IAEE European Conference, Vienna, September 4, 2017

A Sector-coupling Spatial Optimization Model for the German Electricity Market

Bringing Gas and Heat Into the Equation

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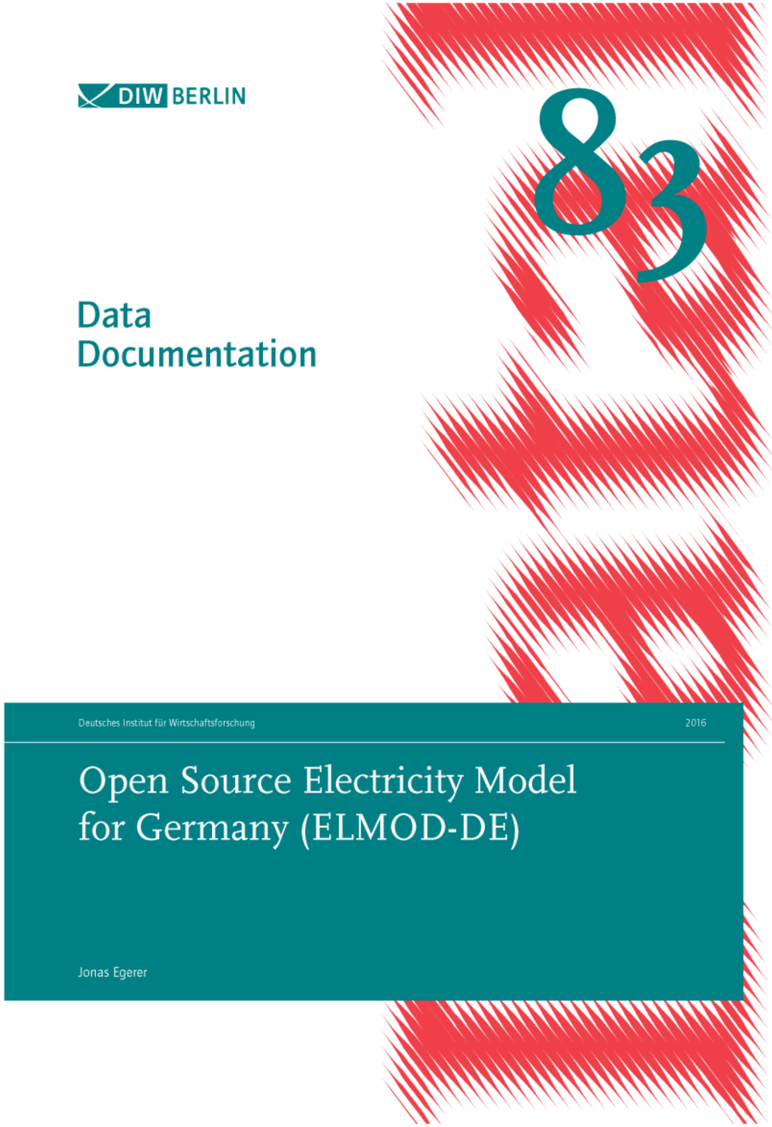
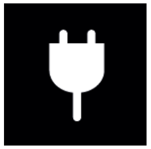
Extending ELMOD-DE by CHP and Natural Gas



ELMOD-DE (2016)

ELMOD-DE is an open source electricity market dispatch model for Germany, supplied with data for the year 2012.



New Developments (2017)

– Update of all data to the year 2015
– Inclusion of CHP power plants
– Coupling with the natural gas market

ELMOD-DE Electricity Market Model

Features

- cost minimizing **linear (LP)** model written in GAMS
- hourly resolution (8760 hours)
  possibility to calculate single weeks
- block sharp representation of power plant portfolio
- fixed imports and exports for neighboring countries

DC Load Flow

$$pf_{1,2} = G_l(V_1^2 - V_1 V_2 \cos(\theta_1 - \theta_2)) + \hat{b}_l V_1 V_2 \sin(\theta_1 - \theta_2) \qquad (1)$$

$$\sin(\theta_1 - \theta_2) \approx \theta_1 - \theta_2 \qquad (2a)$$

$$\cos(\theta_1 - \theta_2) \approx 1 \qquad (2b)$$

$$V_1 \approx V_2 \approx 1 \qquad (2c)$$

$$pf_{1,2} = \hat{b}_l(\theta_1 - \theta_2) \qquad (3)$$

$$|pf_{lt}| \le \overline{pf}_l \qquad \forall \quad l,t \qquad (4a)$$

$$pf_{lt} = \sum_n \theta_{nt} h_{ln} \qquad \forall \quad l,t \qquad (4b)$$

$$ni_{nt} = \sum_k \theta_{kt} b_{nk} \qquad \forall \quad n,t \qquad (4c)$$

$$\theta_{\hat{n}t} = 0 \qquad \forall \quad t \qquad (4d)$$

Generation Cost Minimizing Objective Function

$$\min_{g^{\text{unit}}} c = \sum_{pt} g_{pt}^{\text{unit}} \hat{c}_{pt}^{\text{unit}} \qquad (5)$$

