Improving the Coordination between Electricity and Gas Systems: A Distributed Market -Clearing Approach

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Agenda

Motivation

1 2 3 4 5

General challenges

Decarbonization
- High shares of renewables require infrastructure expansion + flexibility

Decentralization
- Spatio-temporal decoupling of generation and demand

Digitalization
- Extended possibilities of interconnection and participation, e.g., of „prosumers"

Specific challenges

Compliance with EU regulation [1]
- Confidentiality of sensitive comm. information
- Understandable transparent market rules

Risks and uncertainty of cross-sector operation
- Trading energy (electricity and gas) on multiple asynchronous markets leads to inefficiencies [2]

Flexibility market-integration
- Coordination of intertemporal constraints required to incentivize congestion relief

Existing coordination approaches

Central coordination: Requires some kind of third-party operator (e.g., an ISO) + disclosure of commercial sensitive information [3]

Decentralized coordination: Either local third-party operators [4] (+ information disclosure) or peer-to-peer trading, lacking scalability [5] + too complex [6]

Requirements for a coordination mechanism

Independence of units: Preserve confidentiality [1]

Limited exchange of information: Limited knowledge of other networks & units [7]

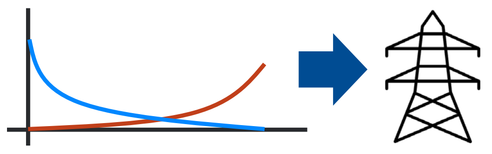
Reliability & scalability: Large-scale applications

Status quo & towards a novel market clearing framework

1 2 3 4 5

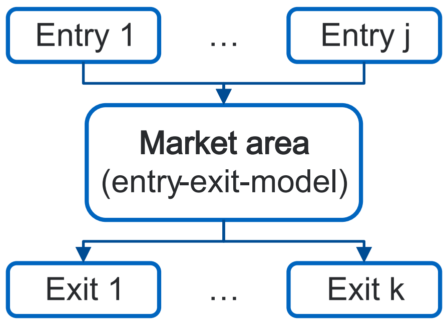
Status quo: Market & network operation (in Germany)

Electricity [8]



- Missing incentives for flexibilities
- No cross-sectoral coordination
- Inefficient congestion management
- Reduction of economic welfare

Natural gas [9]



- Theoretical congestions limit capacities
- Fees poss. discriminate market participants
- Reduction of economic welfare

Locational marginal prices (LMPs) & crosssector coordination

Natural gas

- Only actual congestions limit technical capacities
- LMPs adequately allocate network usage and congestions

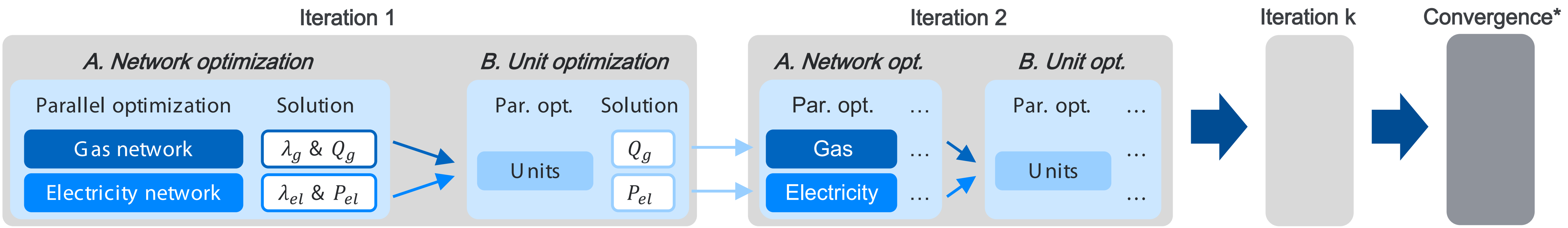
Electricity

- Local incentives for flexibilities to avoid congestions
- Joint market clearing and congestion mgmt.

Cross-sectoral

- Empowering usage of cross-sectoral flexibility
- Reducing complexity for cross-sectoral units by harmonizing asynchronous market clearings
- Leveraging economic welfare

Proposed architecture: Distributed iterative multi -period market clearing



*Evaluation is performed by gas and electricity network operator

Casestudy: German electricity & natural gassystems(24-h)

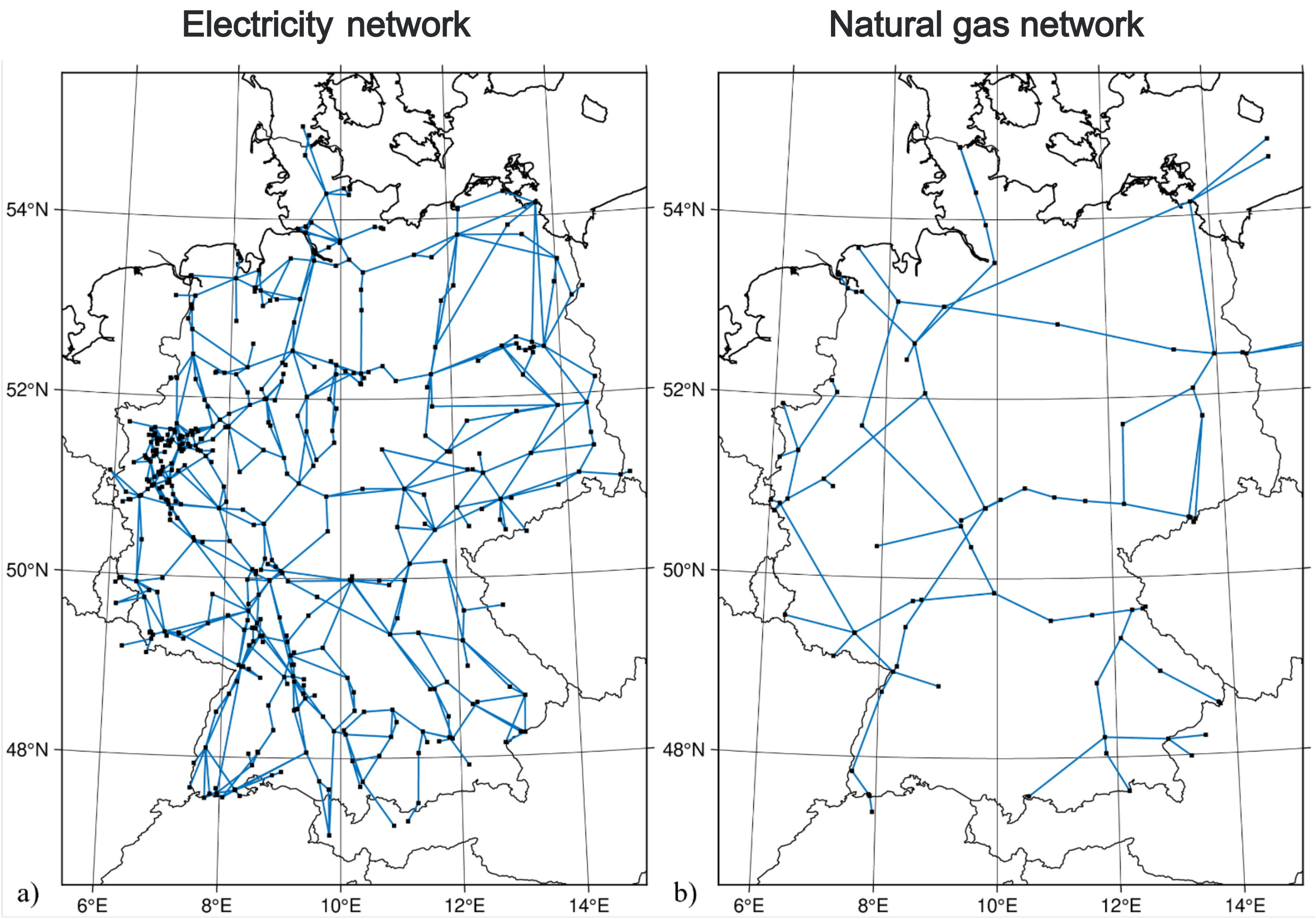
- Electricity network data [11]
  - LKD-EU – Reference data (2017)

