

Séminaire de Recherches en Économie de l'Énergie de Paris-Sciences-Lettres

Power System Transformation toward Renewables: the Modelling of Investment Scenarios for Germany

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Université Paris-Dauphine, 10.02.2015

Content

1. Motivation and research questions
2. The optimization model
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4. Results
5. Discussion of limitations
6. Conclusions

Motivation and research questions

As of today: Renewable technologies are the only option for the low carbon system transformation in Germany

Target for share of gross power demand*

2013: 23.4%

2014: 27.3%

2020: 35%

2030: 50%

2050: 80%

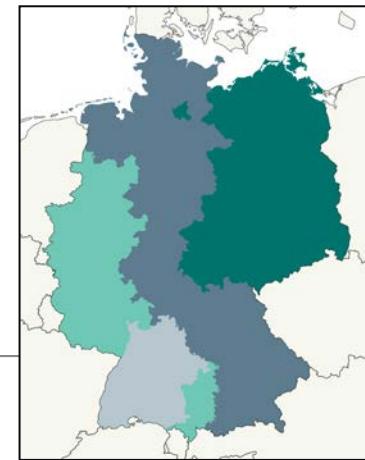
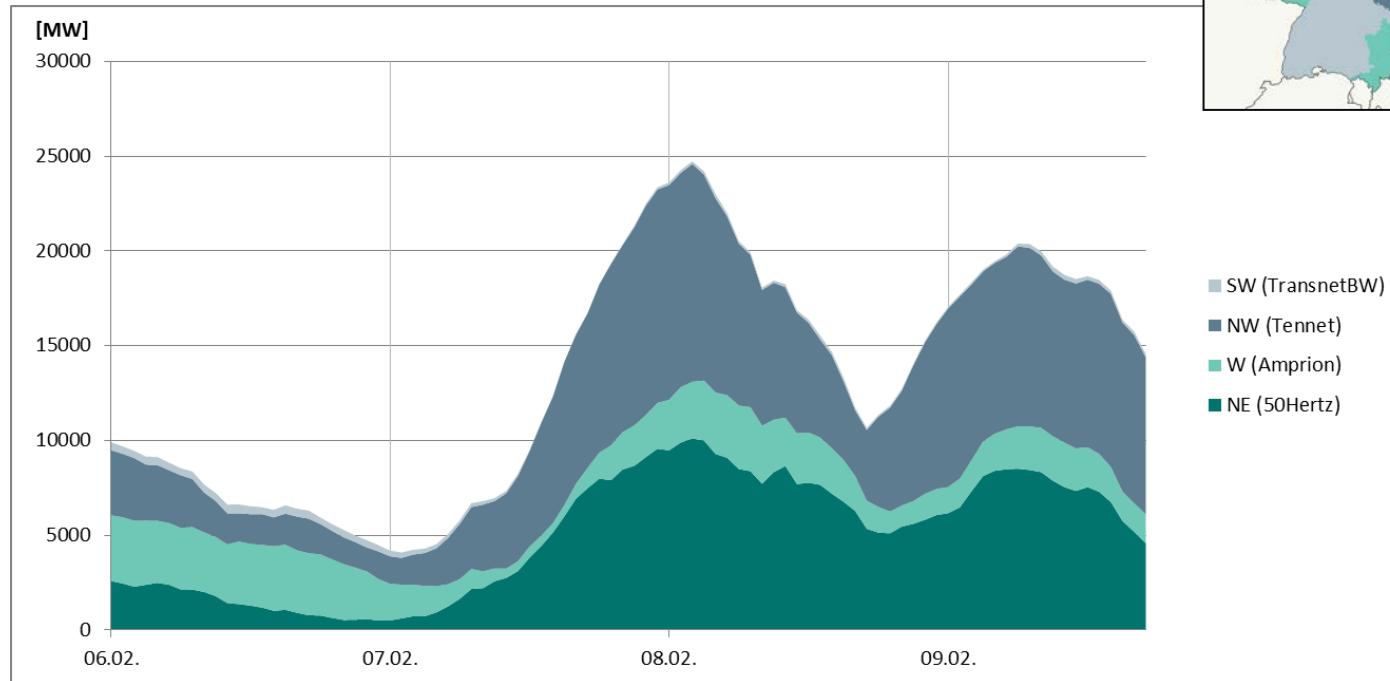
How can the traditional / conventional power system adapt to an increasing share of renewable generation?

Source: BMWi and BMU (2010). Energy Concept for an Environmentally Sound, Reliable, and Affordable Energy Supply. Federal Ministry of Economics and Technology and Federal Ministry for the Environment, September 2010.

