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EXPANDING NATURAL GAS CROSS-BORDER FLOWS IN EUROPE THROUGH THE OPTIMAL USE OF THE PIPELINE GRID: A STYLIZED MODEL COMPARISON (here: Focus on Germany and neighbours)

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Agenda

1) Introduction

2) Theory and State of Literature

3) Scenarios with the Global Gas Model (GGM)

4) Scenarios with GENeSYS-MOD

5) Discussion and Conclusion

Introduction: Short-term consideration …
Russian gas dependency, Ukrainian War and European gas supply

2019 | 2020 | 2021 | 2022 | 2023

- 2020: COVID Pandemic
- 2022: Russia invades Ukraine Germany suspends Nord Stream II certification
- 2022: Russia suspends supplies through Nord Stream I
- 2022: Blow up of Nord Stream I and Nord Stream II
- 2022: EU announces gas price cap

Source: https://www.wallstreet-online.de/rohstoffe/dutch-ttf-daily-natural-gas-forward-daily-futures-preis#t:5y||s:lines||sfill:true||a:abs||v:week||ads:null

… and a long-term consideration (1)

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Utilities Policy 16 (2008) 1–10

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Infrastructure, regulation, investment and security of supply: A case study of the restructured US natural gas market

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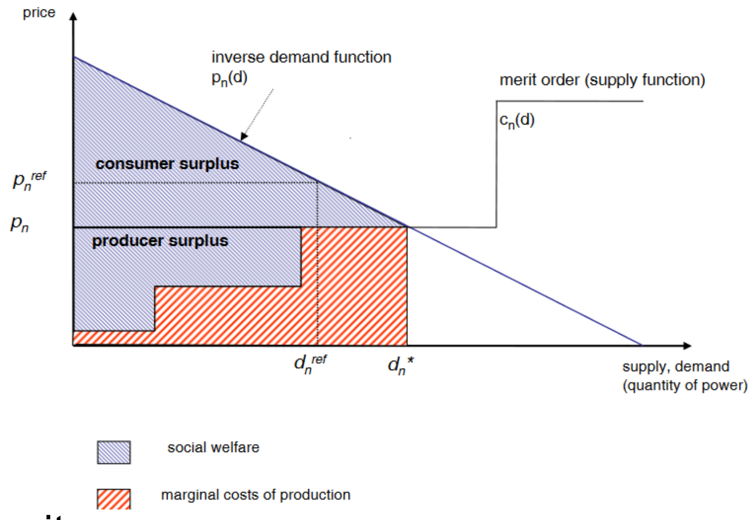
… and a long-term consideration (2): Why does Europe not adopt locational marginal pricing?

~ Importance of trans-boundary grid infrastructure for flexibility and supply security

~ Long-term issue, with regular peak of attention:

- FERC Order 636 (1992), the "final restructuring rule", was a milestone in moving from "simple" non-discriminatory third-party access (TPA) towards a fundamental vertical unbundling of transportation and sales activities
- EU Directive 98/92: unbundling and efficient use of capacities
- First Russian-Ukrainian gas crisis 2006 …
- … natural gas / energy crisis of 2022



~ Theoretically: "nodal pricing" yields short-term welfare optimization / cost minimization

~ Application gap:

- US applies nodal pricing since the 1990s
- Europe started reforms in the 2000s, but is still stuck with entry-exit

~ Topic gained importance through the energy and natural gas crisis

~ Particular issue with "reverse flows", i.e., differentiated capacity caps on flows from A ➔ B ≠ B ➔ A

➔ In this paper, we compare existing network regulation in Europe with entry-exit and uni-directional caps with a (hypothetical) situation of bidirectional nodal prices

Agenda

Theory and state of literature

~ Nodal pricing has its origins in the electricity sector (Schweppe et al. 1988; Hogan 1992), recent update by Hogan and Harvey (2022)

~ Based on simple welfare maximization

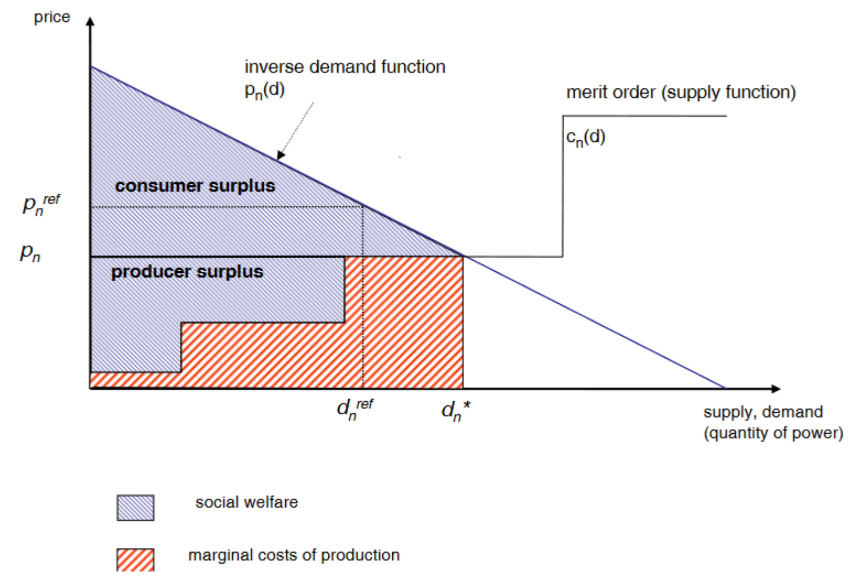
~ First applications in the US:

  ~ Electricity after US FERC order 888 ("provide open access transmission service on a comparable basis to the transmission service they provide themselves")

  ~ Natural gas (Cremer, et al, 2003, Lochner et al., 2010) :

    ~ Technically less complex than electricity (no loop flows)

    ~ But complexity through non-linear flows ("Weymouth equation", etc.)



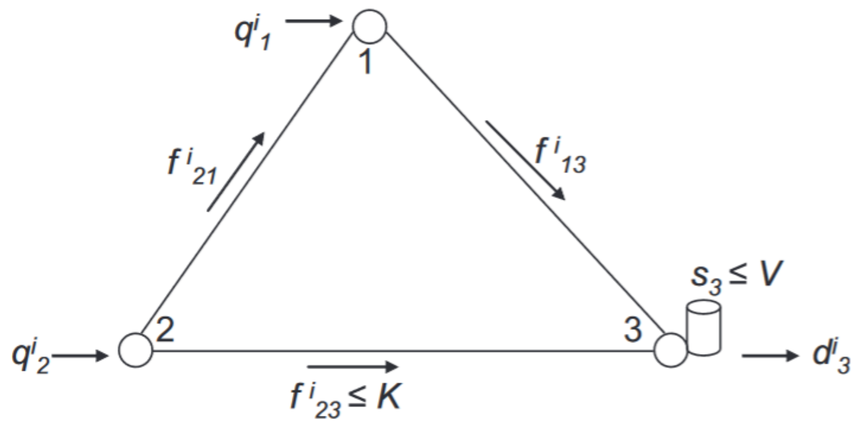
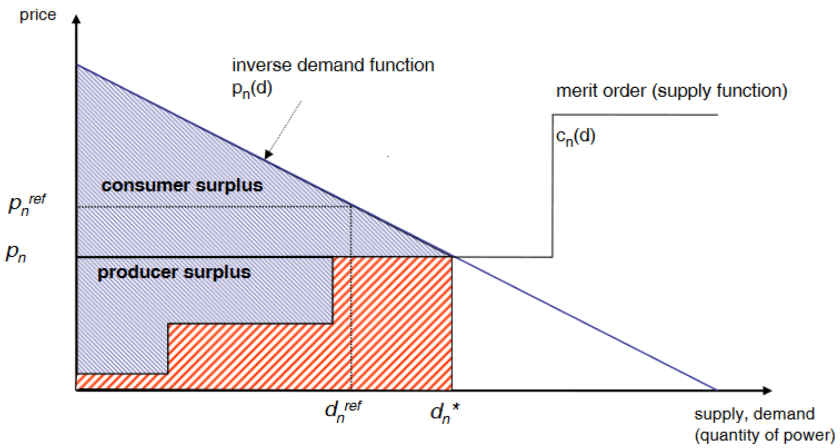


Fig. 1. Simple pipeline network with storage.

The principle of “nodal pricing”

Problem: uniform pricing → congestion not properly determined?

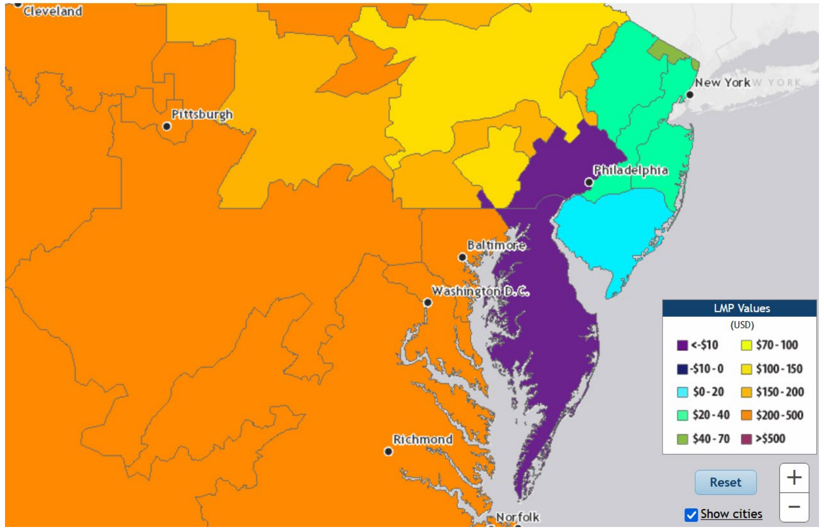


Nodal Pricing

= location value of energy:

Node specific costs from energy generation and transmission (e.g., losses and congestion)