Elements	No.
Nodes	450
Transmission lines	724

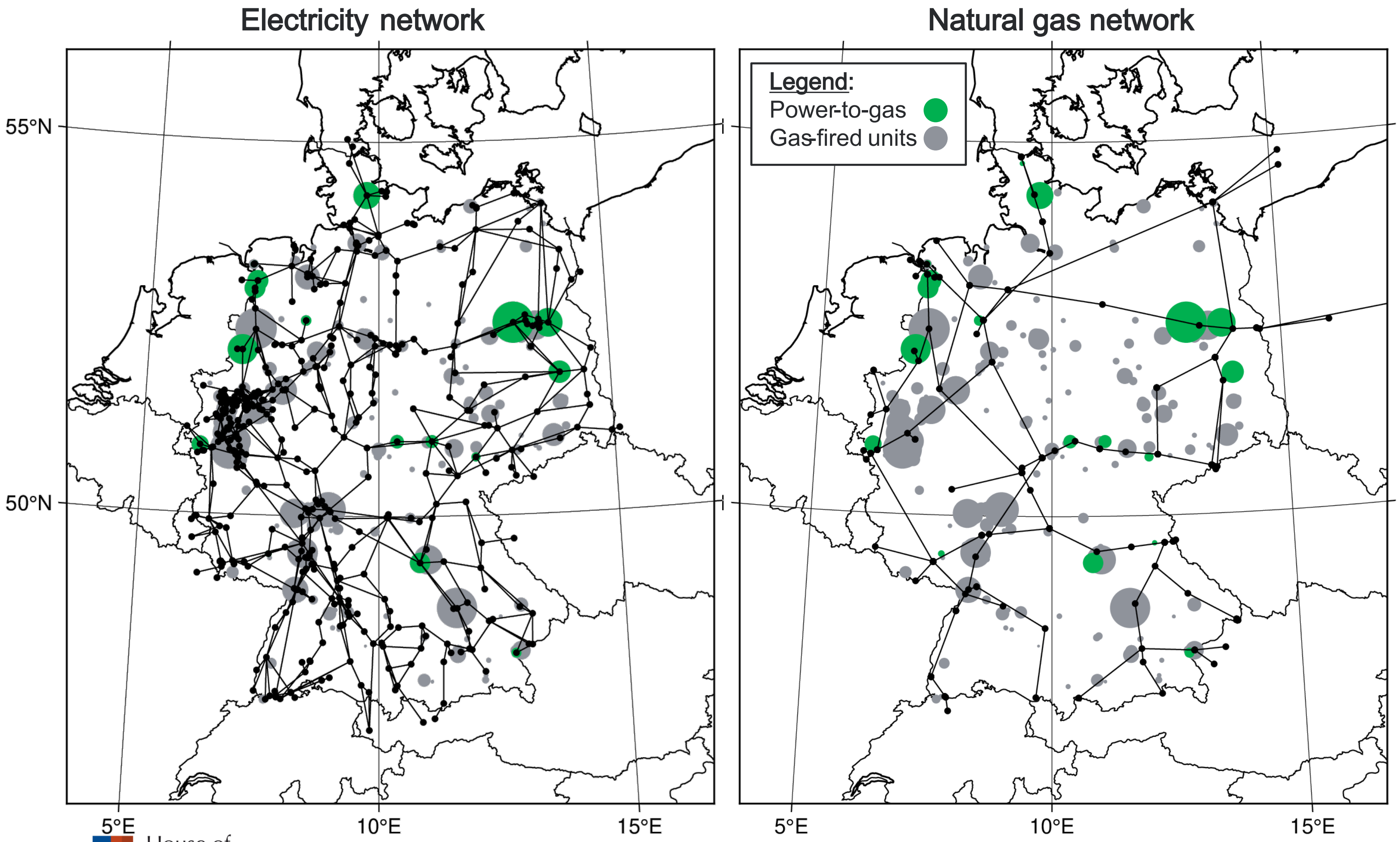
- Gas network data [12]
  - SciGRID_gas data

Elements	No.
Compressor stations	32
Nodes	202
Pipeline segments	123
Supply nodes	33

- Time-series data (demand & renewables)
  - Typical winter day 24 h period
  - Reference year: 2017