Specific characteristics of wind and solar power:

- Fluctuating availability

Hourly wind generation in Germany (last 4 days)

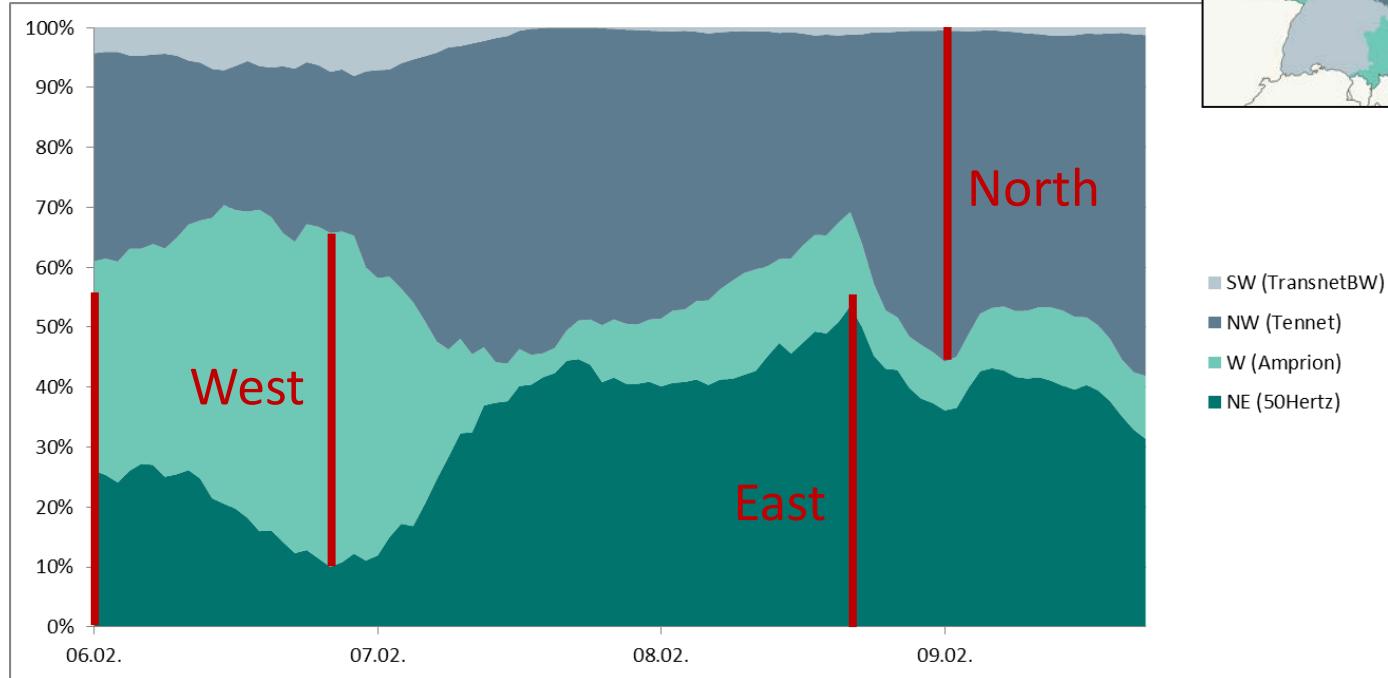


Source: 50Hertz, Amprion, Tennet, TransnetBW (2015).

Specific characteristics of wind and solar power:

- Fluctuating availability
- Spatial disparities

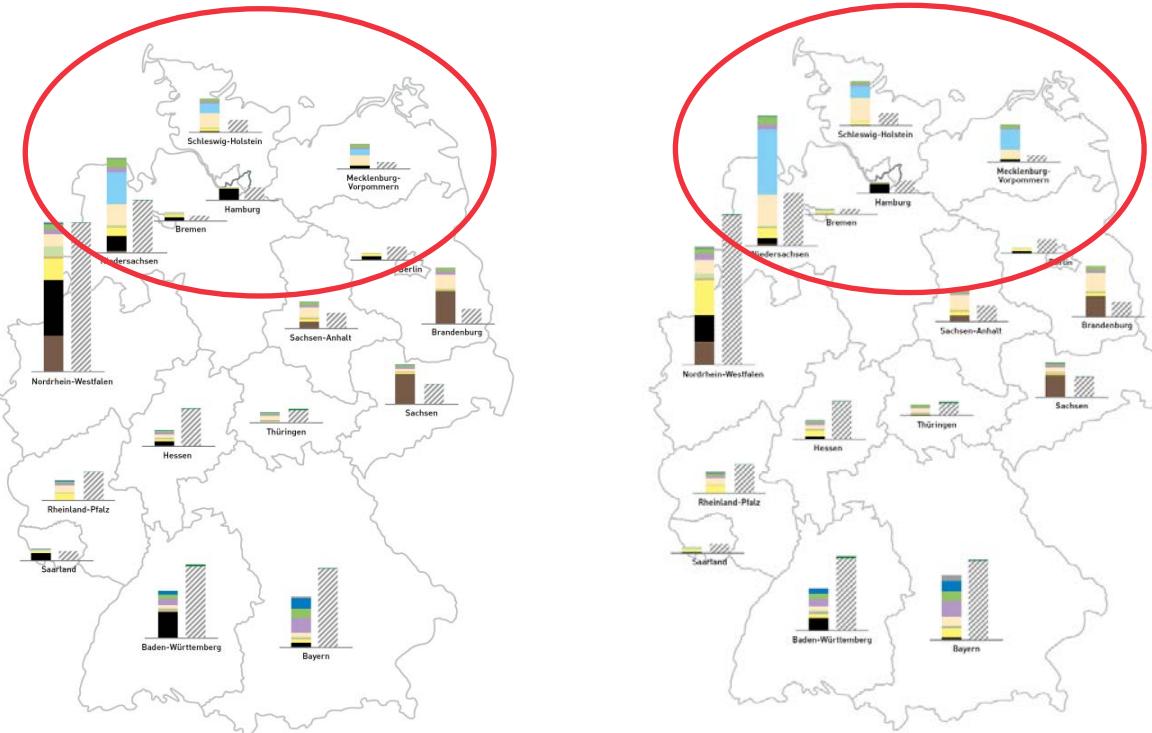
Regional distribution



Source: 50Hertz, Amprion, Tennet, TransnetBW (2015).

Low carbon system transformation:

- Wind power (north) and some photovoltaic (south)



Source: Netzentwicklungsplan Strom 2014, Zweiter Entwurf, p.48/49.

Different infrastructure investment („flexibility options“) are being discussed:

- Generation capacity



- (Pumped) storage



- Transmission networks

- (Demand side)

Low carbon system transformation:

- Wind power (north) and photovoltaic (south)
- Conventional / storage / network (regional considerations)

Specific characteristics of wind and solar power:

- Fluctuating availability
- Spatial disparities

Different infrastructure investment („flexibility options“) are being discussed

- Supply side, storage, networks, and demand side

Separated assessment:

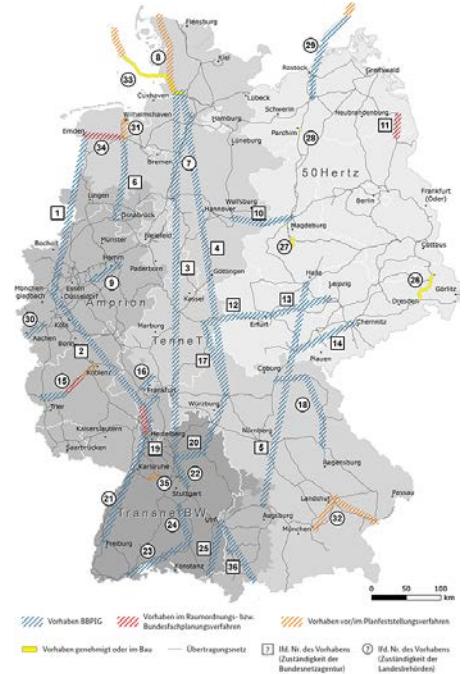
- Scenario on generation capacity
- Market dispatch (copper plate)
- Network extension

Integrated approach:

Modelling of Investment Scenarios for Germany

Positive analysis to understand interactions of scenario & implications

Source: Bundesbedarfsplangesetz (2013).



Cost-optimal combination of infrastructure options for renewable integration in Germany by 2024 / 2034?

Options included in the analysis:

- Flexible gas-fired power plants (CCGT and OCGT)
- Pumped hydro storage
- Transmission lines (AC and DC)
- Renewable curtailment (no investments)

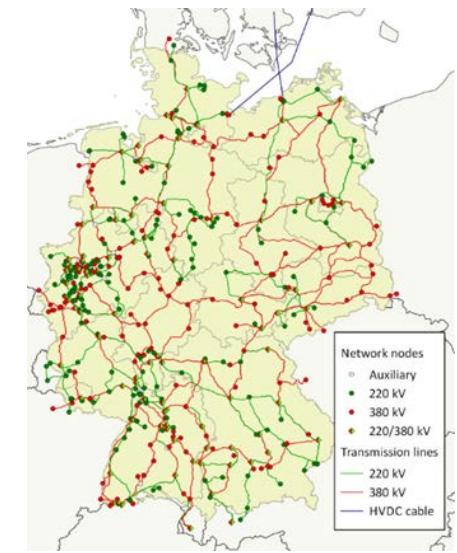
Integrated planning perspective, based on scenarios