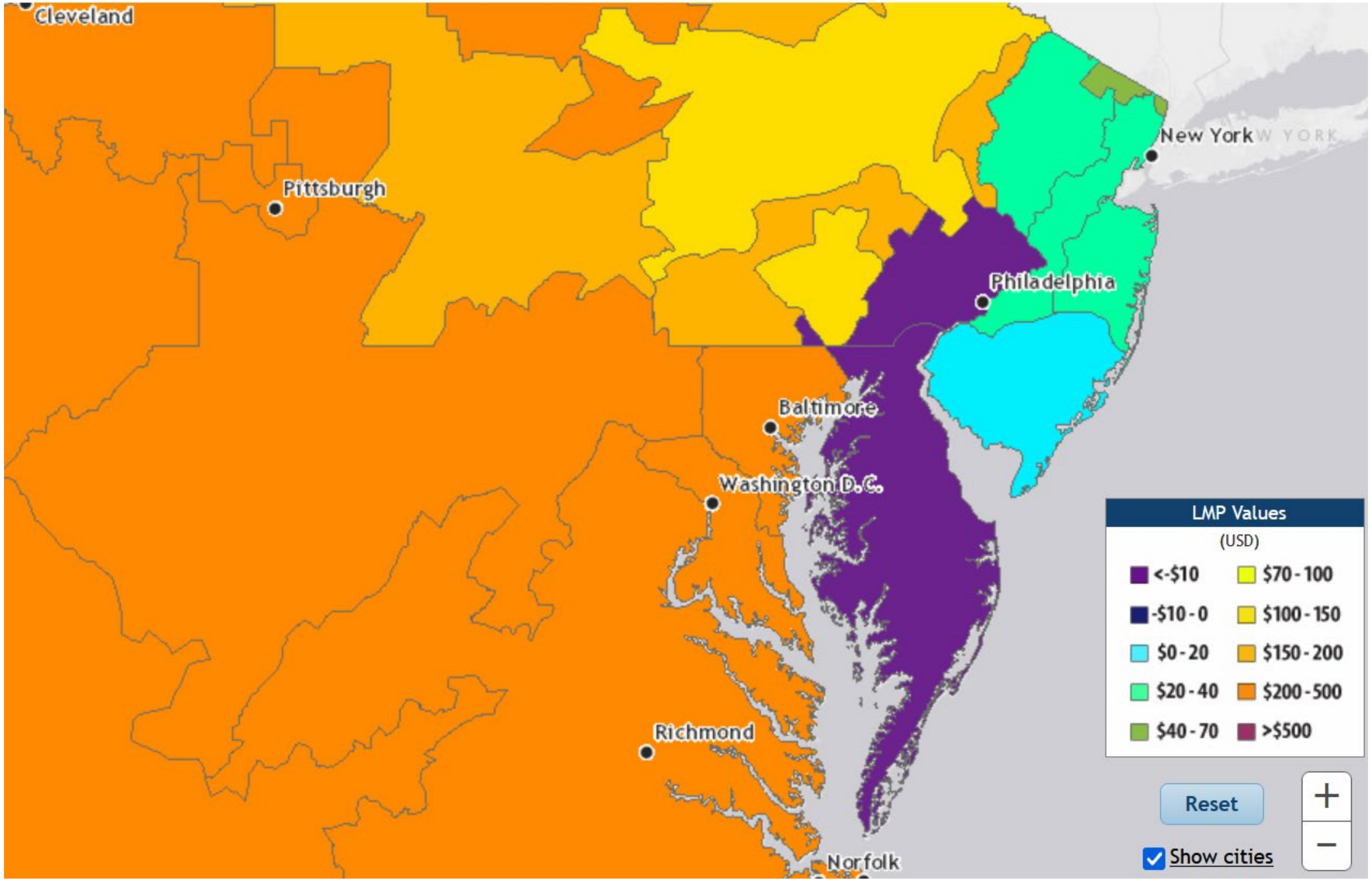
Node: physical location on the transmission grid (incl. generators and loads)



Calculation: market clearing prices for all nodes subjects to physical and security constraints

-> reflects real conditions and costs in the grid for every node
-> Indicate and price congestions when overstepping transmission limits

The principle of “nodal pricing”: LMPs in PJM



https://www.pjm.com/library/maps/lmp-map.aspx

Optimization Problem

Objective function: Social welfare

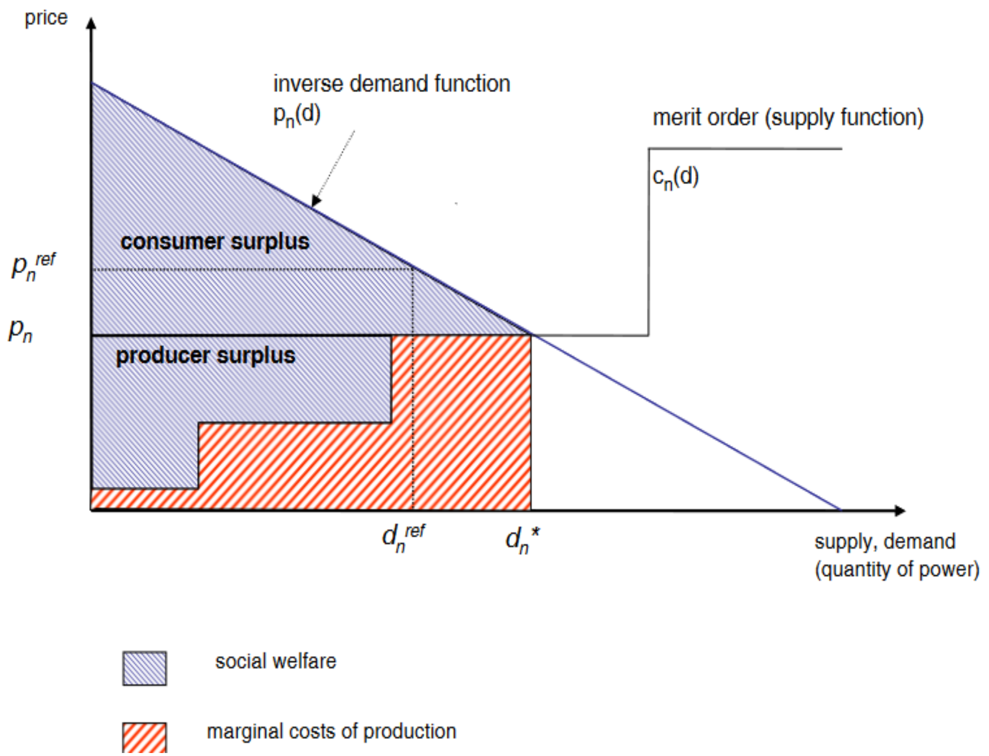
$$\max W(d_n^*) = \left(\int_0^{d_n^*} p^*(d_n^*)d * d_n^* - \int_0^{d_n^*} c(d_n^*)d * d_n^*\right)$$

s.t.

s.t.	$\lvert P_i \rvert \leq P_i^{max}$	line flow constraint
	$\sum_n g_n = \sum_n d_n + L$	energy balance constraint
	$\sum_{n,t} g_n^t \leq \sum_{n,t} g_n^{t,max}$	generation constraint (per type of plant)

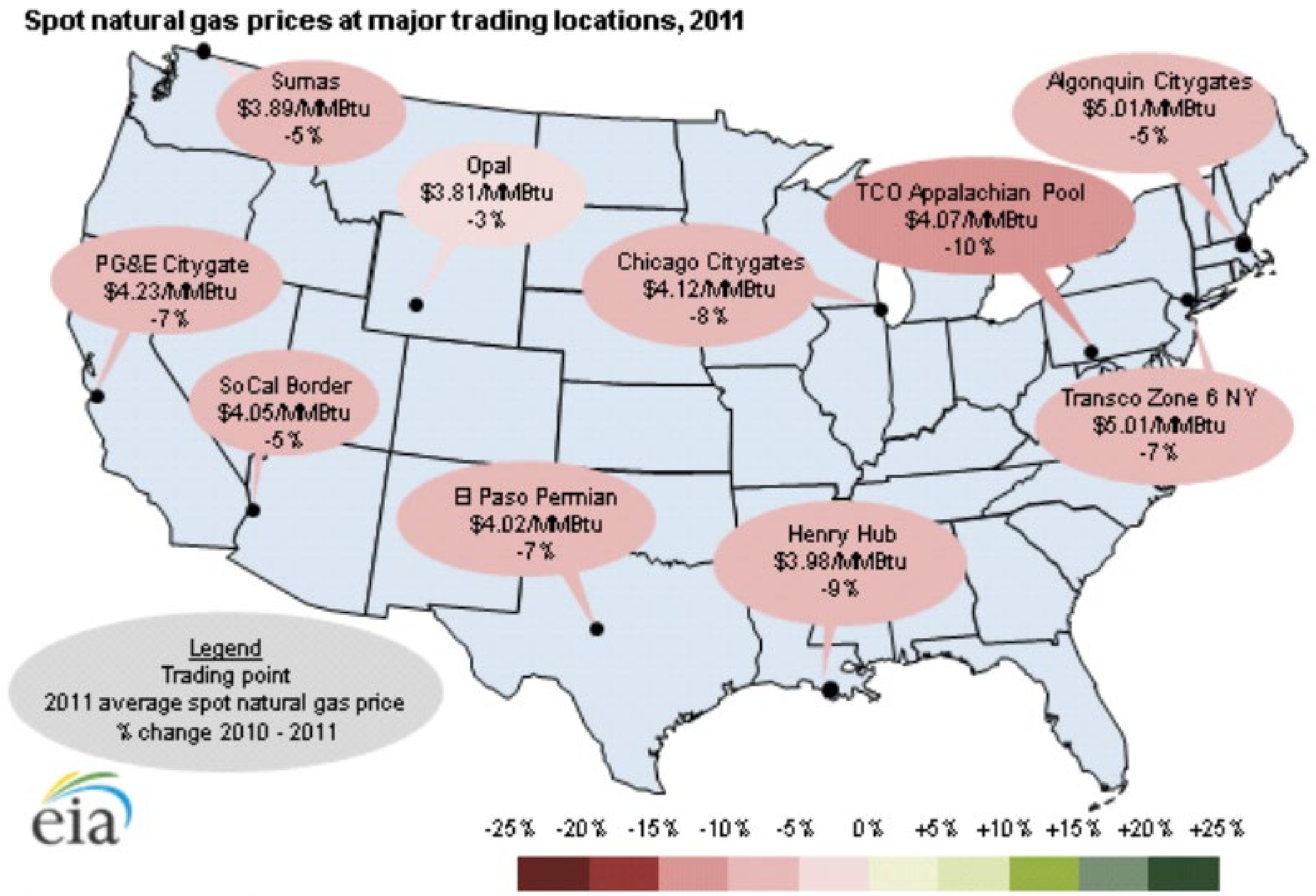
Inverse demand function or each node

$$p_n = p_n^{ref} + \frac{1}{\varepsilon} * p_n^{ref} * \left(\frac{d_n^*}{d_n^{ref}} - 1\right)$$