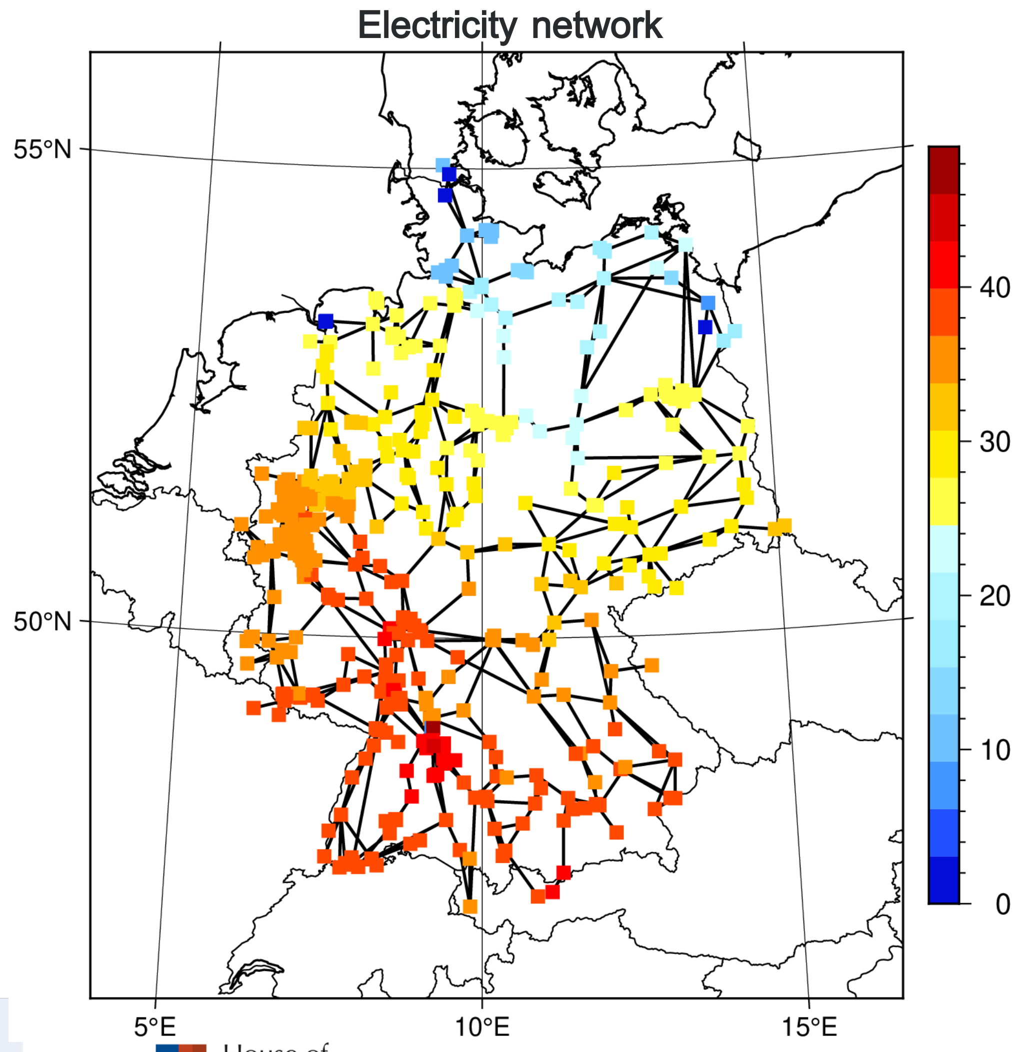


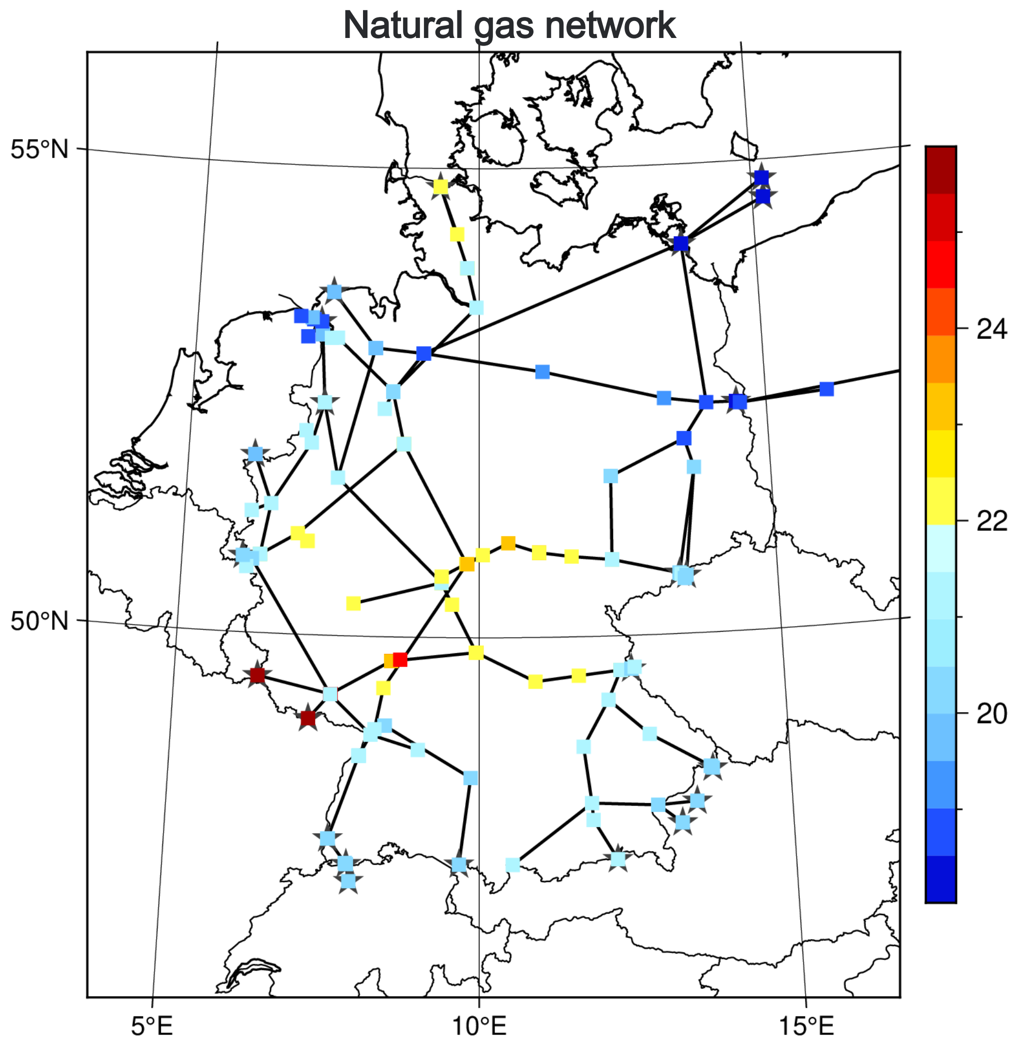
Casestudy: Cross-sectoral units & capacities



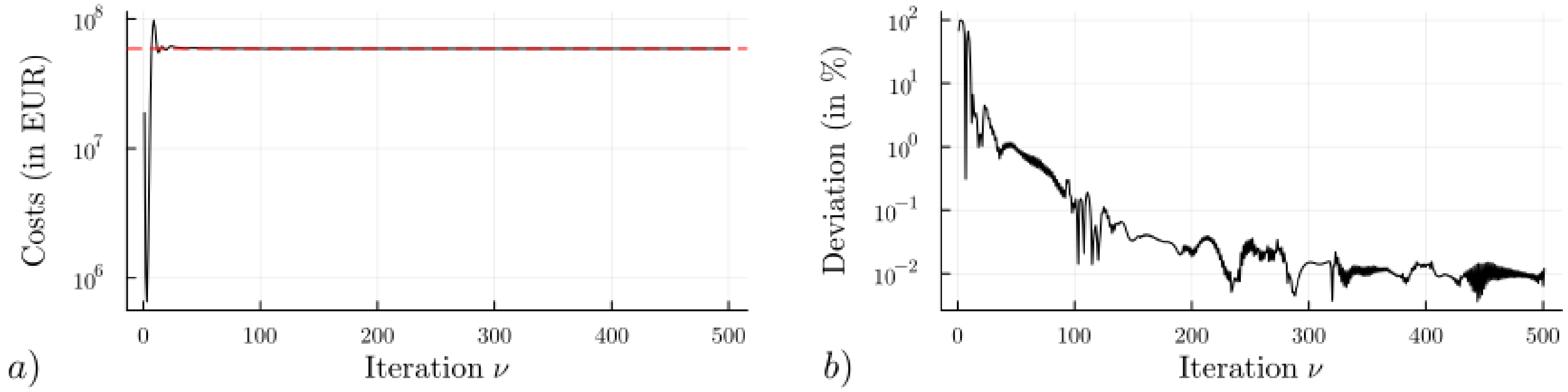
Technology	Capacity (in GW)	No.
Power-to-gas	5.06	19
Gas-fired units	23.62	271
Solar	26.23	315
Wind	35.11	269
Conventionals	79.30	436

Case study: Economic results– LMPs (in EUR/MWh)