- Renewable curtailment / network investment / pumped storage

The optimization model

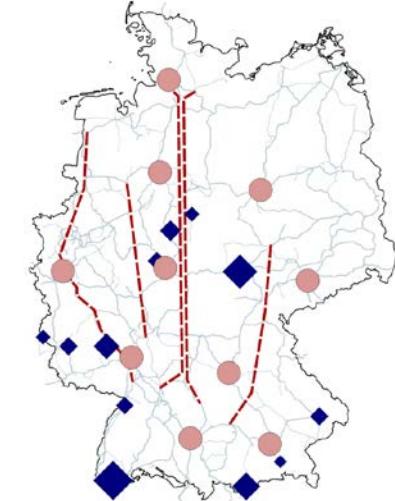
Dispatch: variable costs

- Network nodes (≈ 420) with hourly merit order and load
- Connected by transmission lines (≈ 700)
- Existing pumped storage (efficiency)



Investment: fixed costs (+variable costs)

- Generation (adds to merit order)
- Storage (inter-hourly flexibility)
- Network (spatial flexibility)



Scenario	Investments in			Costs of RES curtailment
	Gas power plants	Transmission lines	Pumped hydro storage	
Reference scenario	✓	✓	✓	0
Decreased curtailment 100	✓	✓	✓	100 EUR/MWh
Decreased curtailment 1000	✓	✓	✓	1000 EUR/MWh
No network extension	✓	-	✓	0
Exogenous storage	✓	✓	Exogenous (NEP)	0

Combined optimization of dispatch, transmission, and investments

- Minimization of annualized system costs
- DC load-flow approach
- Integer investment variables (MILP)

Endogenous variables:

- Dispatch of generation capacities
- Load flows
- Storage operation
- Investments

Exogenous parameters:

- Baseline stock of thermal generation capacities
- Existing transmission network (2012)
- Renewable capacities
- Load (selected hours)
- Variable and investment cost parameters

Time resolution: 4 weeks x 84 hours (every 2nd hour)

We draw on assumptions of the
Network Development Plan 2014

Objective: Minimization of annualized system costs

$$\begin{aligned}
 \min_{\substack{g_{p,t}, r_{n,s,t}, ps_{b,t} \\ i.cap_{n,cap}, g.cap_{n,cap,t} \\ i.sto_{n,sto}, ps.sto_{sto,t} \\ i.ac_{ac}, i.dc_{dc}}} \quad & costs = [\sum_{p,t} (C_{p,t} * g_{p,t}) + \sum_{cap,t} (VC_{cap} * g.cap_{n,cap,t})] * Yh && \text{Variable generation cost} \\
 & + \sum_{n,cap} (FC.cap_{cap} * i.cap_{n,cap}) && \text{Investment costs generation capacity} \\
 & + \sum_{sto} (FC.sto_{sto} * i.sto_{sto}) && \text{Investment costs storage} \\
 & + \sum_{ac} (FC.ac_{ac} * i.ac_{ac}) && \text{Investment costs AC lines} \\
 & + \sum_{dc} (FC.dc_{dc} * i.dc_{dc}) && \text{Investment costs DC lines}
 \end{aligned}$$

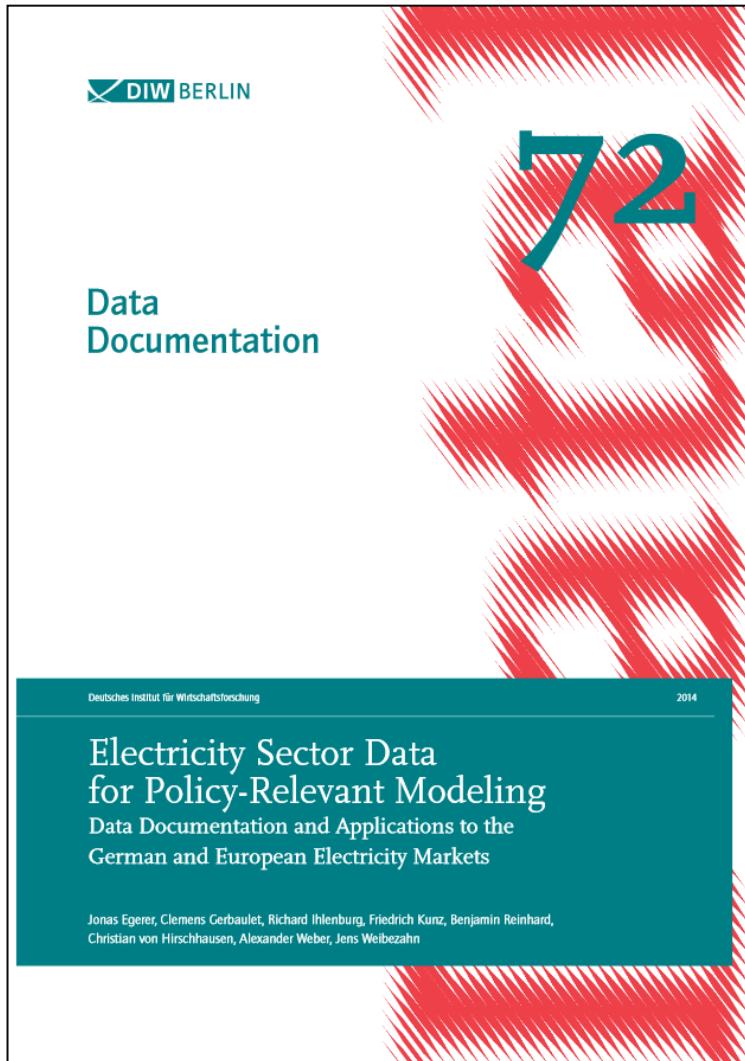
Constraints:

$$\begin{aligned}
 g_{p,t} &\leq \bar{G}_{p,t} \\
 r_{n,s,t} &\leq \bar{R}_{n,s,t} \\
 \bar{ps}_{b,t} + \bar{ps}_{b,t} &\leq \bar{PS}_b \\
 pslevel_{b,t} &\leq \bar{LS}_b \\
 pslevel_{b,t} &= 0.75 \bar{ps}_{b,t} - \bar{ps}_{b,t} + pslevel_{b,t-1} \\
 |pf_{ac,t}| &\leq (\bar{P}_{ac} + i.ac_{ac} * 1.7) * TRM \\
 ni_{n,t} &= \sum_{nn} (\theta_{nn,t} * B_{n,nn}) \\
 pf_{ac,t} &= \sum_n (\theta_{n,t} * H_{ac,n}) \\
 slack_n * \theta_{n,t} &= 0
 \end{aligned}$$

$$\begin{aligned}
 g.cap_{n,cap,t} &\leq i.cap_{n,cap} * 0.5 \\
 \frac{\overrightarrow{ps.sto}_{sto,t} + \overleftarrow{ps.sto}_{sto,t}}{ps.level.sto_{sto,t}} &\leq \overline{PS.sto}_{sto} * i.sto_{sto} \\
 pslevel.sto_{sto,t} &\leq \overline{LS.sto}_{sto} * i.sto_{sto} \\
 pslevel.sto_{sto,t} &= 0.75 \overrightarrow{ps.sto}_{sto,t} - \overleftarrow{ps.sto}_{sto,t} + pslevel.sto_{sto,t-1} \\
 |ni.dc_{dc,t}| &\leq i.dc_{dc} * 1.0
 \end{aligned}$$

$$\begin{aligned}
 \sum_{p \in n} g_{p,t} + \sum_s r_{n,s,t} - Q_{n,t} \\
 + \sum_{b \in n} (\bar{ps}_{b,t} - \bar{ps}_{b,t}) \\
 + \sum_{cap} g.cap_{n,cap,t} \\
 + \sum_{sto \in n} (\overrightarrow{ps.sto}_{sto,t} - \overleftarrow{ps.sto}_{sto,t}) \\
 + ni_{n,t} + (\sum_{dc \in n} ni.dc_{dc,t} * Inc.dc_{dc,n}) &= 0
 \end{aligned}$$