Nodal Energy Balance

$$\sum_{p \in P_n} g_{pt}^{\text{unit}} + \sum_i r_{nit}^{\text{tech}} + \sum_{s \in S_n} \overrightarrow{ps}_{st} + ni_{nt} = q_{nt} + \sum_{s \in S_n} \overleftarrow{ps}_{st} \qquad \forall \quad n,t \qquad (6)$$

Generation Constraints

$$g_{pt}^{\text{unit}} \le \overline{g}_p^{\text{unit}} av_{pt}^{\text{unit}} \qquad \forall \quad p,t \qquad (7a)$$

$$r_{nit}^{\text{tech}} \le \overline{r}_{nit}^{\text{tech}} av_{nit}^{\text{tech}} \qquad \forall \quad n,i,t \qquad (7b)$$

PSP Storage Constraints

$$\overrightarrow{ps}_{st} + \overleftarrow{ps}_{st} \le \overline{ps}_s \qquad \forall \quad s,t \qquad (8a)$$

$$ls_{st} \le \overline{ls}_s \qquad \forall \quad s,t \qquad (8b)$$

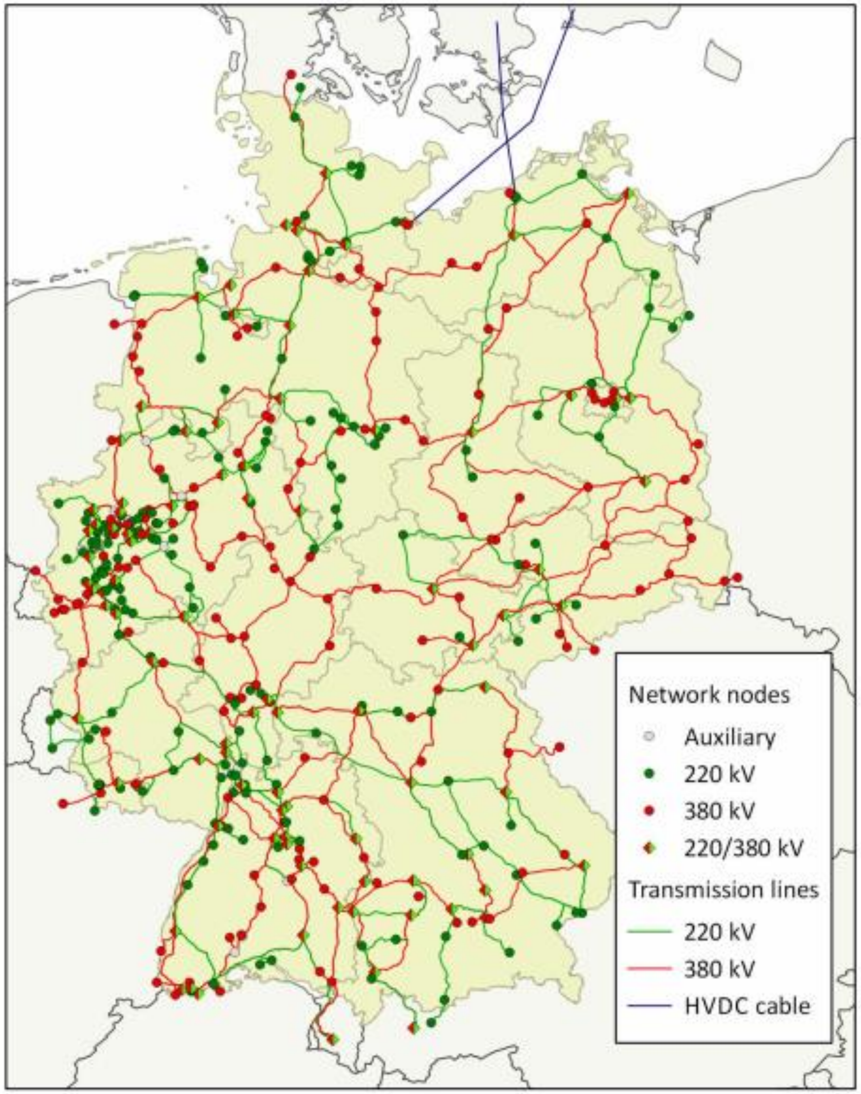
$$ls_{st} = 0.75\overleftarrow{ps}_{st} - \overrightarrow{ps}_{st} + ls_{s(t-1)} \qquad \forall \quad s,t \qquad (8c)$$

Input Data ELMOD-DE

Update to 2015 data

Type	Data description	References[10]
Network	- Topology according to network plans	VDE & TSOs
	- Geo-referenced data for nodes and lines	OpenStreetMap (2013)
	- Technical parameters overhead power lines	Kießling et al. (2001)
Demand	- Load level of Germany (hourly)	ENTSO-E (2013)
	- Adjustment to statistic of annual demand	BDEW (2013)
	- Spatial allocation to network nodes with statistic on population and GDP	Eurostat (EC, 2013) on NUTS 3 level
Generation	- Power plant list for the German system	BNetzA (2013)
	- Renewable data of the EEG support scheme	TSOs
	- Price data for fossil fuels (monthly)	Kohlenwirtschaft e.V.
	- Price data for CO_2 certificates (daily)	EEX (2013)
	- Coal transport cost (dena zones)	Frontier & Consentec
Trade	- Physical cross-border flows (hourly)	TSOs and ENTSO-E
Availability	- Regional time series for wind and PV (hourly)	TSOs