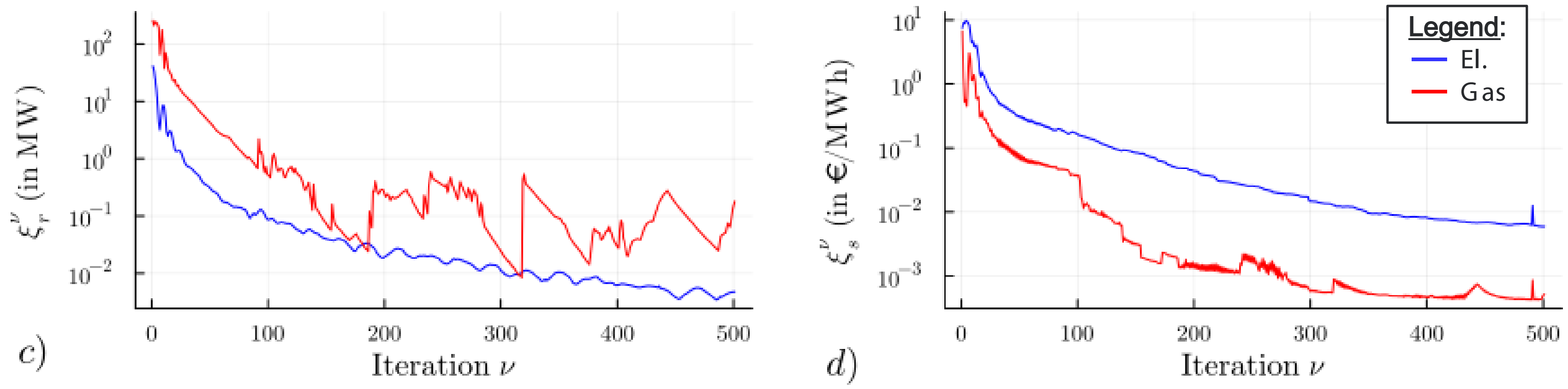




Total system costs– Absolute value & deviation



NRMSE– ξ_r^ν: network vs. unit results & ξ_s^ν: successive price updates



- Objective function
  - Deviation drops below 0.1 % after 110 iterations
- NRMSE (for each unit and hour) after 140 iterations:
  - Deviation between networks' and units' results falls below:
    - EL: 0.1 MW (for each hour)
    - Gas: 1 MW (for each hour)
  - Change of price updates between two iterations
    - EL: 0.1 €/MWh
    - Gas: 0.01 €/MWh
- Preliminary conclusion
  - Changes on a holistic level appear to be reasonably small
    → indicating convergence

Dispatch (in GWh) for 24-h after $\nu = \{250, 500\}$ iterations

	Technology	Single operator	DMC $\nu = 250$	DMC $\nu = 500$	Difference $\nu = 250$	Difference $\nu = 500$
Electricity	Conventionals	637.54	637.27	637.89	-0.27	0.35
	Wind	617.77	617.12	617.25	-0.65	-0.52
	Solar	7.26	7.33	7.42	0.07	0.16
	Gas-fired	96.95	98.22	97.06	1.27	0.11
	Power-to-gas	19.6	19.87	19.68	0.27	0.08
	Demand	1,262.76	1,262.87	1,262.75	0.11	-0.01
	Wind curt.	35.12	35.76	35.63	0.64	0.51
	Solar curt.	0.32	0.26	0.16	-0.06	-0.16
	Demand shed.	0	-0.11	0.01	-0.11	0.01
	Total supply	1,359.52	1,359.93	1,359.62	0.41	0.1
	Total demand	1,282.36	1,282.74	1,282.43	0.38	0.07
	Trans. losses	77.16	77.19	77.19	0.03	0.03
Natural gas	Import	6,529.11	6,531.36	6,529.28	2.25	0.17
	Power-to-gas	12.77	12.95	12.82	0.18	0.05
	Gas-fired	169.36	171.6	169.51	2.24	0.15
	Export	2,036.71	2,036.71	2,036.72	0	0.01
	Res. demand	2,852.13	2,852.13	2,852.16	0	0.03
	Ind. demand	1,076.71	1,076.71	1,076.74	0	0.03
	Export shed.	0	0	0	0	0
	Res. shed.	0	0	0	0	0
	Ind. shed.	0	0	0	0	0
	Total supply	589.36	589.58	589.38	0.22	0.02
	Total demand	552.7	552.9	552.71	0.2	0.01
	Trans. losses	36.66	36.68	36.66	0.02	0

- Overall observations for DMC
  - Deviations per technology are relatively small
  - Total supply, demand and losses are met better
- How imperfect is the DMC? Largest deviations
  - 250 iterations: 2.25 GWh (day) ~ 93.75 MWh (hour)
  - 500 iterations: -0.52 GWh (day) ~ 21.67 MWh (hour)
- Insights into DMC imperfections:
  - Units with (almost) identical costs are affected most
    - Renewables, conventionals, gas imports and exports
  - Sector coupling units take longer to converge
    - Two prices need to converge properly

Conclusion & outlook

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- Distributed market clearing (DMC)
  - Could serve as a basis for cross-sector coordination, preserving independence of units
  - Suitable for large-scale applications with limited information exchange
- Implementational aspects
  - Today, low latency **algorithmic traders** react to capital markets in under 1 ms
    - DMC with approx. 10^3 iterations could be achieved **within a couple of seconds**
  - Crucial factors:
    - Processing time of network and unit optimization
    - Physical distance between units and network operators
    - Handling of communication and algorithmic errors
- Handling of non-convexities
  - Despite the availability of proper & tight convex relaxations: More accurate models for unit commitment and gas network operation require mixed-integer models
  - Non-convexities lead to distortions and question the interpretability of prices
    - Revenue adequacy and cost recovery not guaranteed
- Extension of framework
  - Integration of balancing markets and ancillary services procurement
  - Integration of multiple network operators and distribution networks
  - Investigation of market power within a DMC

Thank you for your attention!

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Backup: Mathematical foundation

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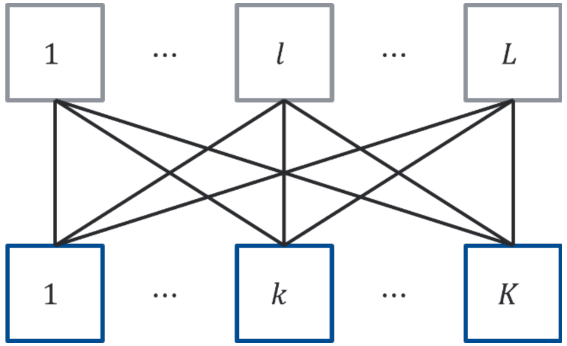
- Abstract structure
  - Units
  - Sectors



- Convex multi-period problem: An omniscient single-operator

$$\min_{x,y} \sum_{l\in\mathcal{L}} f_l(x_l) + \sum_{k\in\mathcal{K}} g_k(y_k)$$

$$\text{s.t.} \quad \sum_{l\in\mathcal{L}} A_{k,l}\tilde{x}_{k,l} + B_k\tilde{y}_k = c_k \quad : \lambda_k, \quad \forall k \in \mathcal{K},$$

$$x_l \in \mathcal{X}_l, \quad \forall l \in \mathcal{L},$$

$$y_k \in \mathcal{Y}_k, \quad \forall k \in \mathcal{K}.$$

E.g. loss minimization

Energy balance (nodal)

