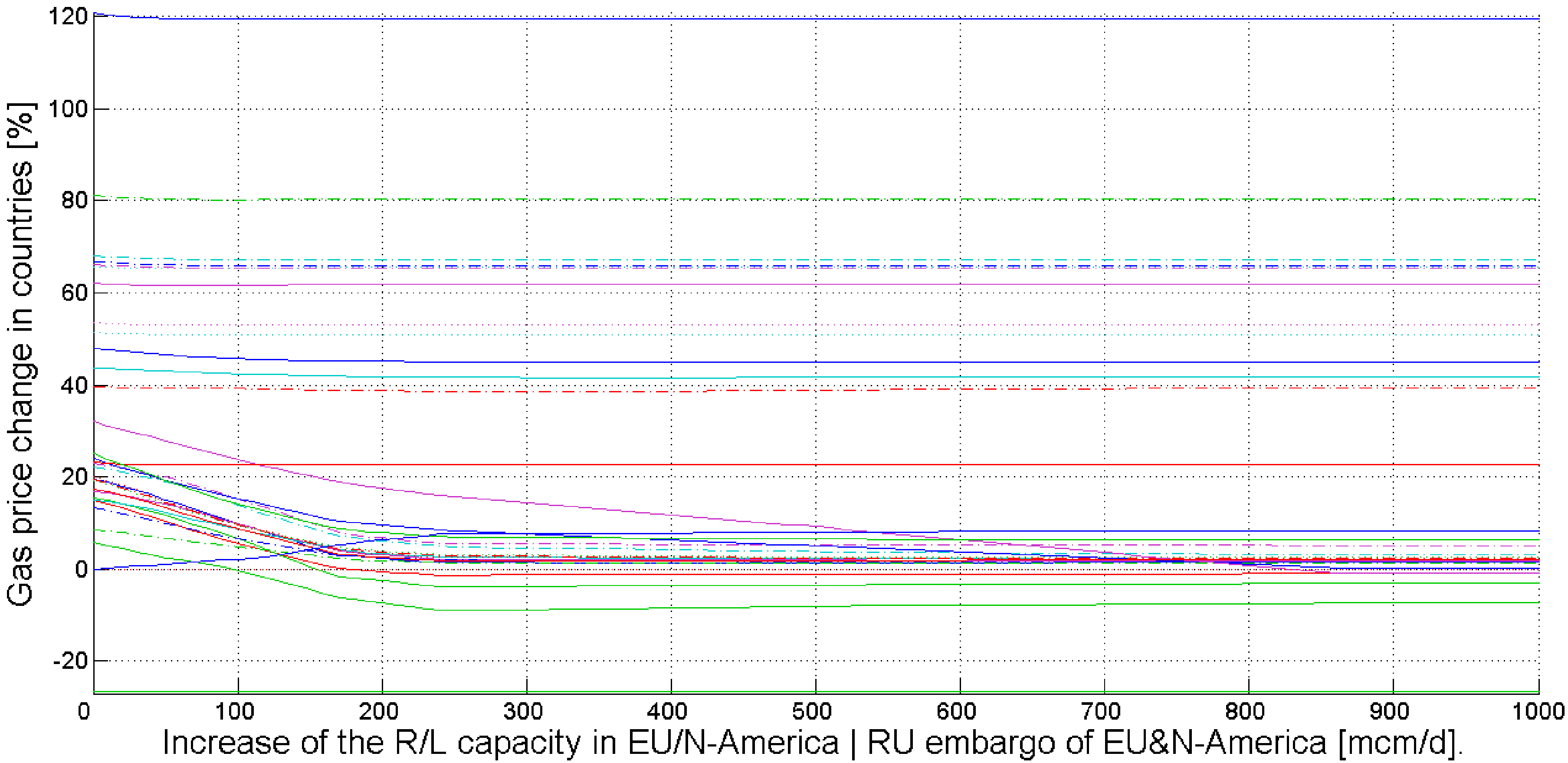


EU AND N-AMERICAN JOINT ACTION <-> ROBUSTNESS IN CASE OF A RUSSIAN EMBARGO



X8: N-America

EU AND N-AMERICAN JOINT ACTION <-> ROBUSTNESS IN CASE OF A RUSSIAN EMBARGO



THANK YOU FOR YOUR ATTENTION