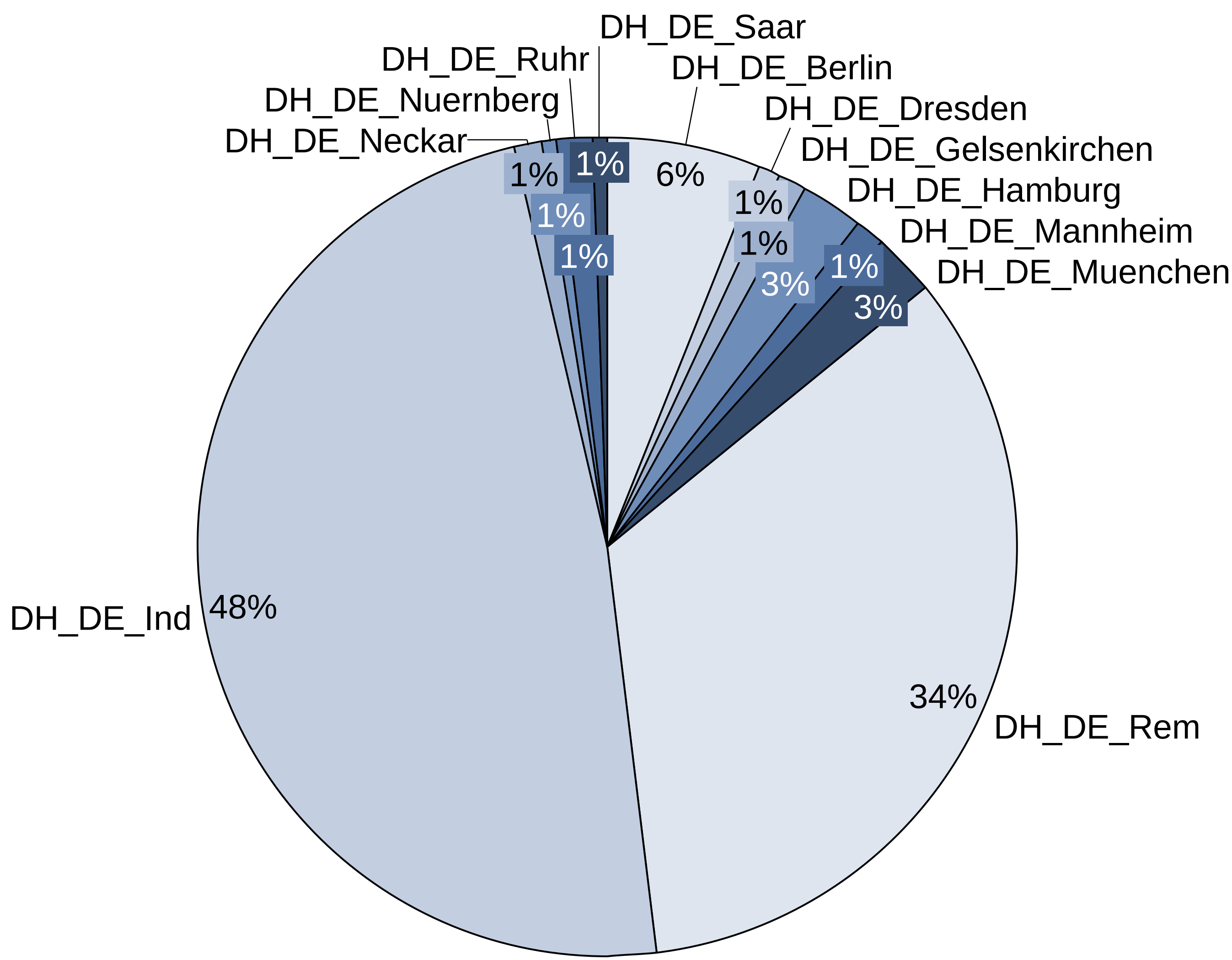
Table 2: Overview on institutions for data sources