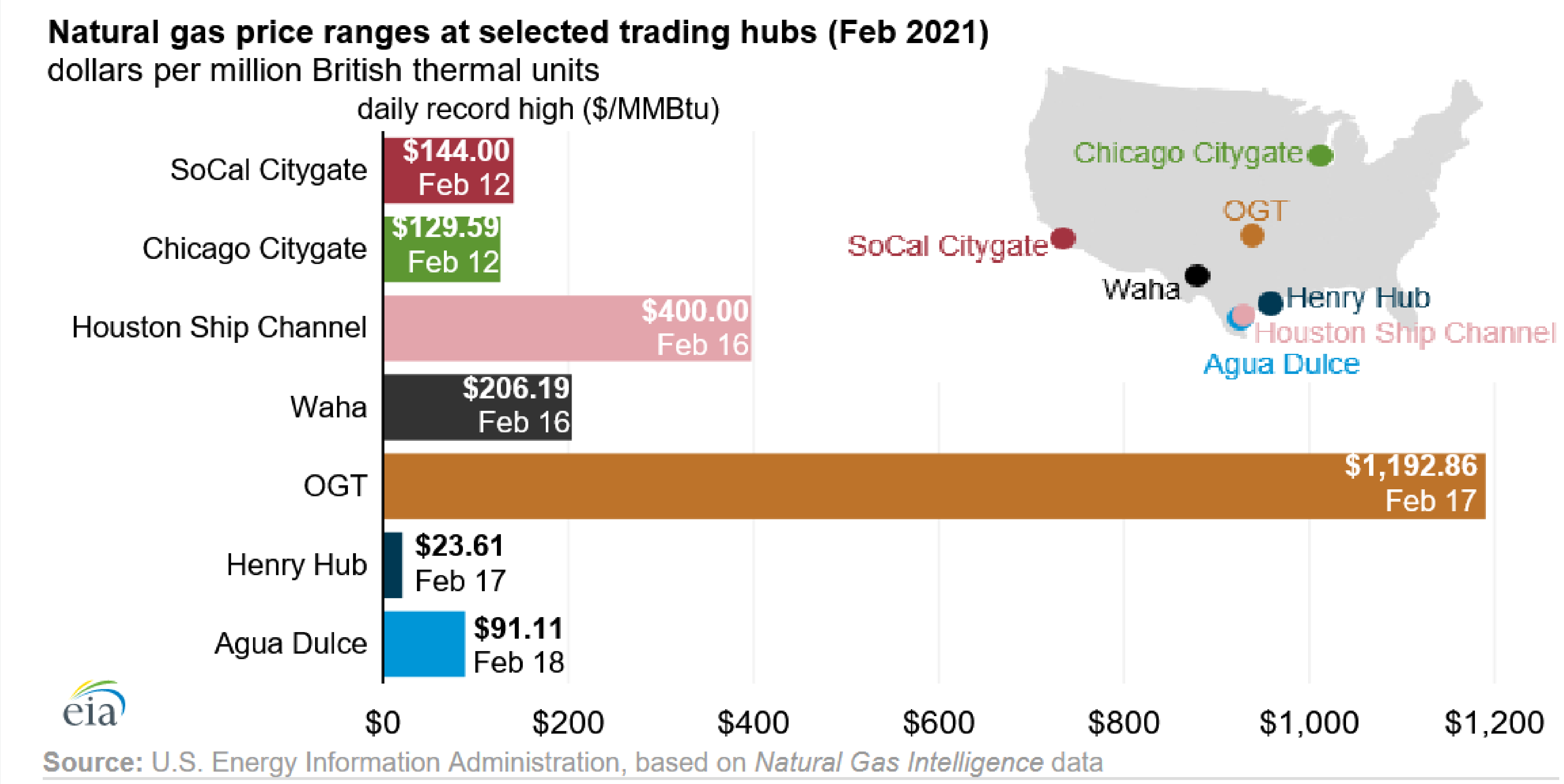
Assumption: Competition

US Trading Points (2011)



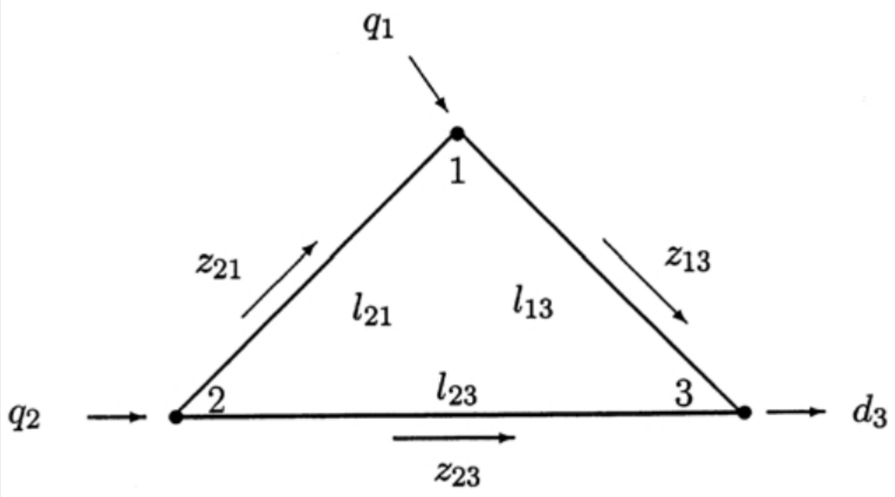
Source: U.S. Energy Information Administration, based on Bloomberg.
Note: Average spot natural gas prices reported in the map for 2011 are based on data from InterContinentalExchange and vary slightly values reported in the current Short-Term Energy Outlook, which are based on Reuters data.

Gas Price Ranges @ Trading Hubs (February 2021)



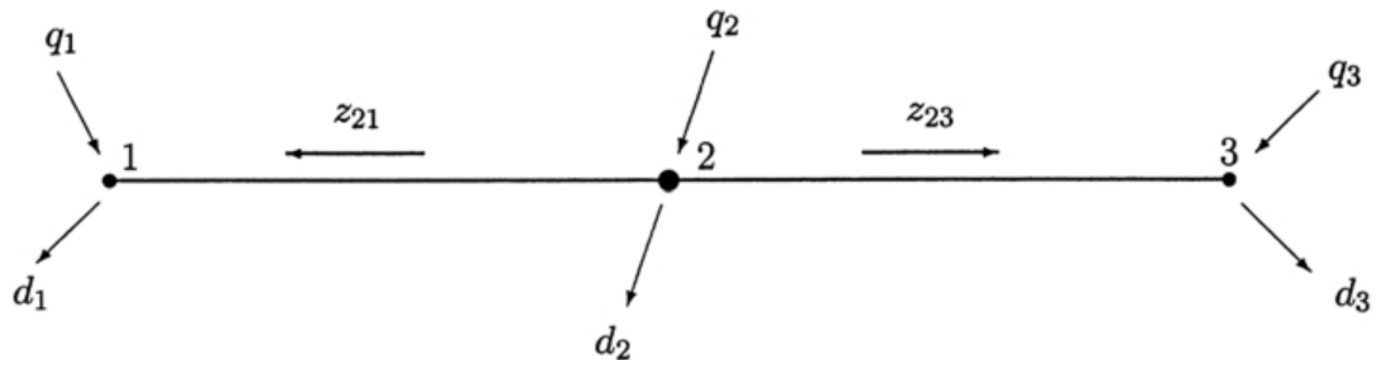
“Nodal prices” in natural gas: Uni- vs. bidirectional
(Cremer et.al., 2003)

Unidirectional-flow gas network



Source: Figure 1, Cremer et.al., 2003

Bidirectional-flow gas network



Maximizing this social welfare function under the assumption of competitive supply yields first – order conditions which, using the transport tariffs t_{ij} , are written as