Input parameters



Data Documentation 72

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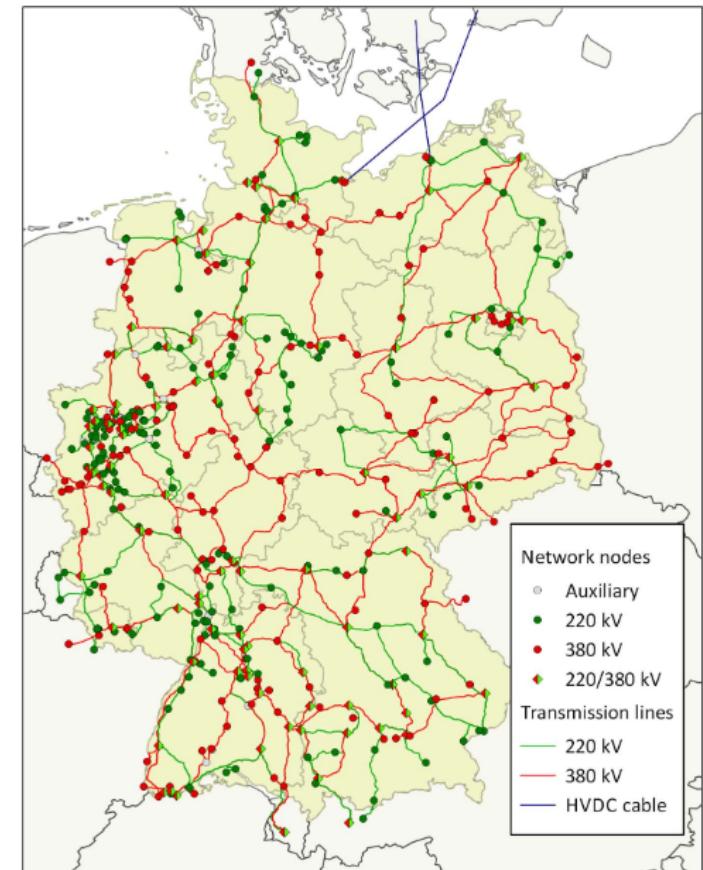
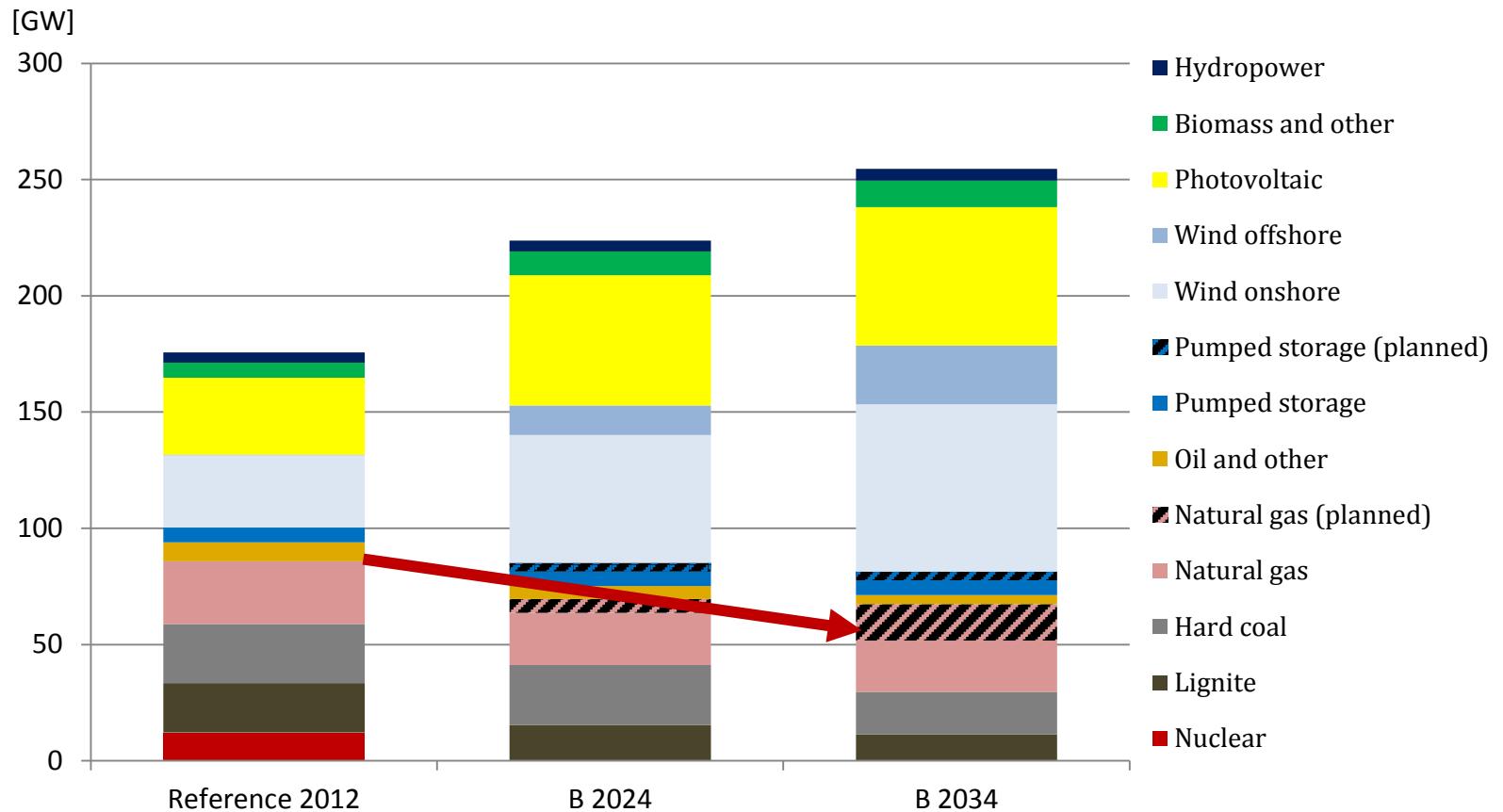