CHP: pooling for district heating

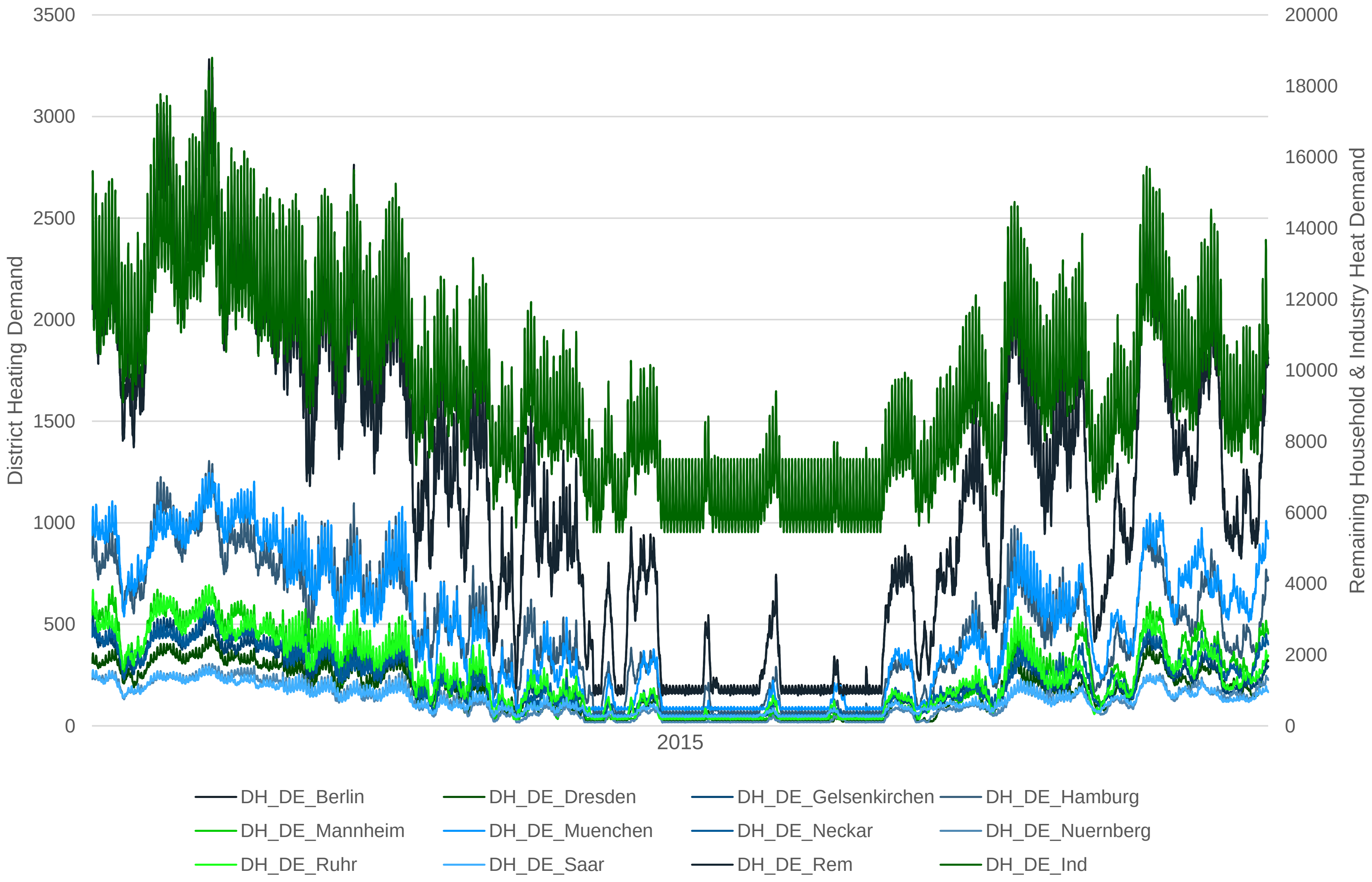
- **Idea: modeling pools of CHP plants in district heating networks with common minimum heat production constraints for household demands**
  - modeling must-run conditions for CHP plants decreases their production flexibility (more realistic – was not yet included in the original ELMOD-DE)
  - (incomplete) inclusion of pools for district heating increases the flexibility
  - problem: (open) data basis – the ten biggest district heating systems only account for about 35% of household heat demand
  - is the effort and increased complexity of the model worth the outcome?

Data Input: Heat Demand Time Series



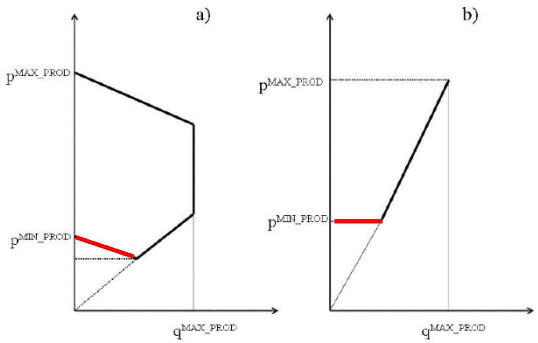
Network	Q [TWh]
DH_DE_Berlin	10.36
DH_DE_Dresden	1.47
DH_DE_Gelsenkirchen	1.83
DH_DE_Hamburg	4.09
DH_DE_Mannheim	2.19
DH_DE_Muenchen	4.25
DH_DE_Rem	57.90
DH_DE_Ind	82.10
DH_DE_Neckar	1.92
DH_DE_Nuernberg	1.03
DH_DE_Ruhr	2.11
DH_DE_Saar	1.10