$$t_{21} = p_1 - p_2 = c'_{21} l_{21}, \tag{29}$$

and

$$t_{23} = p_3 - p_2 = c'_{23} l_{23}. \tag{30}$$

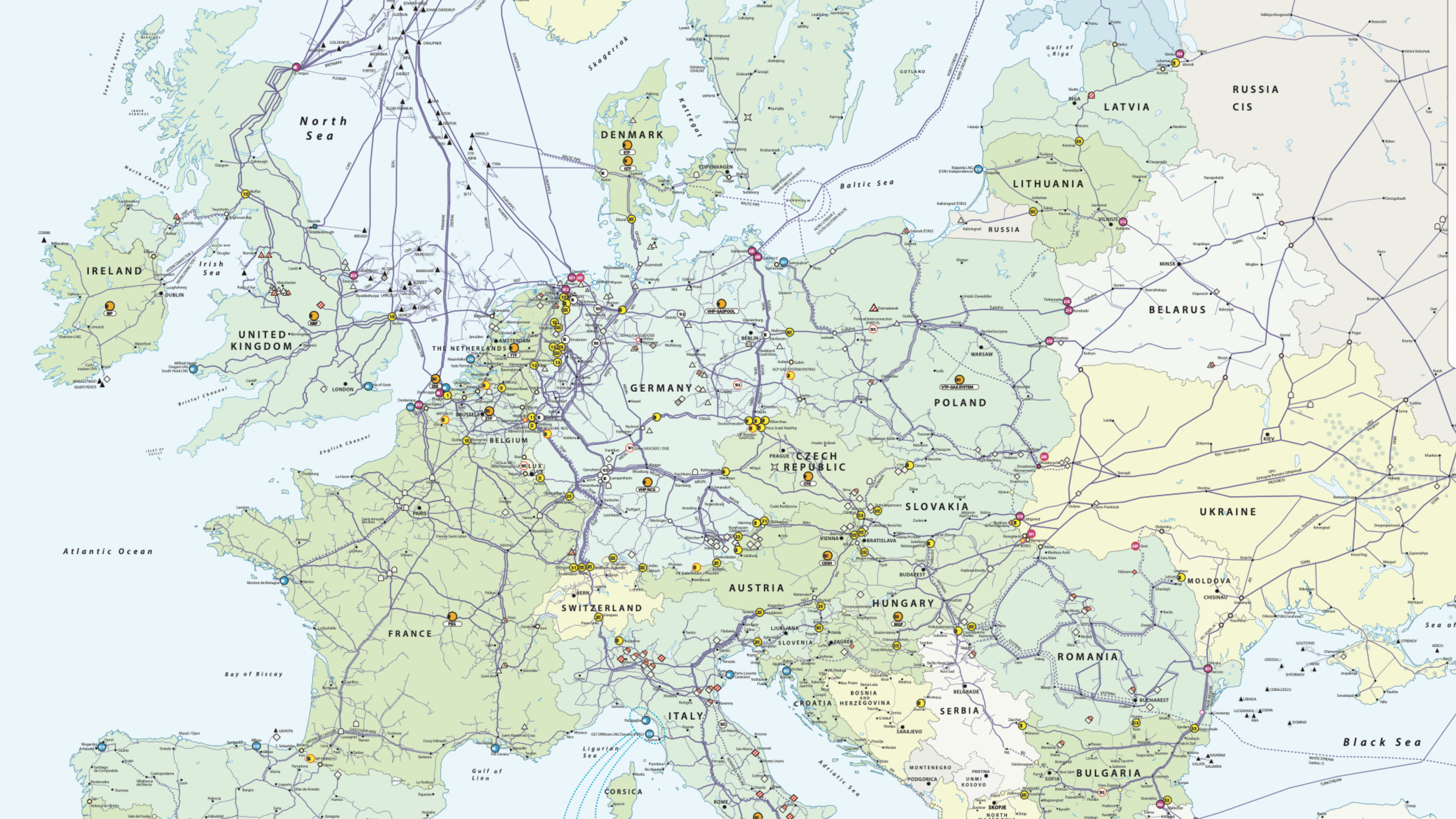
We see that these conditions also imply

$$t_{13} = p_3 - p_1 = c'_{23} l_{23} - c'_{21} l_{21} \gtreqless 0. \tag{31}$$

Source: Figure 2, Cremer et.al., 2003

ENTSOG – Central European Natural Gas Network

(source: https://www.entsog.eu/sites/default/files/2021-11/ENTSOG_CAP_2021_A0_1189x841_FULL_066_FLAT.pdf)


North Sea
Skagerrak
Kattegat
Baltic Sea
Gulf of Riga
IRELAND
UNITED KINGDOM
Irish Sea
North Channel
Bristol Channel
English Channel
DENMARK
LATVIA
LITHUANIA
RUSSIA
RUSSIA CIS
BELARUS
POLAND
GERMANY
THE NETHERLANDS
BELGIUM
LUX
CZECH REPUBLIC
SLOVAKIA
UKRAINE
MOLDOVA
AUSTRIA
HUNGARY
ROMANIA
SWITZERLAND
FRANCE
ITALY
SLOVENIA
CROATIA
BOSNIA AND HERZEGOVINA
SERBIA
MONTENEGRO
KOSOVO
BULGARIA
CORSICA
Atlantic Ocean
Bay of Biscay
Gulf of Lion
Ligurian Sea
Adriatic Sea
Black Sea
DUBLIN
LONDON
PARIS
AMSTERDAM
BRUSSELS
BERLIN
WARSAW
PRAGUE
VIENNA
BRATISLAVA
BUDAPEST
BERN
LJUBLJANA
ZAGREB
SARAJEVO
BELGRADE
PODGORICA
PRISTINA
SKOPJE
SOFIA
BUCHAREST
CHISINAU
KIEV
MINSK
VILNIUS
RIGA
ROME
COPENHAGEN

Cross-country Capacities

Region A	Region B	Capacity A → B	Capacity B → A
DE	AT	**20.99**	10.44
DE	BE	**12.16**	9.91
DE	CH	**10.07**	5.31
DE	CZ	**55.37**	37.81
DE	DK	**4.18**	0.13
DE	FR	**18.84**	**18.84**
DE	NL	58.76	**74.56**
DE	NO	0	**67.86**
DE	PL	7.17	**28.60**
AT	IT	**35.30**	5.94
BE	FR	**26.71**	8.29
CH	IT	**19.66**	13.64
FR	ES	5.05	**6.89**

Table 1: Selection of cross-country capacities for gas pipelines in bcm

Cross-country Capacities

ion A	Region B	Capacity A → B	Capacity B → A
	NONEU-Balkan	**13.01**	10.29
	PL	**0.86**	**0.86**
	SK	**41.2**	16.33
	HU	1.49	**2.38**
	SI	0.24	**1.65**
	NONEU-Balkan	**4.36**	0
	RO	**2.38**	1.54
	SK	1.56	**3.96**
	BG	**24.74**	4.55

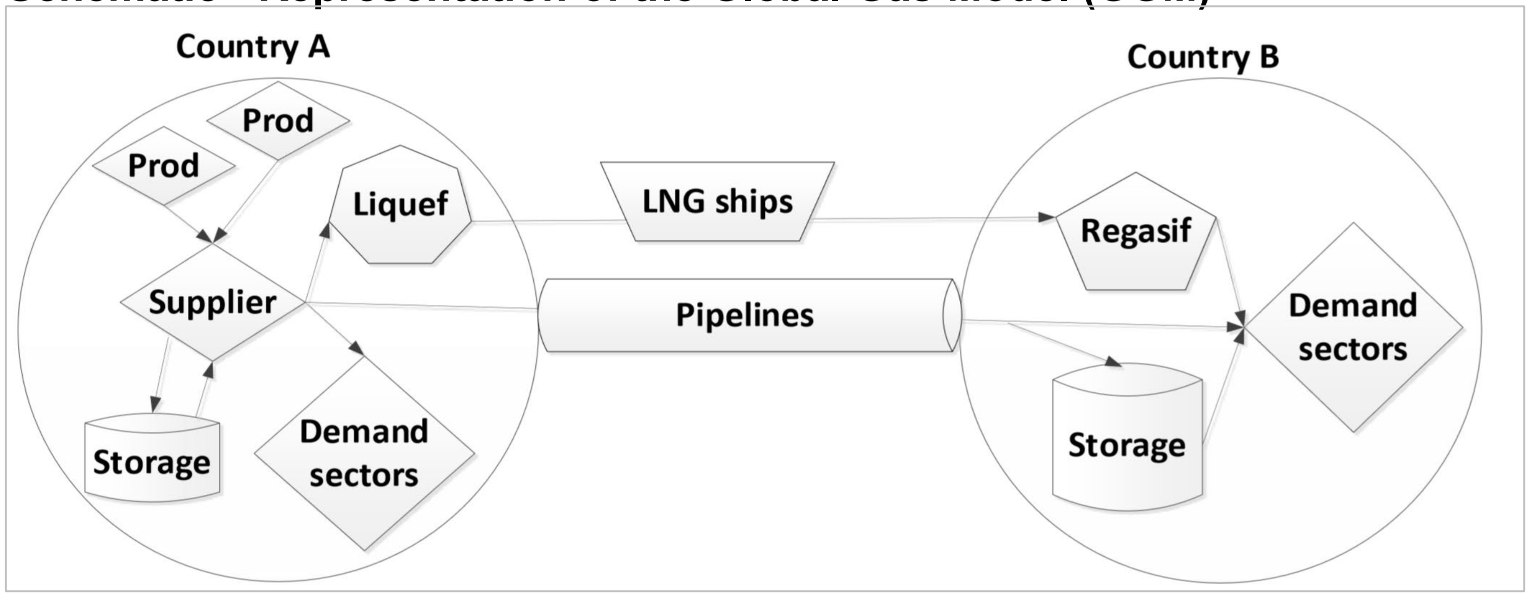
Table 1: Selection of east European cross-country capacities for gas pipelines in bcm

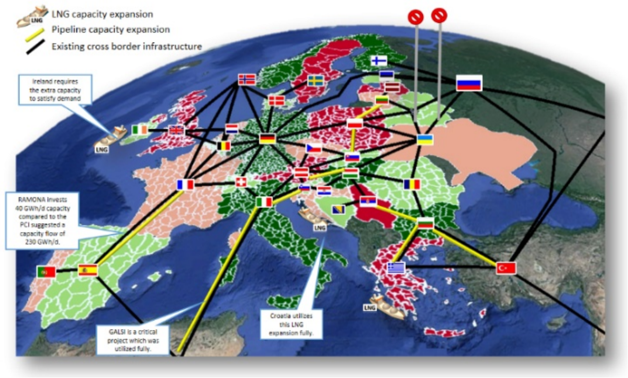
Agenda

The Global Gas Model (Structural Overview)

- Multi-Period Model of oligopolistic competition in natural gas markets à la Nash-Cournot
- Single commodity partial equilibrium model
- Covering practically the entire global natural gas production and consumption value chain
- Exertion of market power happens via traders that channel production from multiple model nodes (e.g., different regions in the US, Canada or Russia)

Schematic - Representation of the Global Gas Model (GGM)





Source: https://www.ntnu.edu/iot/energy/energy-models-hub/ggm

The Global Gas Model (Details)

$$\max_{\substack{q^S_{tndy},\, q^P_{tnrdy},\\ f^Z_{tzdy},\, \Delta^Z_{z,y}}} \sum_y r_y \Bigg[\sum_d d_d \Bigg[\sum_{t,n} \Big(INT_{ndy} - SLP_{ndy} \sum_{t'} q^S_{t'ndy} \Big) q^S_{tndy} + \frac{1}{2} \sum_n SLP_{ndy} \Big(\sum_t q^S_{tndy} \Big)^2 - \frac{1}{2} \sum_n SLP_{ndy} \sum_t cv_{tny} \left(q^S_{tndy}\right)^2 - \sum_{t,n,r} c^{Pl}_{tnry} q^P_{tnrdy} - 0.5 \sum_{t,n,r} c^{Pq}_{tnry} \left(q^P_{tnrdy}\right)^2 - \sum_{t,a} c^A_{ay} f^A_{tady} - \sum_{t,n,w} c^X_{nwy} f^X_{tnwdy} \Bigg] - \sum_a c_{ay}^{\Delta^A_{ay}} \Delta^A_{ay} - \sum_x c_{xy}^{\Delta^X_{xy}} \Delta^X_{xy} - \sum_w c_{wy}^{\Delta^W_{wy}} \Delta^W_{wy} \Bigg] \quad (1)$$