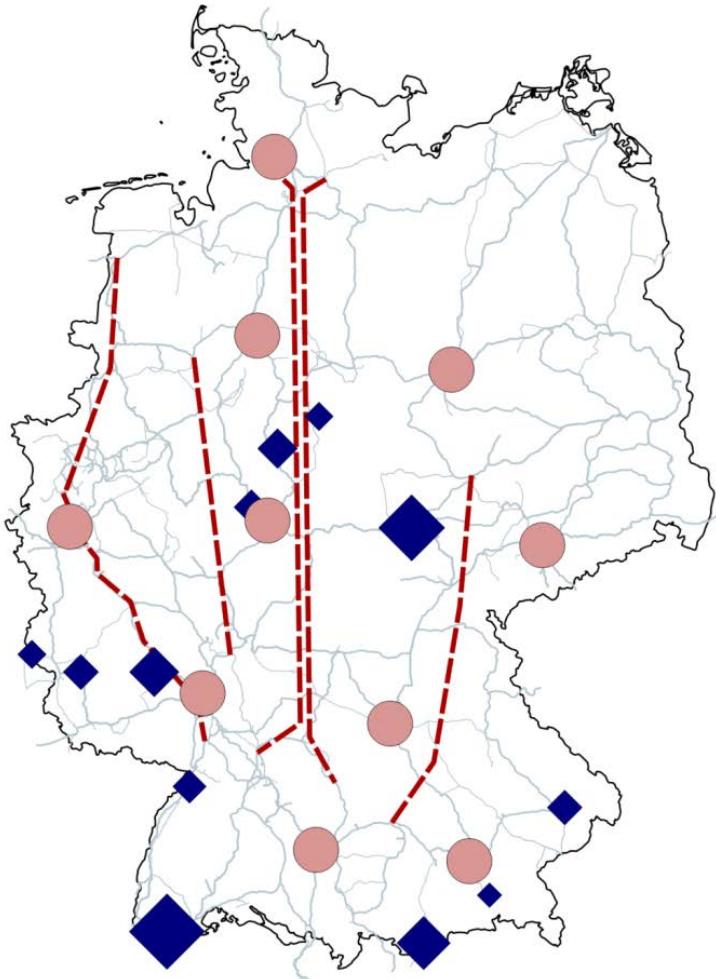
Figure 4: The German high-voltage electricity transmission system in 2012

Source: Own depiction based on VDE (2010), OpenStreetMap contributors (2013), 50Hertz (2013a), TenneT (2013a), and Joost (2013).

Installed generation capacity



2024: 10 GW planned (12%) // 2034: 20 GW planned (25%)



AC lines:

- Extensions of all existing lines possible with additional 380 kV circuits (1.7 GW)

DC point-to-point connections:

- Six connectors in steps of 1 GW

Gas-fired power plants:

- CCGT and OCGT in steps of 500 MW
- At ten important network nodes

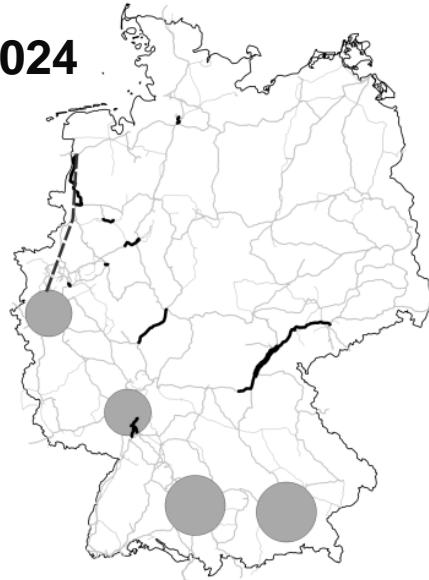
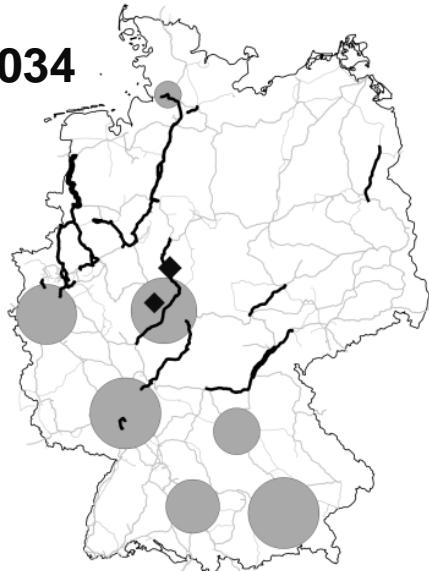
Pumped hydro storage:

- Projects with specific capacities and locations

	Specific investments (mn EUR/km)	Life time in years	Efficiency in percent
AC transmission lines	1.4	40	
DC transmission lines	1.4	40	
	(mn EUR)		
AC transformer	4	40	
DC converter	338	40	
	(mn EUR/GW)		
CCGT power plants	800	35	60
OCGT power plants	400	30	45
Pumped hydro storage power stations	1200	40	80

Results

Scenario	Investments in			Costs of RES curtailment
	Gas power plants	Transmission lines	Pumped hydro storage	
Reference scenario	✓	✓	✓	0
Decreased curtailment 100	✓	✓	✓	100 EUR/MWh
Decreased curtailment 1000	✓	✓	✓	1000 EUR/MWh
No network extension	✓	-	✓	0
Exogenous storage	✓	✓	Exogenous (NEP)	0