Data Input: Heat Demand Time Series



CHP and District Heating

Extraction-condensing and backpressure turbines



Simplified PQ-chart for a) extraction-condensing turbines and b) back pressure turbines (Source: WILMAR)

$P \leq p_{max} - \gamma \times Q$	$P \leq p_{max}$
$P \geq p_{min} - \gamma \times Q$	$P \geq p_{min}$
$P \geq \delta \times Q$	$P = \delta \times Q$

$$Q \leq q_{max}$$

Heat Demand

$$q \geq Q_{MIN}$$

Household Q_{MIN}

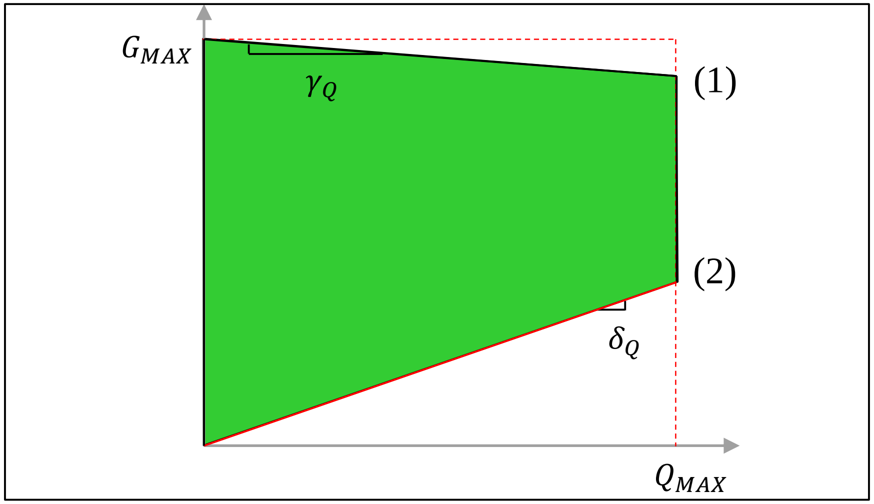
- **Pooled District Heating Q_{MIN}**
  The ten largest district heating systems have a shared heat demand time series for their CHP plants
- **Separate Q_{MIN}**
  Time series are allocated to plants via their share of maximum heat generation

Industrial Q_{MIN}

Time series are allocated to plants via their share of maximum heat generation

All parameters and variables dependent on time and production unit/district heating pool

CHP and District Heating



Extraction-condensing turbines (EXT)

$$g \leq G_{MAX} - \gamma_Q \times q \qquad (1)$$

$$g \geq \delta_Q \times q \qquad (2)$$

$$q \leq Q_{MAX}$$

Backpressure turbines (BKP)