Source: https://www.ntnu.edu/iot/energy/energy-models-hub/ggm

The Global Gas Model (Details 2)

$$\text{s.t.} \quad \forall t,n,r,d,y \qquad q^P_{tnrdy} \leq CAP^P_{tnry} \qquad (2a)$$

$$\forall t,n,d,y \qquad \sum_r q^P_{tnrdy} + \sum_{a \in A^+_n} \left(1 - l^A_a\right) f^A_{tady} + \sum_w f^X_{tnwdy} = q^S_{tndy} + \sum_{a \in A^-_n} f^A_{tady} + \sum_w f^I_{tnwdy} \qquad (2b)$$

$$\forall a,y \qquad \Delta^A_{ay} \leq \bar{\Delta}^A_{ay} \qquad (2c)$$

$$\forall a,y \qquad \sum_t f^A_{tady} \leq CAP^A_{ay} + \sum_{y'<y} \Delta^A_{ay} \qquad (2d)$$

$$\forall t,w,d,y \qquad \left(1 - l^I_w\right) \sum_d f^I_{twdy} = \sum_d f^X_{twdy} \qquad (3a)$$

$$\forall n,w,y \qquad \Delta^X_{nwy} \leq \bar{\Delta}^X_{nwy} \qquad (3b)$$

$$\forall n,w,y \qquad \Delta^W_{nwy} \leq \bar{\Delta}^W_{nwy} \qquad (3c)$$

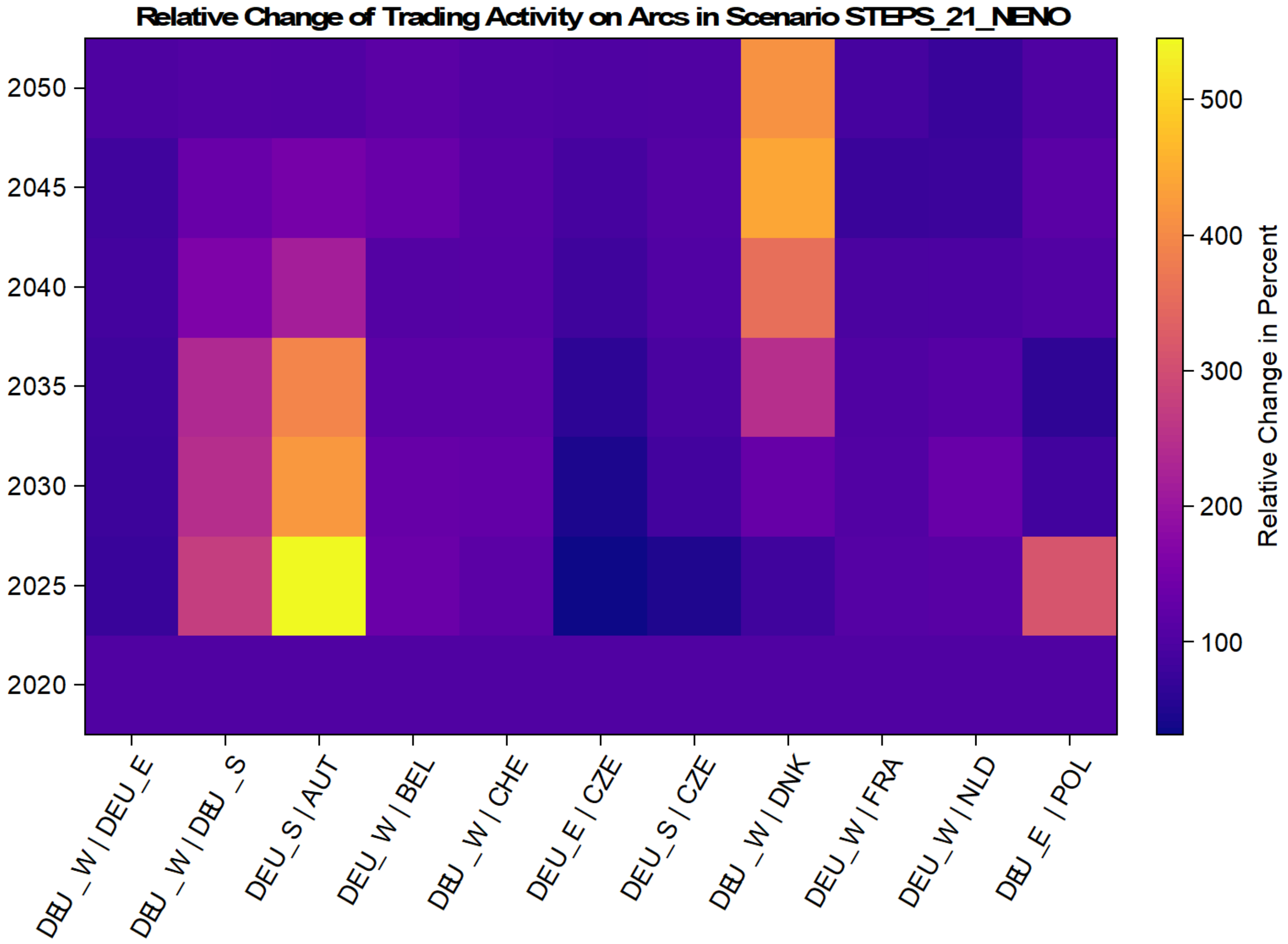
$$\forall n,w,y \qquad \sum_t f^X_{tnwdy} \leq CAP^X_{nwy} + \sum_{y'<y} \Delta^X_{nwy} \qquad (3d)$$

$$\forall n,w,y \qquad \sum_{t,d} d_d f^X_{tnwdy} \leq CAP^W_{nwy} + \sum_{y'<y} \Delta^W_{nwy} \qquad (3e)$$

Extreme case: STEPS with no LNG in East Germany

Heat-Maps with indication on relative changes of total cross border trades

- High demand
- Total activity on trading arcs defined as sum of flows from a->b and b->a
- Flow reversal benefits Bavaria and Austria
- No LNG-Investments in East Germany (necessary)
- More Pipeline imports from Norway via Denmark to south-eastern neighbors (Model artifact, in reality direct pipeline would be preferably expanded)



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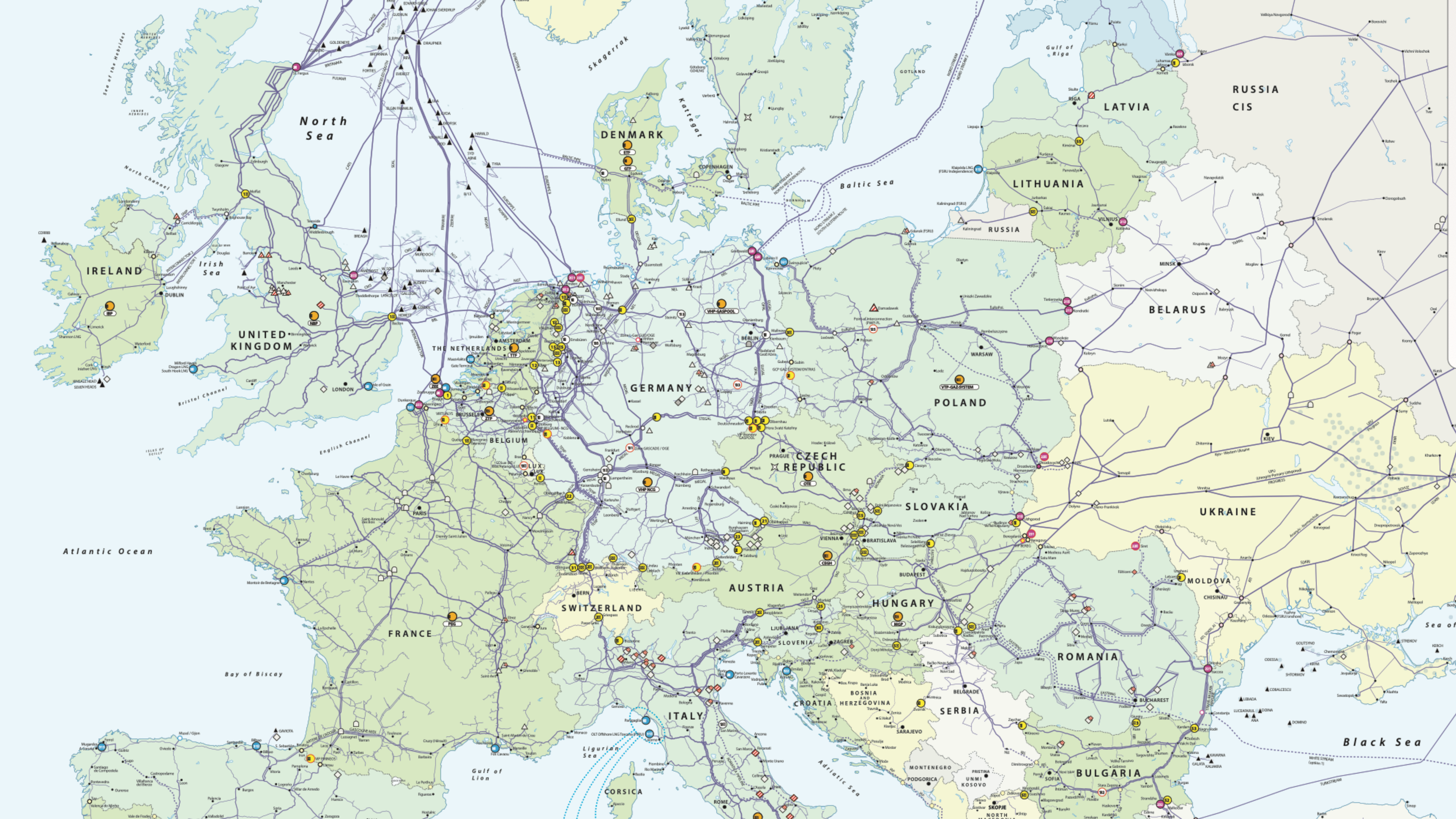
North Sea
Skagerrak
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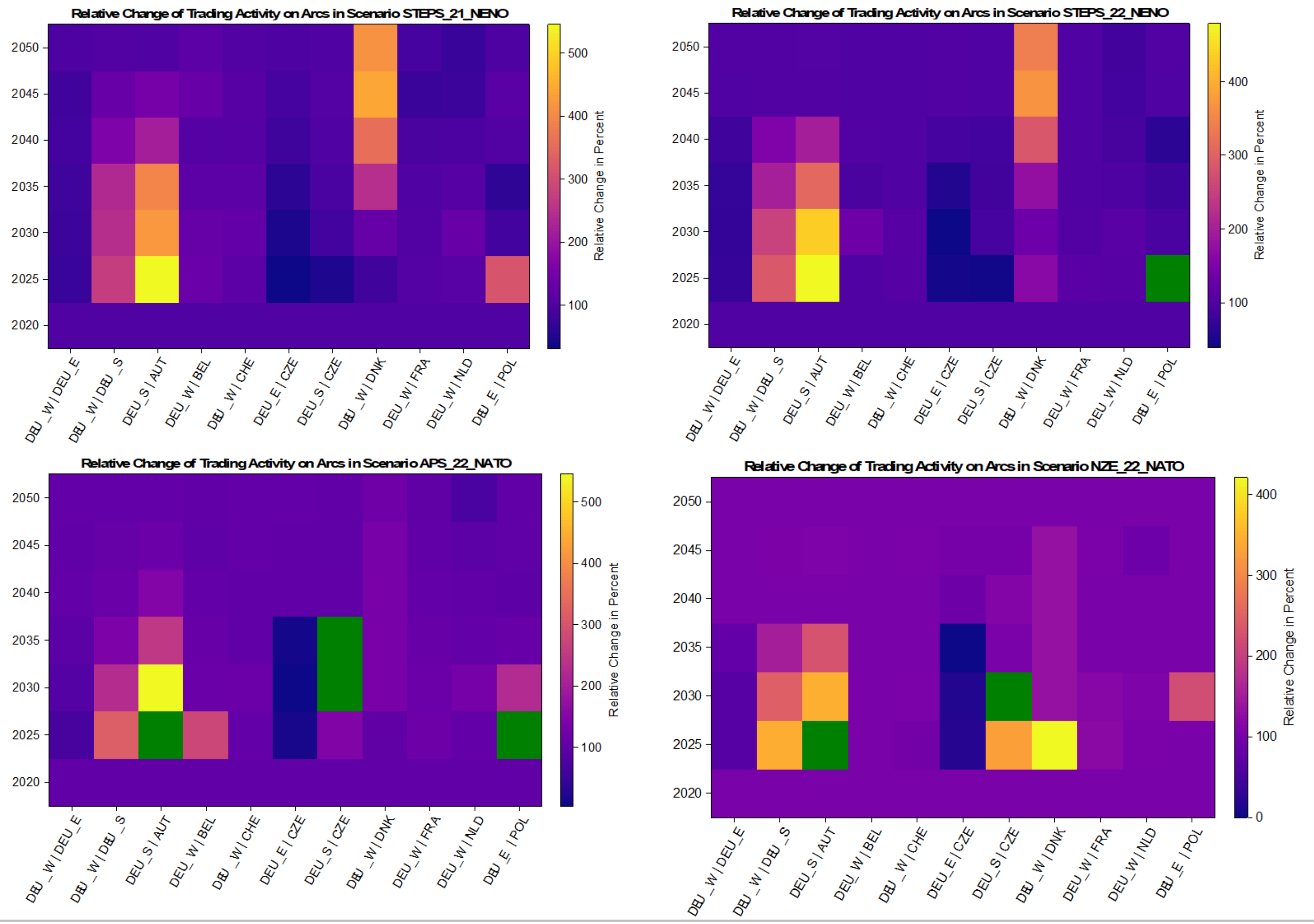
Baltic Sea
Gulf of Riga
Irish Sea
North Channel
Bristol Channel
English Channel
Atlantic Ocean
Bay of Biscay
Ligurian Sea
Gulf of Lion
Adriatic Sea
Black Sea
Sea of the Hebrides
IRELAND
UNITED KINGDOM
DENMARK
THE NETHERLANDS
BELGIUM
LUX
GERMANY
FRANCE
SWITZERLAND
AUSTRIA
ITALY
CORSICA
CZECH REPUBLIC
SLOVAKIA
HUNGARY
SLOVENIA
CROATIA
BOSNIA AND HERZEGOVINA
SERBIA
MONTENEGRO
KOSOVO
ROMANIA
BULGARIA
MOLDOVA
UKRAINE
BELARUS
POLAND
LITHUANIA
LATVIA
RUSSIA
RUSSIA CIS
DUBLIN
LONDON
AMSTERDAM
BRUSSELS
PARIS
BERLIN
PRAGUE
VIENNA
BRATISLAVA
BUDAPEST
BERN
LJUBLJANA
ZAGREB
SARAJEVO
BELGRADE
PODGORICA
PRISTINA
SKOPJE
SOFIA
BUCHAREST
CHISINAU
KIEV
MINSK
VILNIUS
RIGA
WARSAW
COPENHAGEN
ROME
GOTLAND
BORNHOLM
NBP
IBP
ZEE
ZTP
TTF
GTF
ETF
VHP-GASPOOL
VHP NCG
PEG
CEGH
OTE
MGP
VTP-GAZ-SYSTEM