LMP of sector k

E.g. fuel prices for non-cross-sectoral units

Network constraints

Unit constraints

- Distributed market clearing* (Iteration ν)

1. Unit subproblem

$$\min_{x_l} \quad f_l(x_l) + \sum_{k\in\mathcal{K}} \left[-\left(\lambda_{k,l}^{\nu-1}\right)^\top \tilde{x}_{k,l} + \frac{\rho_k}{2}\left\|\psi_{k,l}^{\nu-1} - \tilde{x}_{k,l}\right\|_2^2 \right]$$

$$\text{s.t.} \quad x_l \in \mathcal{X}_l,$$

2. Sectoral network subproblem

$$\min_{y_k} \quad g_k(y_k) + \sum_{l\in\mathcal{L}} \left[\left(\lambda_{k,l}^{\nu-1}\right)^\top \psi_{k,l} + \frac{\rho_k}{2}\left\|\psi_{k,l} - \tilde{x}_{k,l}^{\nu-1}\right\|_2^2 \right]$$

$$\text{s.t.} \quad y_k \in \mathcal{Y}_k^{\psi},$$

3. Price updates (with constants φ_k^{ν} and ρ_k^{ν})

$$\lambda_{k,l}^{\nu+1} = \lambda_{k,l}^{\nu} + \varphi_k^{\nu}\rho_k^{\nu}\left(\psi_{k,l}^{\nu} - \tilde{x}_{k,l}^{\nu}\right),$$

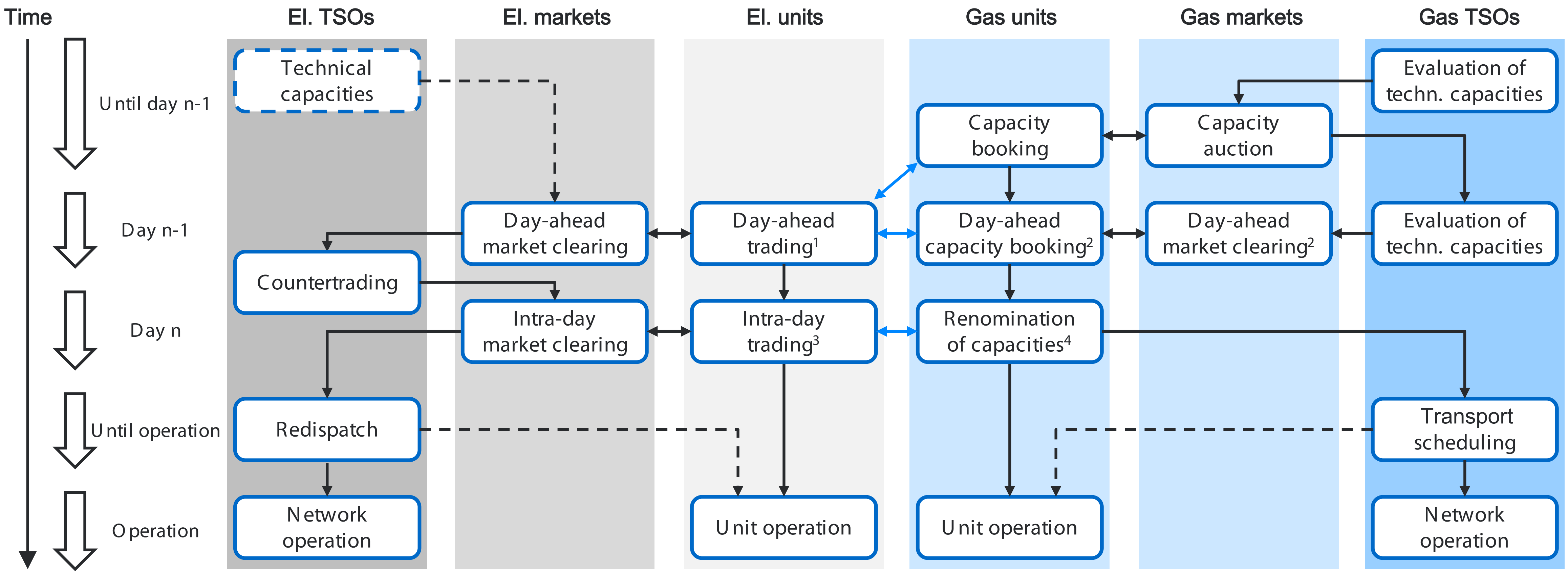
- Reformulating balances as part of networks

$$\sum_{l\in\mathcal{L}} A_{k,l}\psi_{k,l} + B_k\tilde{y}_k = c_k, \quad :\lambda_{k,n}, \quad \forall k \in \mathcal{K},$$

$$\psi_{k,l} = \tilde{x}_{k,l}, \quad \forall l \in \mathcal{L}, \forall k \in \mathcal{K}.$$

** Using decomposition techniques, here, alternating direction method of multipliers (ADMM), cf. [10]*

Backup: Existing market design in Germany



[1] *Hourly prices*
[2] *Daily prices*
[3] *15 min (5 min in advance)*
[4] *Hourly (2 h in advance)*

Backup: Existing market design in Germany

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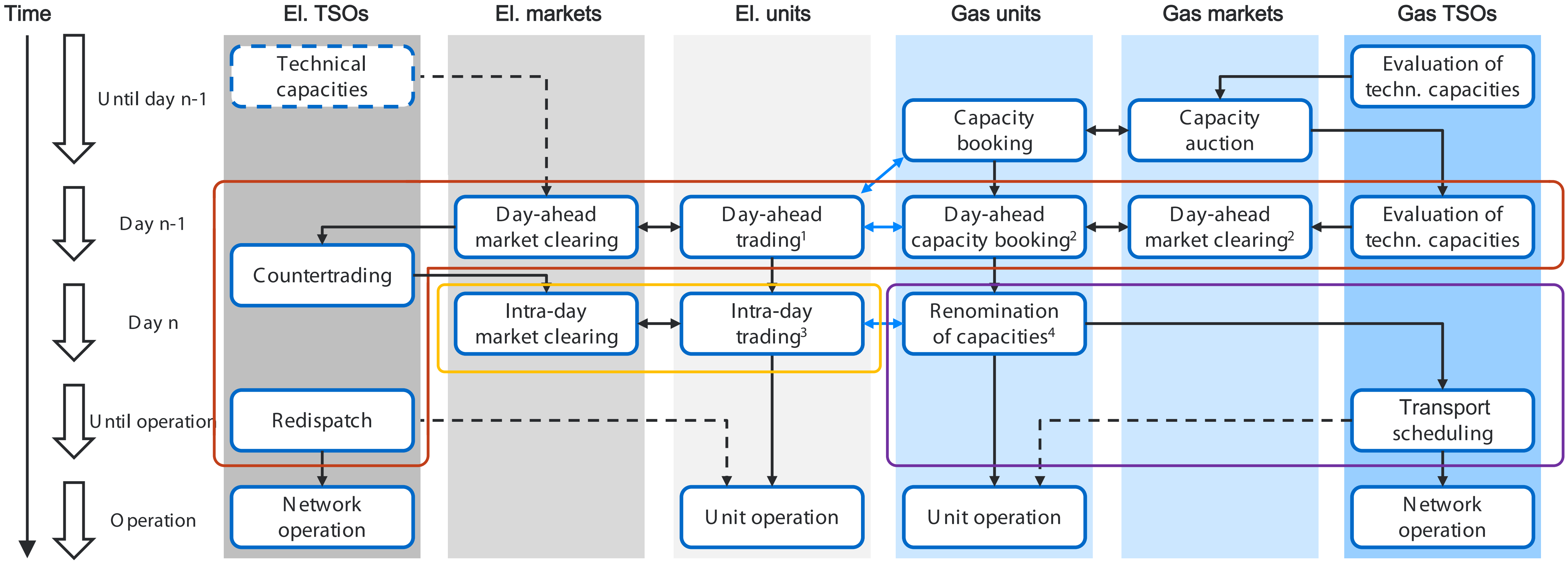