$$g \leq G_{MAX}$$

$$g = \delta_Q \times q \qquad (2)$$

$$q \leq Q_{MAX}$$

Heat Demand

$$q \geq Q_{MIN}$$

Household Q_{MIN}

- Pooled District Heating Q_{MIN}
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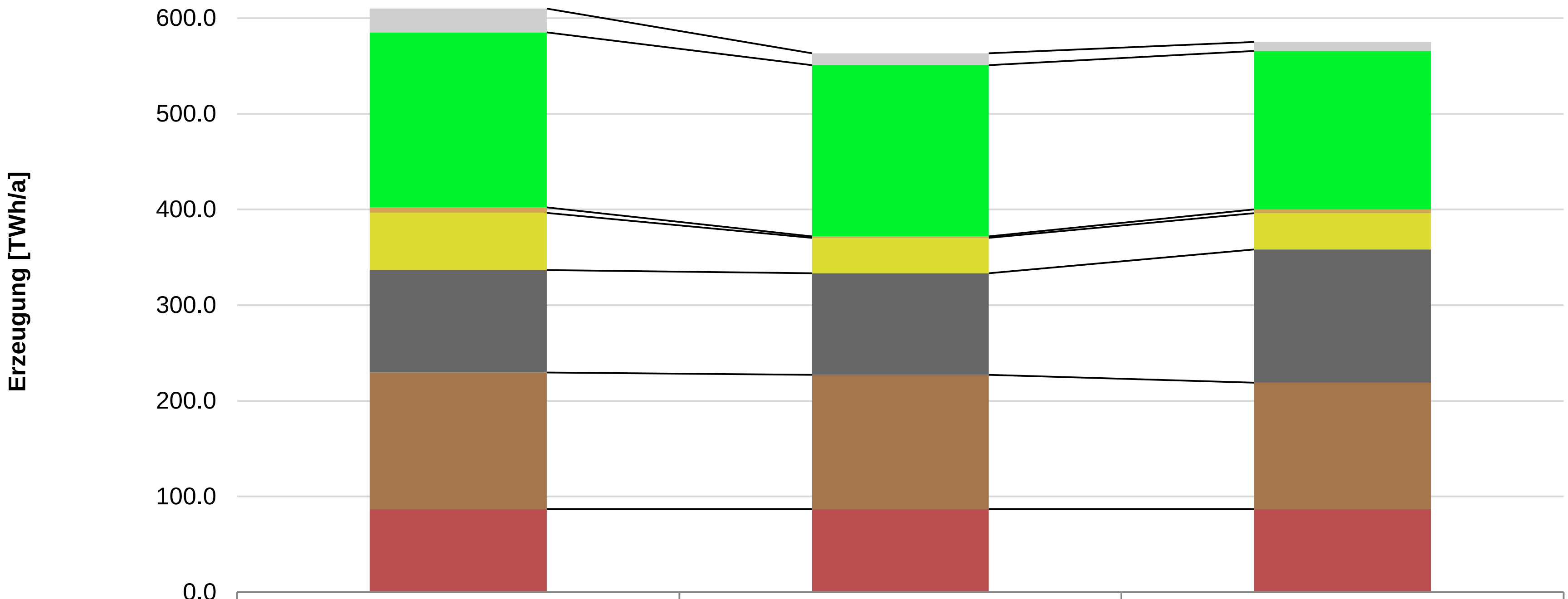
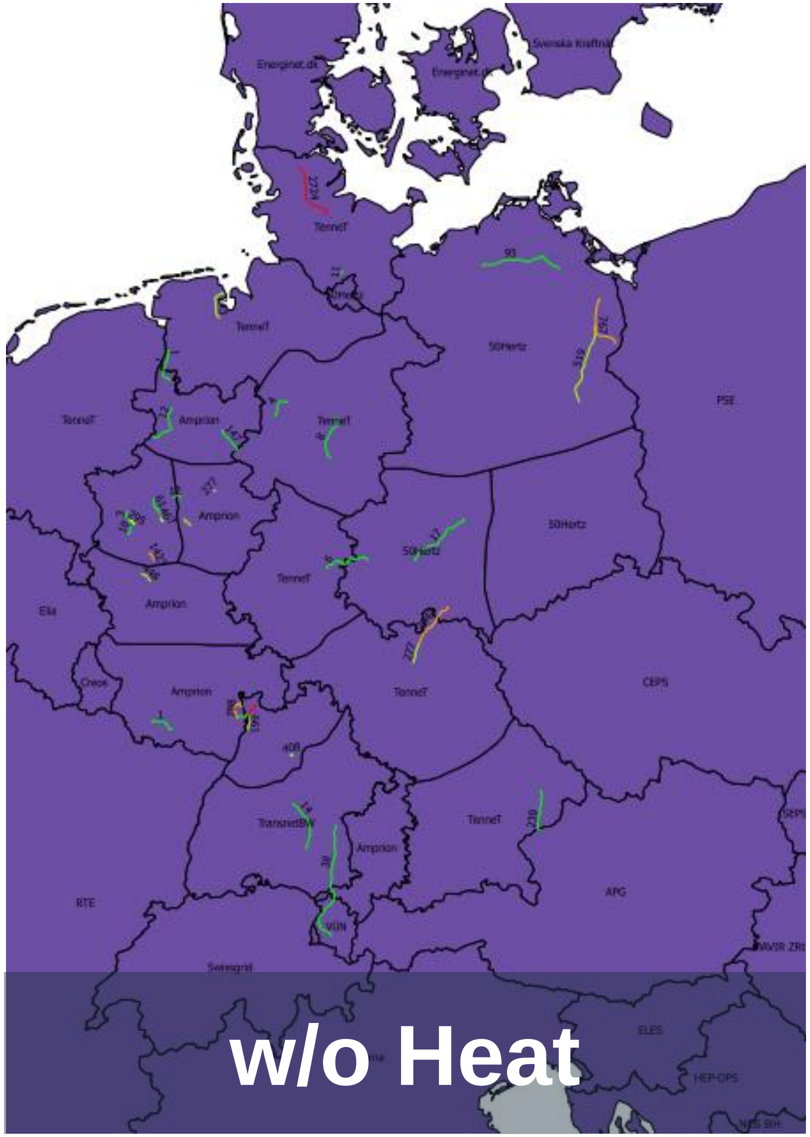
ELMOD-DE-HEAT: Preliminary Results & Validation