First Results with the Global Gas Model (Relative Changes of Trading Activity)

Heat-Maps with indication on relative changes of total cross border trades

- GGM scenarios: STEPS 2021, STEPS 2022, APS 2022, NZE 2022
- Geopolitics: SQAB, NENO, NATO
- No exogenous LNG capacities in the baltic sea



Relative Changes of Prices: Germany

Result – Prices in Germany

- STEPS 2021 NATO
- Relative price changes
- Comparison:
  - Bi-directional without LNG in East Germany (default case)
  - vs uni-directional with LNG in East Germany

Node	Year	Difference
DEU_W	2025	+0.54%
DEU_S	2025	-4.72%
DEU_E	2025	+0.41%
DEU_W	2030	+0.63%
DEU_S	2030	-2.34%
DEU_E	2030	+0.62%

Agenda

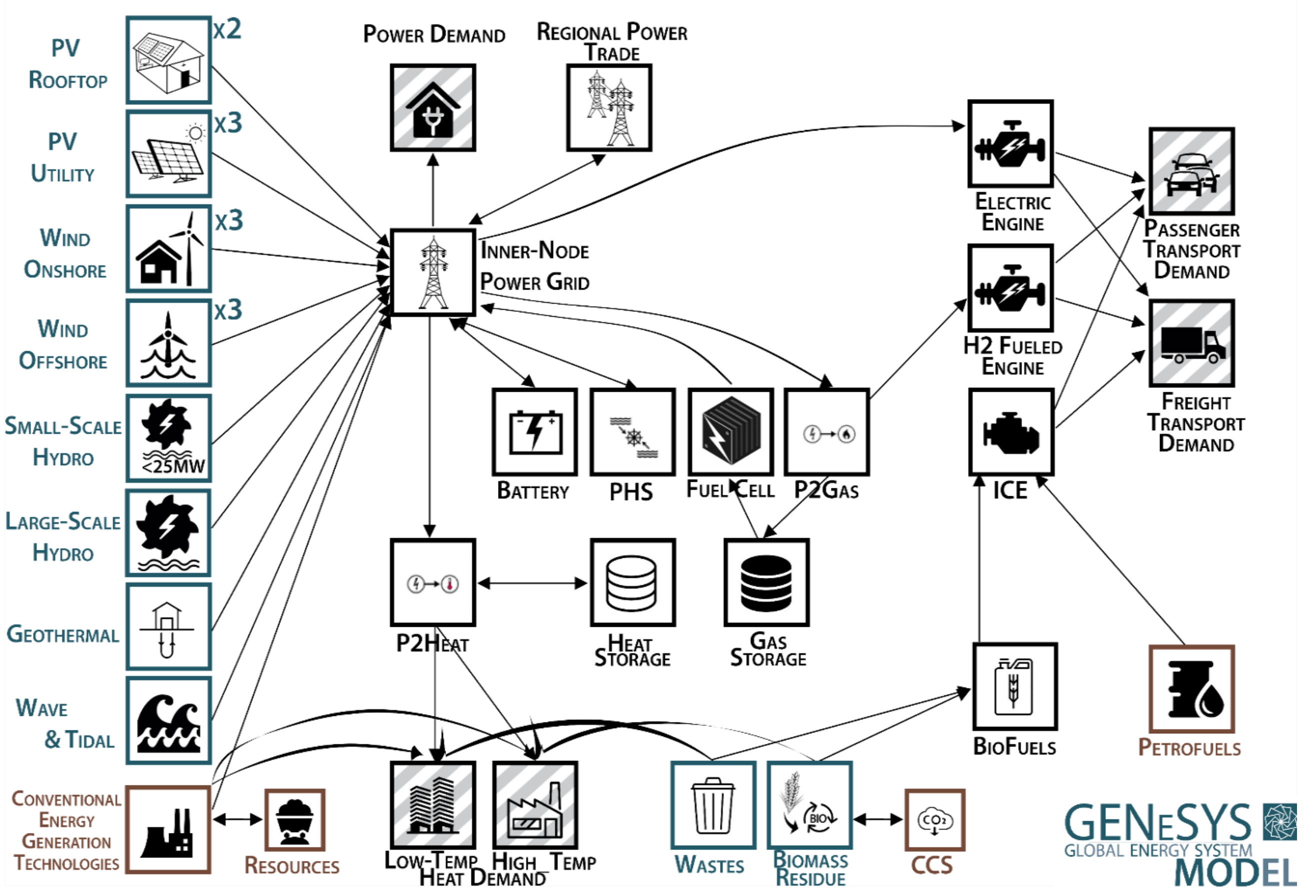
GENeSYS-MOD…

Energy system model resolution

… based on OSeMOSYS and developed since 2016

…publicly available with model, data, and manual[1]

…Results in this presentation (mainly) based on European and German case-studies



1 https://git.tu-berlin.de/genesysmod/genesys-mod-public

Model Formulation – Objective Function

- **Sets:**

y	*Year*	f	*Fuel*	s	*Storage*
t	*Technology*	m	*Mode of Operation*	e	*Emission*
r	*Region*	l	*Time Slice*		

- **Objective Function**

$$\min costs = \sum_y \sum_t \sum_r TotalDiscountedCost_{y,t,r} + \sum_y \sum_r TotalDiscountedTradeCosts_{y,r}$$