[1] *Hourly prices*
[2] *Daily prices*
[3] *15 min (5 min in advance)*
[4] *Hourly (2 h in advance)*

- **Focus:** Day-ahead distributed market clearing (DMC)
- Intra-day or real-time DMC → Balancing + ancillary services
- Part of intra-day DMC or simple renomination

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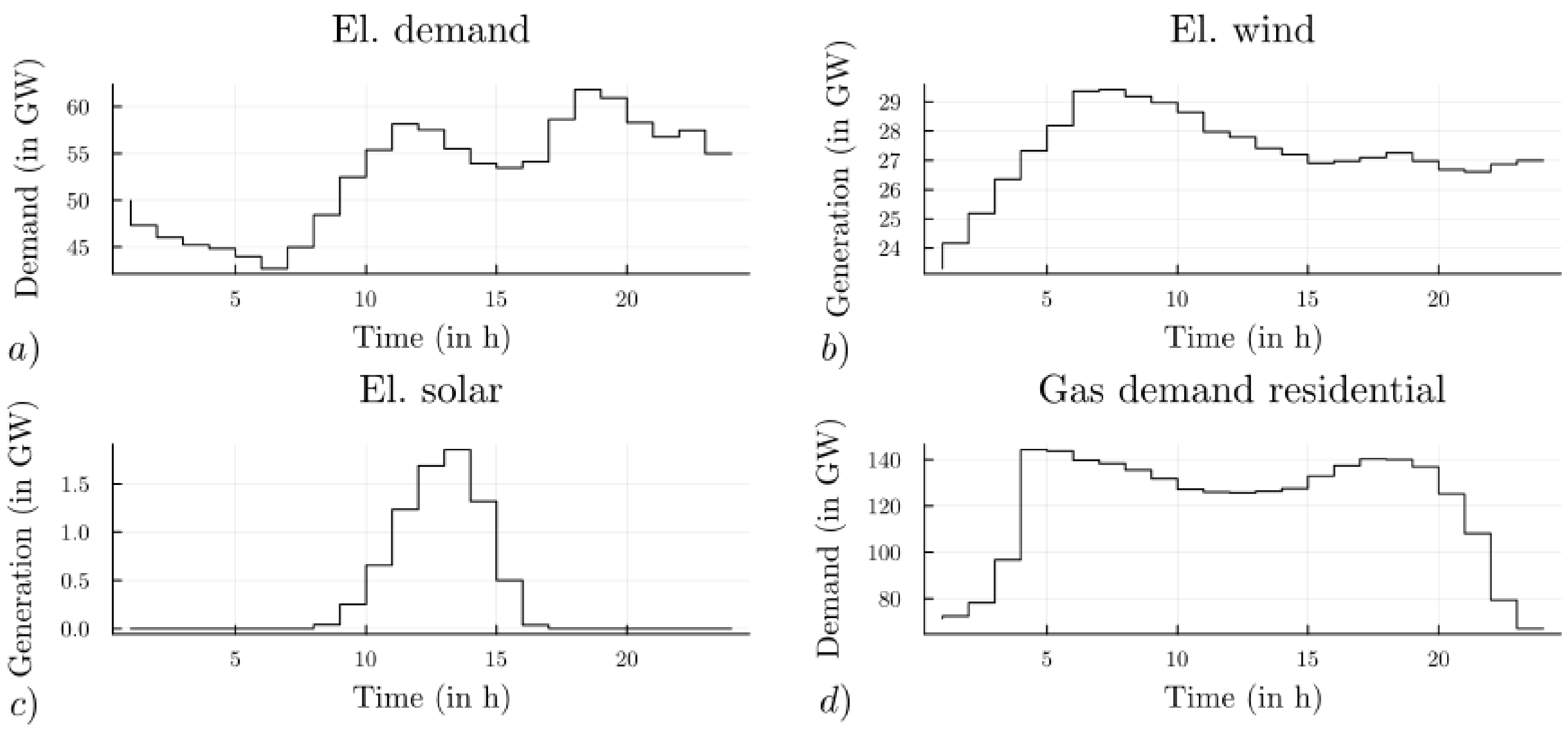
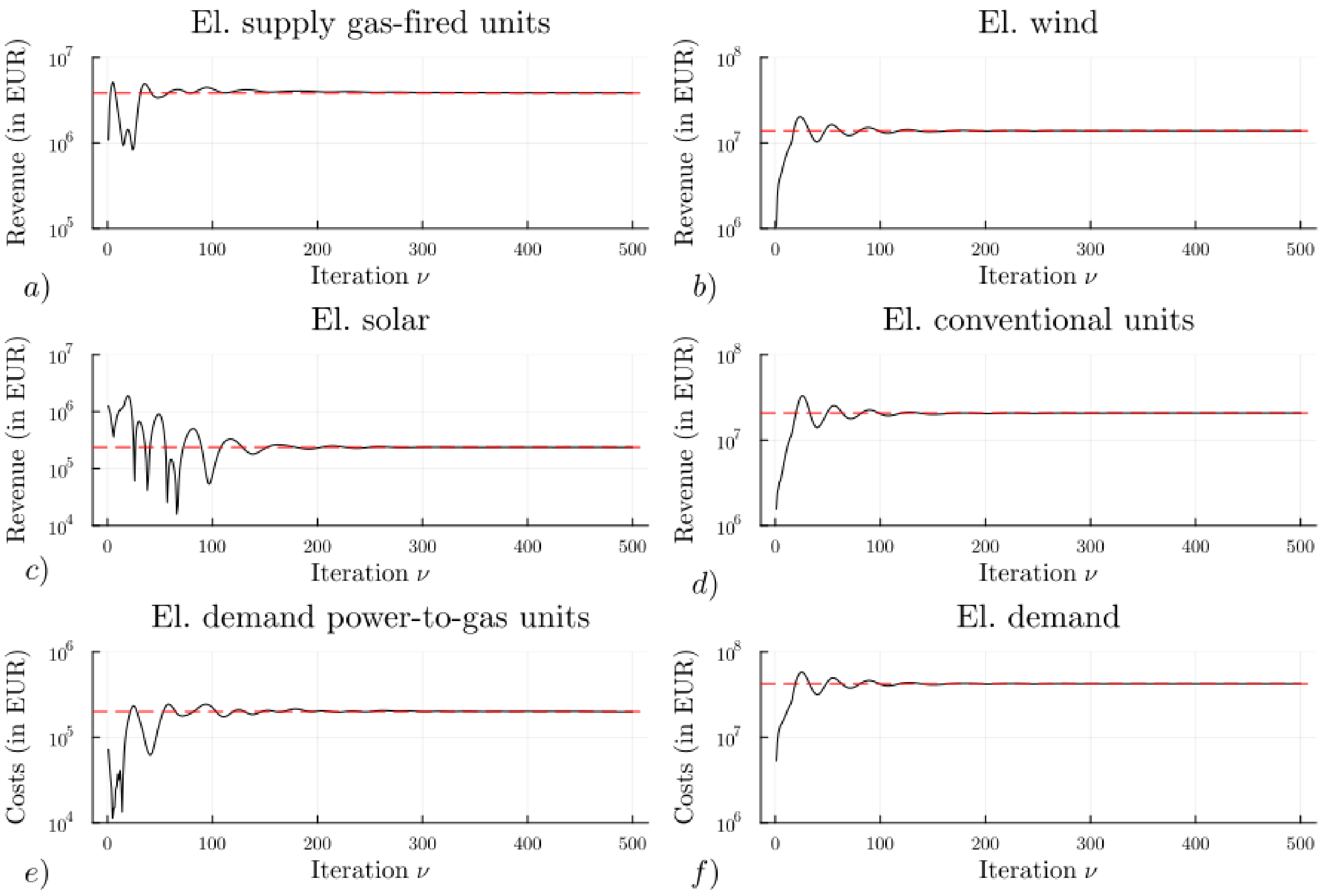
Sources: [8], [9]