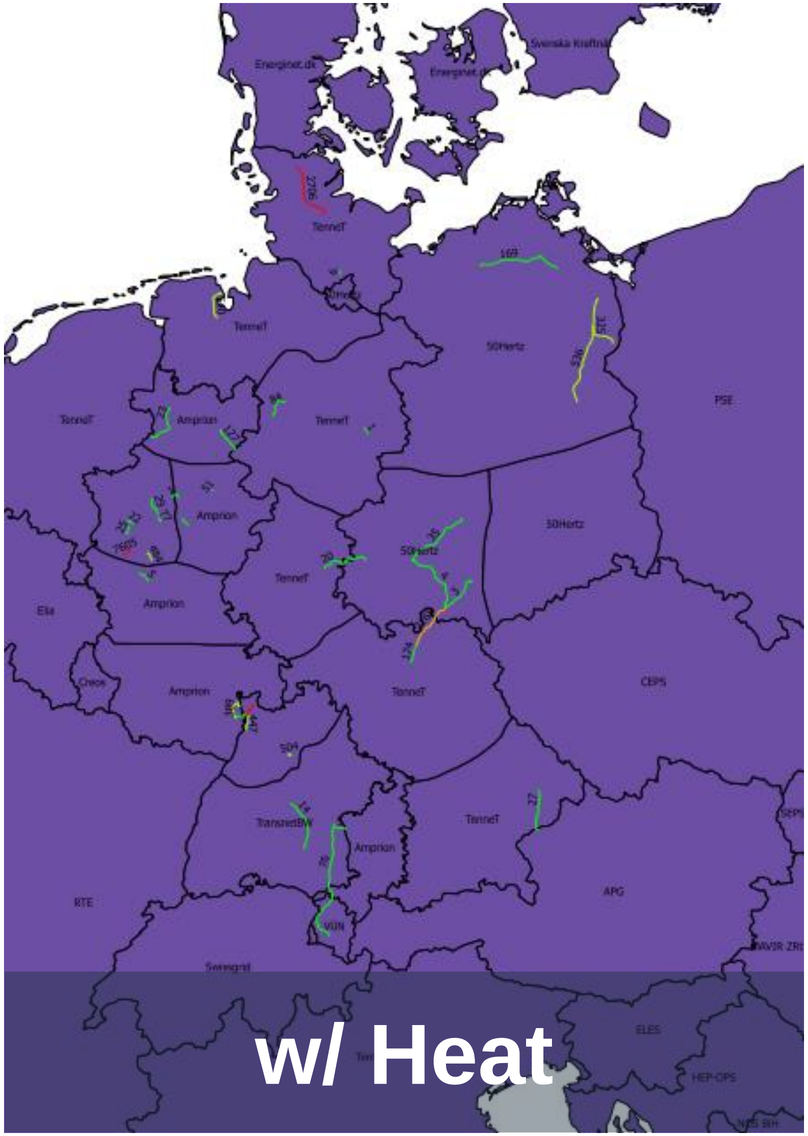


	2015 - BDEW Nettoerzeugung Gesamt	2015 - BDEW Nettoerzeugung allg. Versorgung	ELMOD-DE-HEAT
Übrige	24.8	12.6	9.5
Erneuerbare	183.1	178.8	165.4
Mineralölprodukte	5.6	1.6	4.2
Erdgas	59.8	37.1	37.8
Steinkohle	107.0	106.2	139.3
Braunkohle	143.0	140.3	132.3
Kernenergie	86.8	86.8	86.7

Kernenergie Braunkohle Steinkohle Erdgas Mineralölprodukte Erneuerbare Übrige

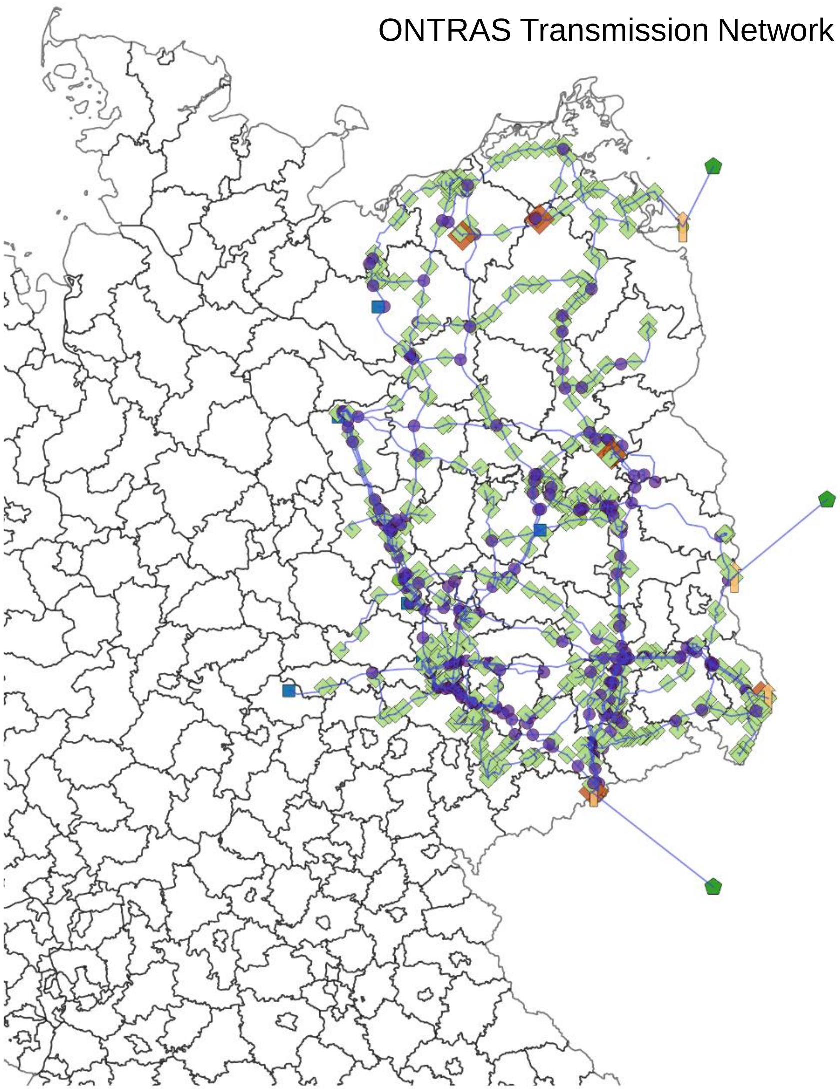
ELMOD-DE-HEAT: Preliminary Results & Validation