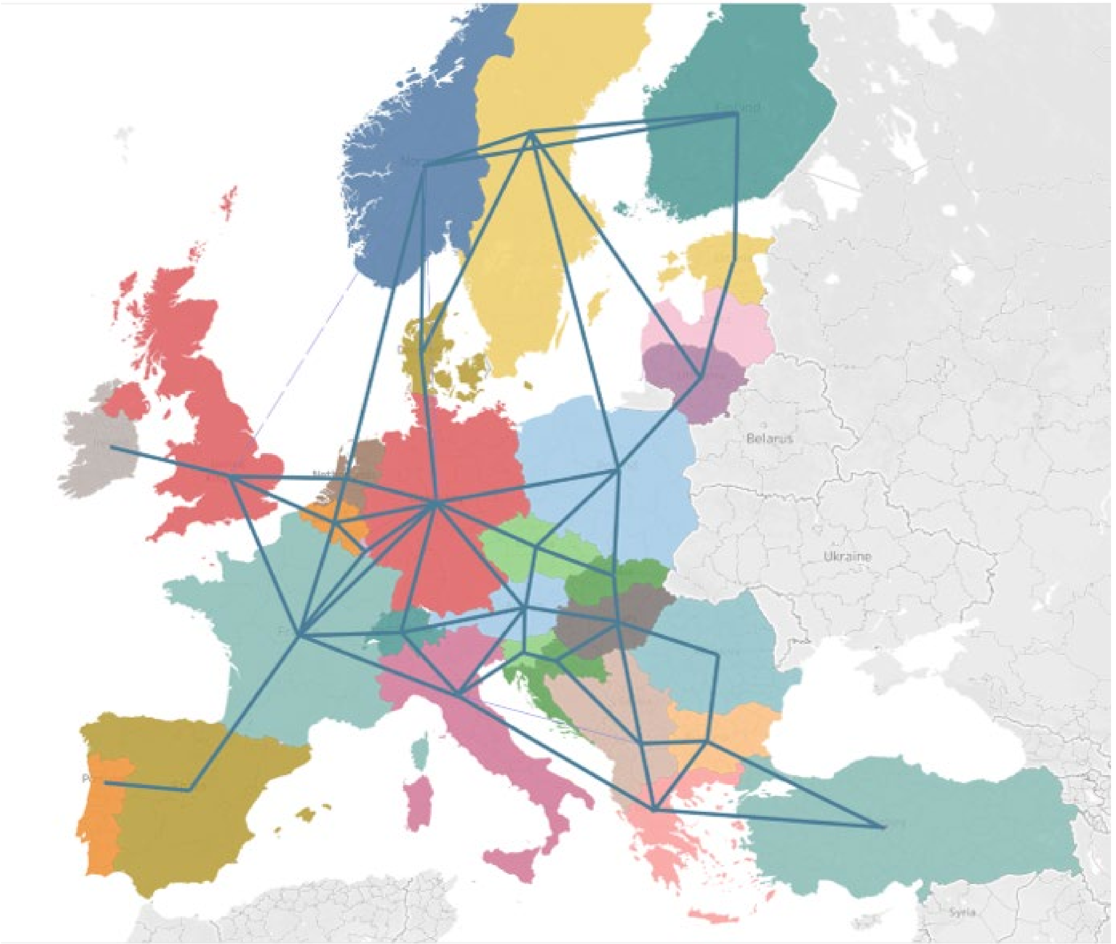
$$TotalDiscountedCost_{y,t,r} = DiscountedOperatingCost_{y,t,r} + DiscountedCapitalInvestment_{y,t,r} + DiscountedCapitalInvestmentStorage_{y,s,r} + DiscountedTechnologyEmissionsPenalty_{y,t,r} - DiscountedSalvageValue_{y,t,r}$$

$$\forall \quad y \in Y, t \in T, r \in R$$

Scenario specific model settings

Spatial and temporal resolution

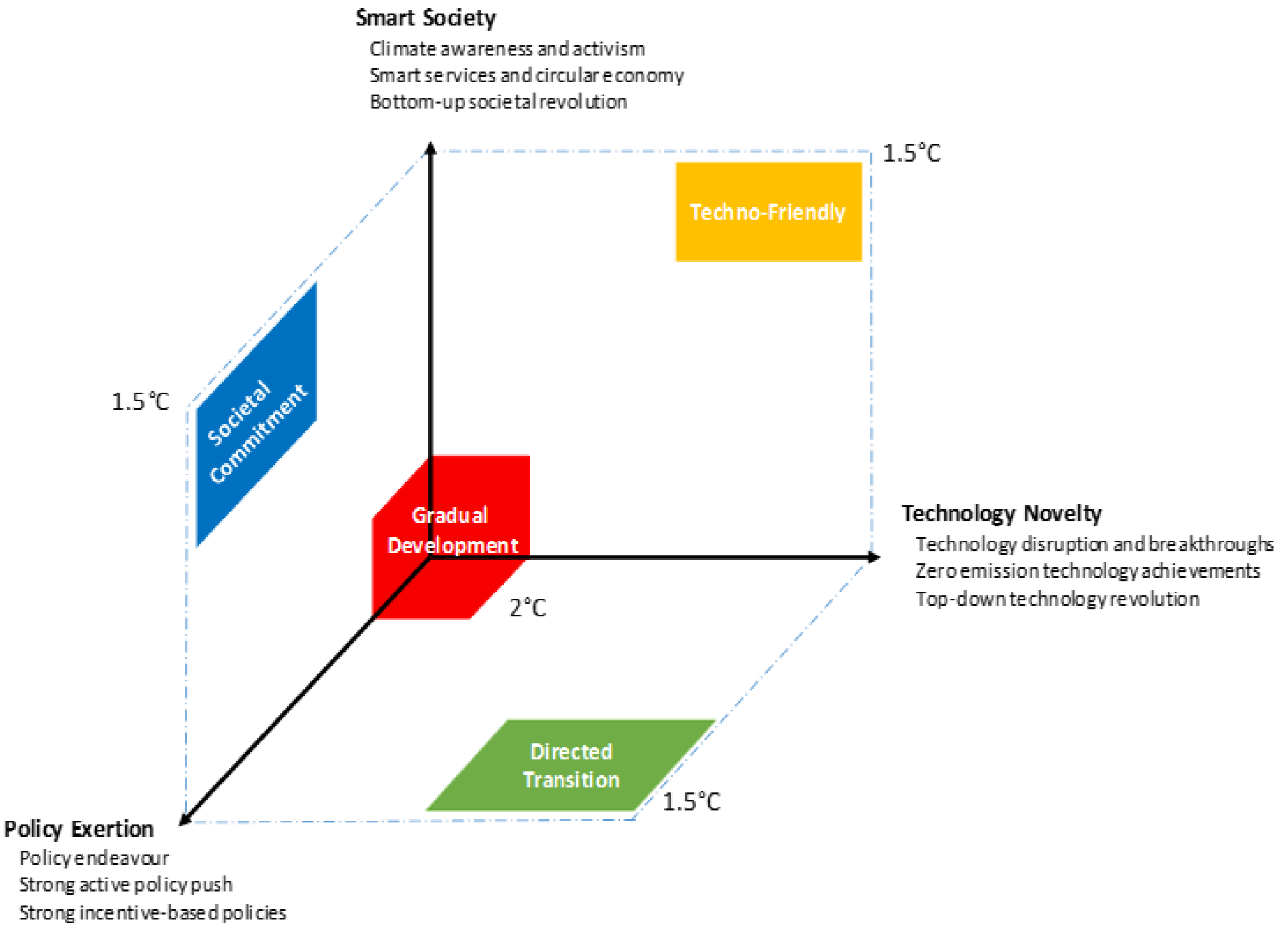
- Europe disaggregated into 30 regions
  - Mainland EU-25
  - Norway, Switzerland, Turkey, UK
  - Aggregated non-EU Balkan region
- Hourly time-series for renewable potentials and demands
  - Reduced by time-series clustering algorithm[1]
  - Results in temporal resolution of every 244th hour (35 time slices)



Scenario definition

H2020 Gradual Development Scenario

- Net-zero 2050 following a 2℃ pathway
- Combines societal, technological, and political aspects
- Carbon price drives decarbonization
  - 2030: 76.4 €/tCO_2
  - 2050: 355 €/tCO_2
- Reductions in energy demand until 2050
  - Electricity demand 2018: 10.48 EJ
  - Electricity demand 2050: 10.33 EJ

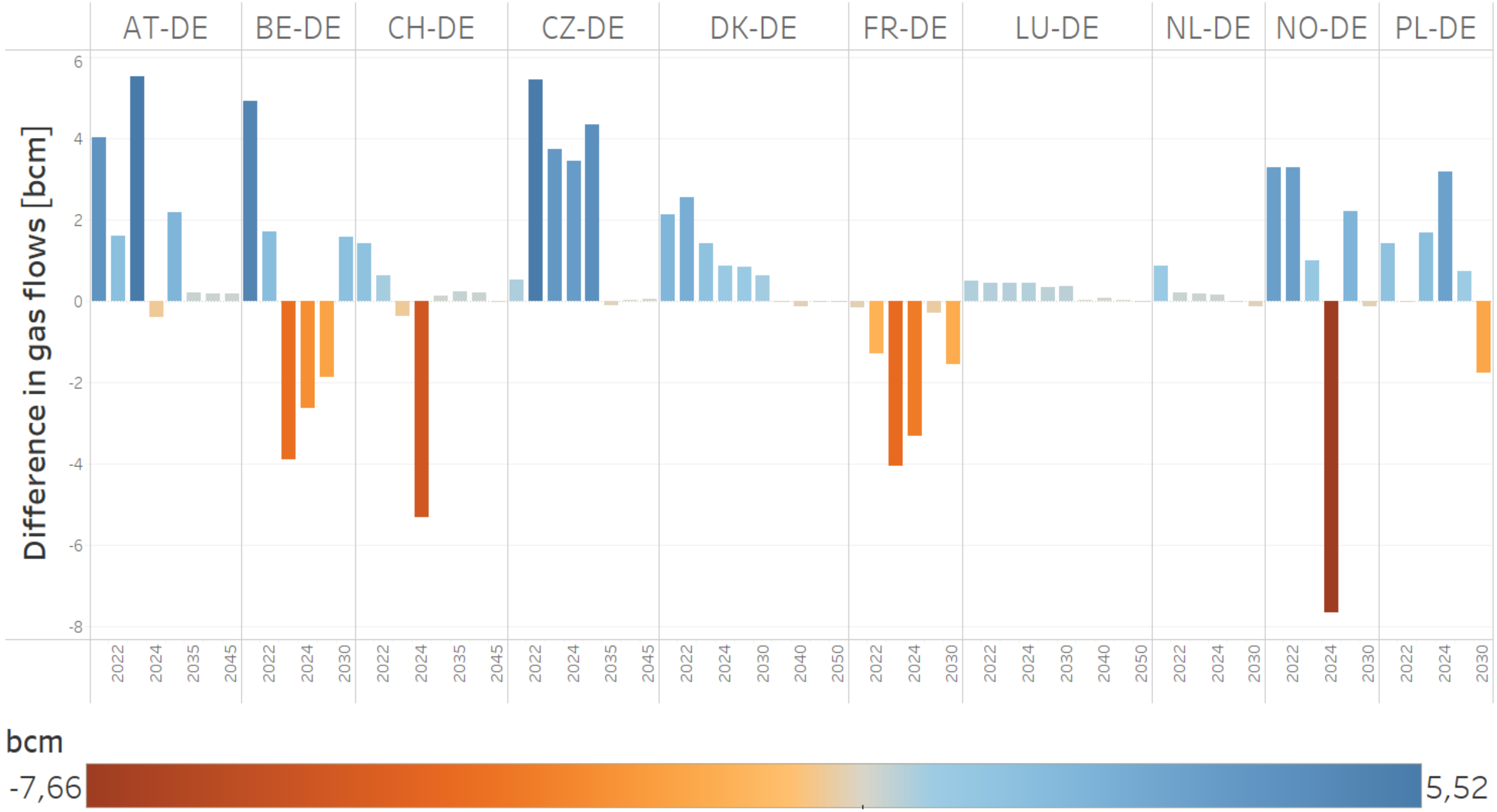


Source: Auer et al 2020

Moskalenko, Barner, Holz, Löffler, Steigerwald, von Hirschhausen
Technische Universität Berlin,German Institute for Economic Research (DIW Berlin),
Europe University Flensburg (EUF),NTNU Trondheim