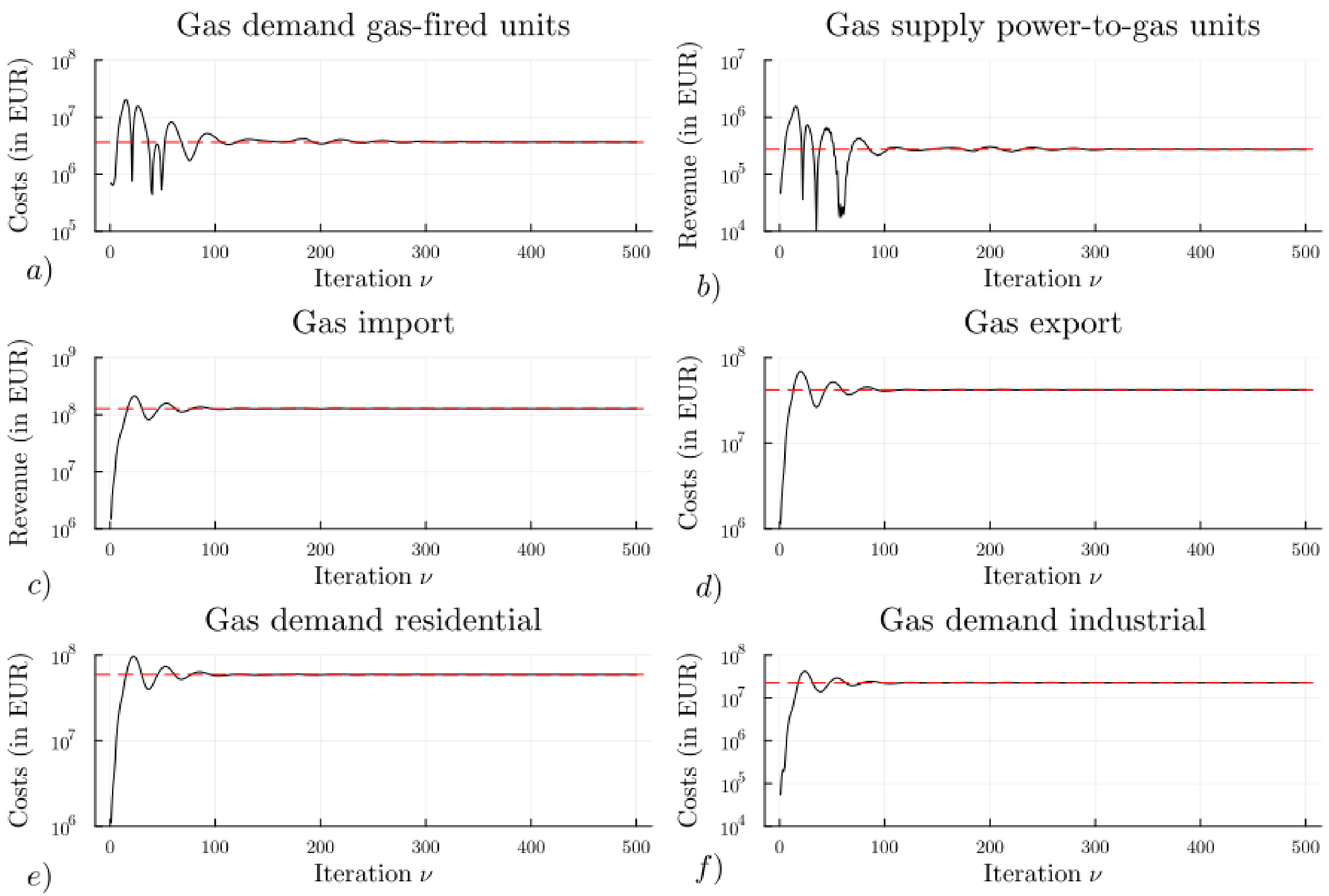
Backup: Electricity and gas time-series data



Backup: Convergence on a technology level- EL



Backup: Convergence on a technology level- Gas



Backup: Gas model

$$\min_{\Xi_t^{gas},\Theta_t^{gas}} \sum_{t\in\mathbb{T},m\in\mathbb{M}} \Bigg[\sum_{s\in\mathbb{S}(m)} c_s^{gas,S} Q_{s,t}^{S} + c_m^{gas,VOLL}\left(Q_{m,t}^{D+} - Q_{m,t}^{D}\right) + c_m^{gas,Ex}\left(Q_{m,t}^{D,Ex+} - Q_{m,t}^{D,Ex}\right)\Bigg]\Delta t, \qquad (20a)$$

s.t.

$$Q_{m,t}^{N,S} + Q_{m,t}^{F} + Q_{m,t}^{C} + Q_{m,t}^{N,S,PtG} = Q_{m,t}^{D} + Q_{m,t}^{N,D,GFU} + Q_{m,t}^{D,Ex}, \qquad \forall m \in \mathbb{M}, t \in \mathbb{T}, \qquad (20b)$$

$$Q_{m,t}^{N,S} = \sum_{s\in\mathbb{S}(m)} Q_{s,t}^{S}, \qquad \forall m \in \mathbb{M}, t \in \mathbb{T}, \qquad (20c)$$

$$Q_{m,t}^{N,S,PtG} = \sum_{k\in\mathbb{K}_{gas}^{PtG}(m)} Q_{k,t}^{S,PtG}, \qquad \forall m \in \mathbb{M}, t \in \mathbb{T}, \qquad (20d)$$

$$Q_{m,t}^{N,D,GFU} = \sum_{k\in\mathbb{K}_{gas}^{GFU}(m)} Q_{k,t}^{D,GFU}, \qquad \forall m \in \mathbb{M}, t \in \mathbb{T}, \qquad (20e)$$