Natural Gas Transmission Grid

ONTRAS Transmission Network



- Relevance: the natural gas network can be used as a short and long term storage facility – there might be some limitations though…
- Challenge: find a linearized representation of the gas flows, pressures and pipe contents

Natural Gas Transmission Model

– **Objective: linearized min costs of operating the network (i.e. energy usage of compressors) – to be included in the overall objective**

$$N' = \frac{QP_i}{\left({}^2/_3\, P_i + {}^1/_3\, P_u\right)^2} P'_u - \frac{QP_u}{\left({}^2/_3\, P_i + {}^1/_3\, P_u\right)^2} P'_i + \frac{P_u - P_i}{\left({}^2/_3\, P_i + {}^1/_3\, P_u\right)^2} Q'$$

– **Constraints:**

- Supply capacity – flow out of supply nodes cannot exceed capacity
- Demand – flow into demand nodes cannot exceed demand

$$\sum_{j \in O(n)} f_{gj} \leq G_g \quad \sum_{j \in I(m)} f_{jm} \leq D_m$$

- Mass balance (Kirchoff's first law) – flow into transportation node has to equal flow out of transportation node

$$\sum_{i \in I(j)} f_{ij} = \sum_{n \in O(j)} f_{jn}$$

- Pressure constraint – Weymouth equation for long pipelines with high pressure

$$W_{ij}\left(p_{ij}^{in}, p_{ij}^{out}\right) = K_{ij}^{W} \sqrt{{p_{ij}^{in}}^2 - {p_{ij}^{out}}^2}$$

K_{ij}^{W} is the Weymouth constant for the pipeline (i.e. length, diameter, …)

Natural Gas Transmission Model

– **Constraints:**

– Pressure constraint – linearization of the Weymouth equation with L linear constraints around a set ouf points (PI,PO)

$$f_{ij} \leq K_{ij}^{W} \frac{PI_l}{\sqrt{PI_l^2 - PO_l^2}} p_{ij}^{in} - K_{ij}^{W} \frac{PO_l}{\sqrt{PI_l^2 - PO_l^2}} p_{ij}^{out}$$

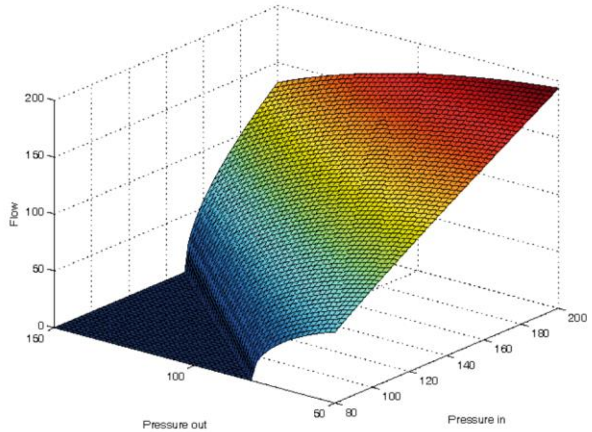


Fig. 3. A three-dimensional illustration of how the Weymouth relates pressure at the inlet and outlet points to the capacity in the pipeline.

Source: Tomasgard, A. et. al. (2007): „Optimization Models for the Natural Gas Value Chain“, pp. 521-558 in: Geometric Modelling, Numerical Simulation, and Optimization, Springer, Berlin, http://link.springer.com/10.1007/978-3-540-68783-2_16

– Compression – The compression factor $\Gamma(f_n) = \left(\frac{W^{max}\eta(K_a - 1)}{100 K_a f_n} + 1\right)^{\frac{K_a}{K_a - 1}}$ dependent on the flow can be simplified to a constant – $\Gamma_n p_{jn}^{out} \geq p_{ni}^{in}$

Conclusion and Outlook

- ELMOD-DE has been extended by a linear representation for CHP plants and a new output variable for natural gas calculations.
- The results improved, having a better match in the backtesting with actual electricity production.
- The model code in GAMS and the used data set for the year 2015 will be published open source by the end of the year.
- Next step: implementation of the gas transmission network model.

Technische Universität Berlin

langfristige Planung und kurzfristige Optimierung des **Elektrizitätssystems in Deutschland** im europäischen Kontext

Research funded through grant „LKD-EU“, FKZ 03ET4028A,
German Federal Ministry for Economic Affairs and Energy

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