Results (overview)

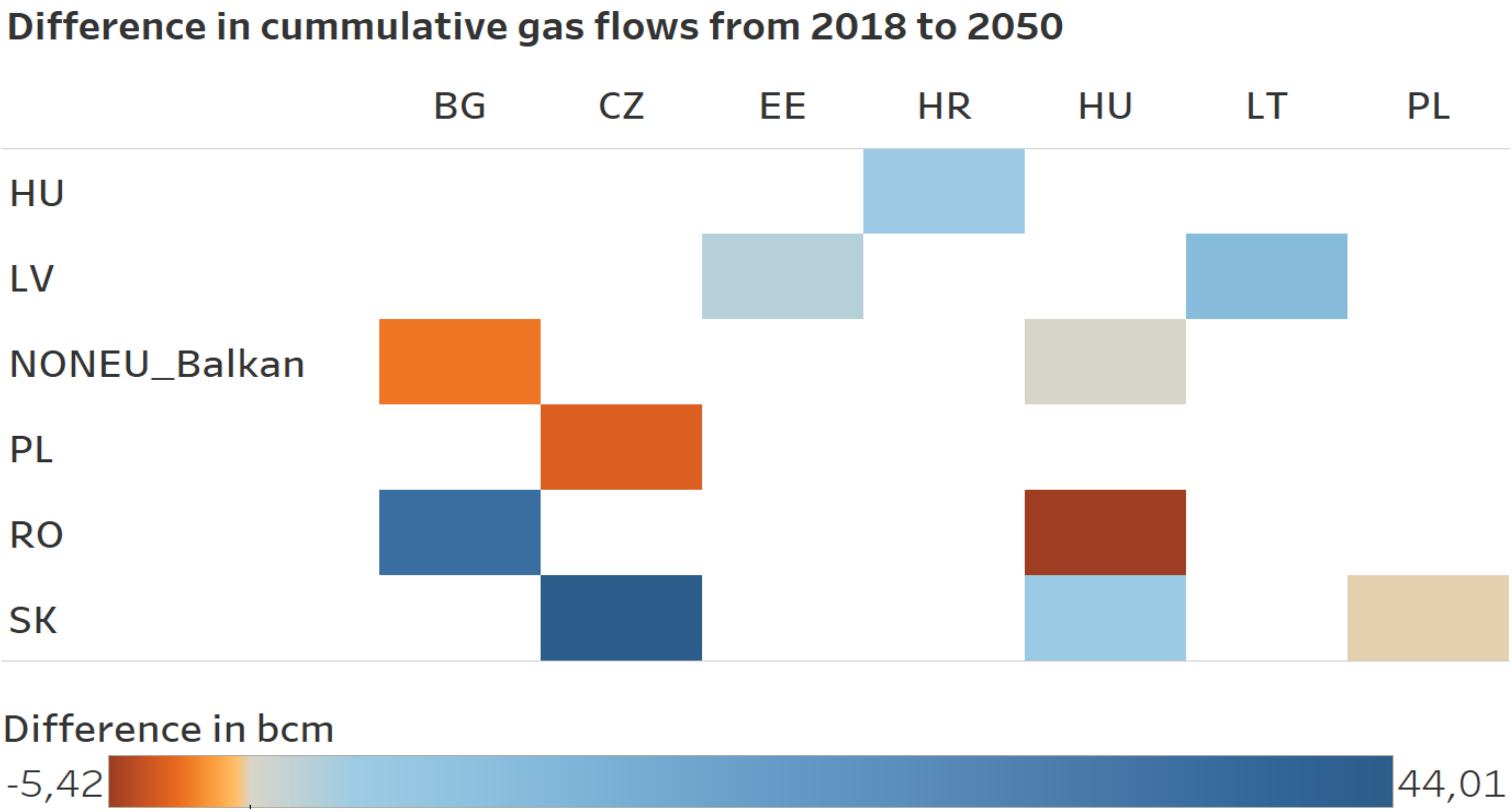
- Difference in gas flows between monodirectional and bidirectional pipeline capacities
- Negative values represent increased gas flows for the scenario with bidirectional capacities
- Trend for bidirectional pipelines to increase gas flows for Western neighbors of Germany, but decrease gas flows for Eastern neighbors



Results

- Difference in cumulative gas flows from 2018 to 2050 between monodirectional and bidirectional pipeline capacities
- Negative values represent increased gas flows for the scenario with bidirectional capacities
- Only pipelines for synthetic gas in 2050:

***~ GR – IT (2050, 60 PJ ~ 1.7 bcm synthetic gas)**
~ TR – BG (2050, 25 PJ ~ 0.7 bcm synthetic gas)
~ Balkan – HU (2050, 18 PJ ~ 0.5 bcm synthetic gas)
~ RO - HU (2050, 9 PJ ~ 0.25 bcm synthetic gas)
~ HU – SL (2050, 6 PJ ~ 0.2 bcm synthetic gas)
~ FI – SE (2050, neglectable)



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Discussion and Conclusion

~ Cross-border flows are an important element of supply security

~ While trading activity differs considerably, influences on prices and quantities remain small for European markets, even in times of scarcity („gas crisis“)

~ Case of East and West Germany highlights importance of bidirection flows

~ Small results are observeed in other regions, in particular Eastern Europe

➔ No reason NOT to proceed with bi-directionality

➔ Wait for another 20 years to be implemented …

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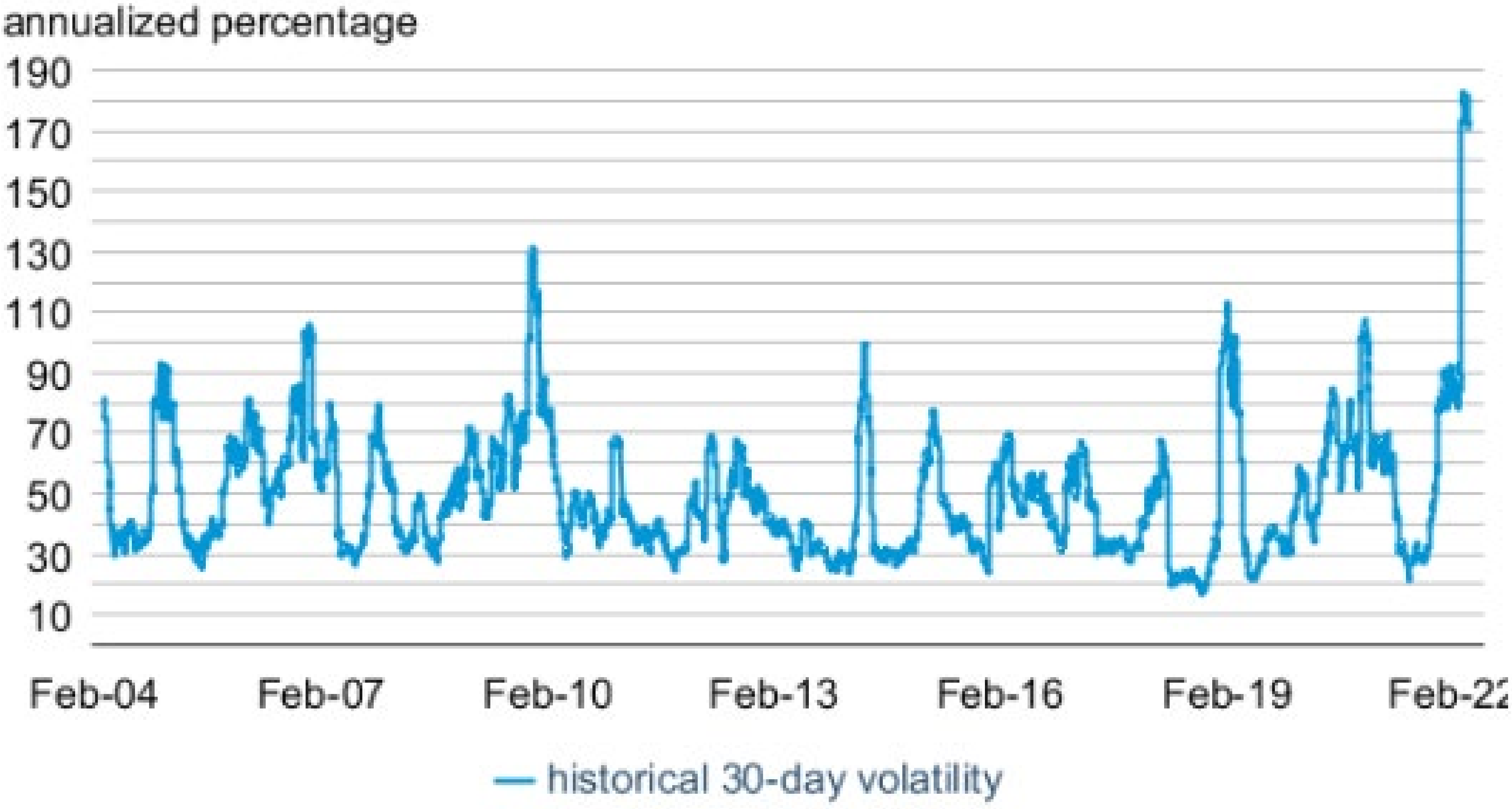
Natural Gas historical volatility



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