$$p_m^{min} \le p_{m,t} \le p_m^{max}, \qquad \forall m \in \mathbb{M}, t \in \mathbb{T}, \qquad (20f)$$

$$0 \le Q_{s,t}^{S} \le Q_{s,t}^{S+}, \qquad \forall s \in \mathbb{S}, t \in \mathbb{T}, \qquad (20g)$$

$$0 \le Q_{m,t}^{D} \le Q_{m,t}^{D+}, \qquad \forall m \in \mathbb{M}, t \in \mathbb{T}, \qquad (20h)$$

$$0 \le Q_{m,t}^{D,Ex} \le Q_{m,t}^{D,Ex+}, \qquad \forall m \in \mathbb{M}, t \in \mathbb{T}, \qquad (20i)$$

$$Q_{m,t}^{C} = \sum_{n\in\mathbb{C}^{in}(m)} \left(Q_{m,n,t}^{C,In} - Q_{m,n,t}^{C,Out}\right) + \sum_{n\in\mathbb{C}^{out}(m)} \left(Q_{n,m,t}^{C,In} - Q_{n,m,t}^{C,Out}\right), \qquad \forall m \in \mathbb{M}, t \in \mathbb{T}, \qquad (20j)$$

$$Q_{n,m,t}^{C,Out} = Q_{m,n,t}^{C,In}, \qquad \forall m,n \in \mathbb{C}, t \in \mathbb{T}, \qquad (20k)$$

$$Q_{m,n,t}^{C,Out} = Q_{n,m,t}^{C,In} + Q_{m,n,t}^{C,Loss}, \qquad \forall m,n \in \mathbb{C}, t \in \mathbb{T}, \qquad (20l)$$

$$\alpha_m^{C,min} p_{m,t} \le p_{n,t} \le \alpha_m^{C,max} p_{m,t}, \qquad \forall m,n \in \mathbb{C}, t \in \mathbb{T}, \qquad (20m)$$

$$Q_{m,n,t}^{C,Out} \le Q_{m,n}^{C,max}, \qquad \forall m,n \in \mathbb{C}, t \in \mathbb{T}, \qquad (20n)$$

$$Q_{m,t}^{F} = \sum_{n\in\mathbb{P}^{in}(m)} \left(Q_{m,n,t}^{F,In} - Q_{m,n,t}^{F,Out}\right), \qquad \forall m \in \mathbb{M}, t \in \mathbb{T}, \qquad (20o)$$

$$\bar{Q}_{m,n,t}^{F} = \left(Q_{n,m,t}^{F,In} + Q_{m,n,t}^{F,Out}\right)/2, \qquad \forall m,n \in \mathbb{P}, t \in \mathbb{T}, \qquad (20p)$$

$$\bar{Q}_{m,n,t}^{F}\left|\bar{Q}_{m,n,t}^{F}\right| = W_{m,n}\left(p_{m,t}^2 - p_{n,t}^2\right), \qquad \forall m,n \in \mathbb{P}, t \in \mathbb{T}, \qquad (20q)$$

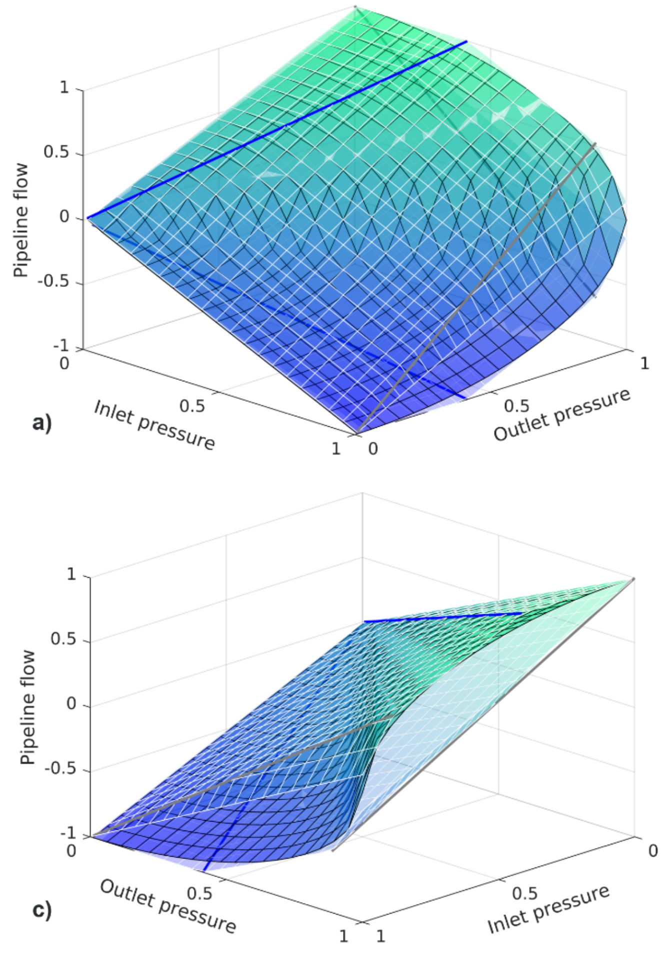
$$\bar{V}_{m,n,t}^{LP} = K_{m,n}^{LP}\left(p_{m,t} + p_{n,t}\right)/2, \qquad \forall m,n \in \mathbb{P}, t \in \mathbb{T}, \qquad (20r)$$

$$\Delta V_{m,n,t}^{LP} = \left(Q_{m,n,t}^{F,Out} - Q_{n,m,t}^{F,In}\right)\Delta t, \qquad \forall m,n \in \mathbb{P}, t \in \mathbb{T}. \qquad (20s)$$

$$\bar{V}_{m,n,t}^{LP} - \bar{V}_{m,n,t-1}^{LP} = \Delta V_{m,n,t}^{LP}, \qquad \forall m,n \in \mathbb{P}, t \in \mathbb{T}. \qquad (20t)$$

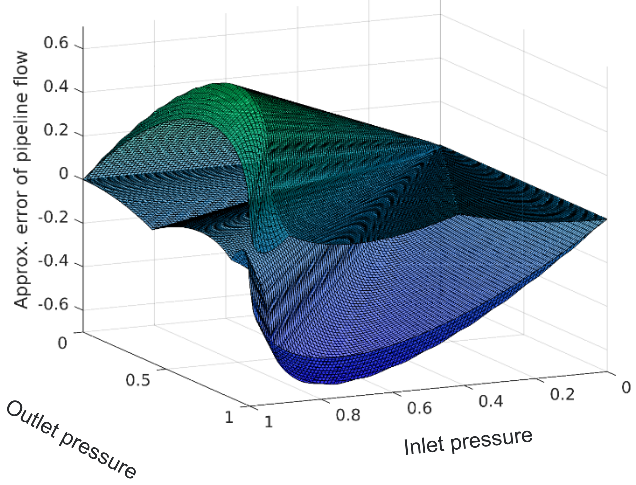
$$\bar{V}_{m,n,t_0}^{LP} = \bar{V}_{m,n,|\mathbb{T}|}^{LP}, \qquad \forall m,n \in \mathbb{P}, \qquad (20u)$$

Relaxation via McCormick envelopes



Approximation error

Relaxation



Mixed-integer approach