2024**2034**

- 8 GW CCGT, largely in southern Germany
- No pumped storage (arbitrage revenues are low)
- Selected network upgrades
- RES-share of 48%, curtailment of 1.3 TWh (0.5%)

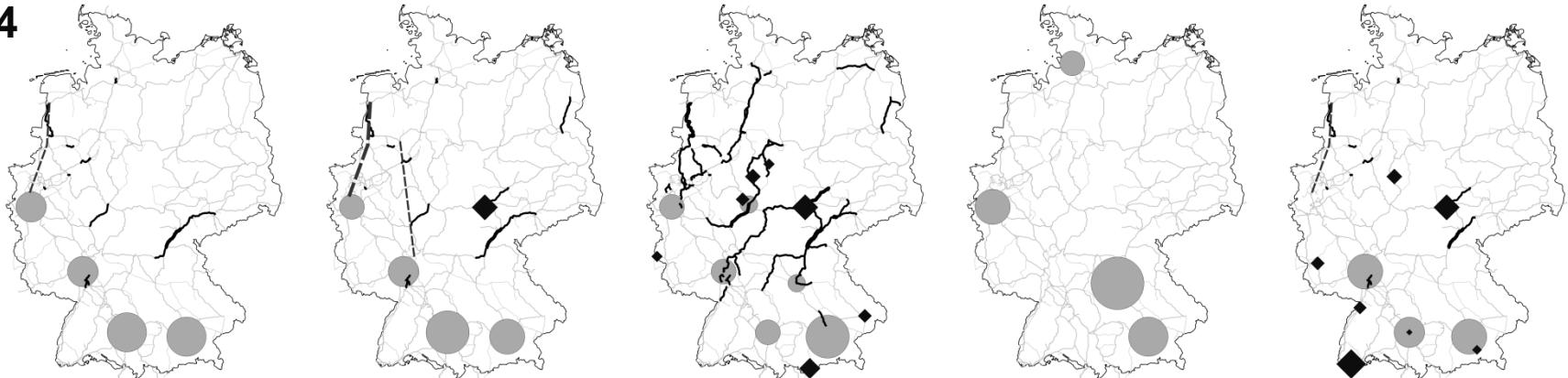
- 16.5 GW CCGT in southern and western Germany
- Small pumped hydro investments
- Network enforcements SN/TH-BY and NI-NW
- RES-share of 60%, curtailment of 5.7 TWh (1.7%)

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Investments in other scenarios

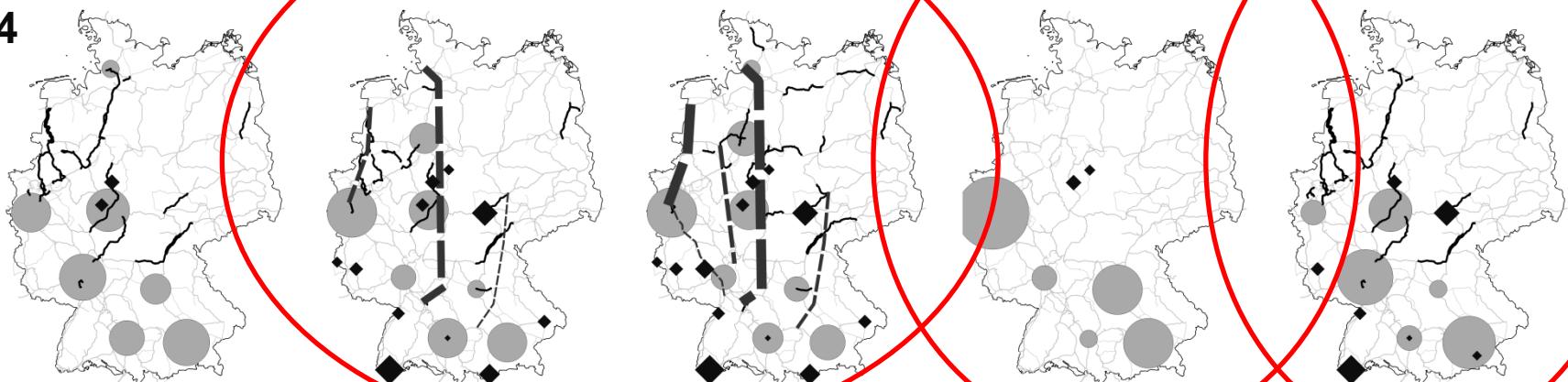
Reference	Decreased curtailment 100 EUR/MWh	Decreased curtailment 1000 EUR/MWh	No network extension	Exogenous storage
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2024



Reference	Decreased curtailment 100 EUR/MWh	Decreased curtailment 1000 EUR/MWh	No network extension	Exogenous storage
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2034

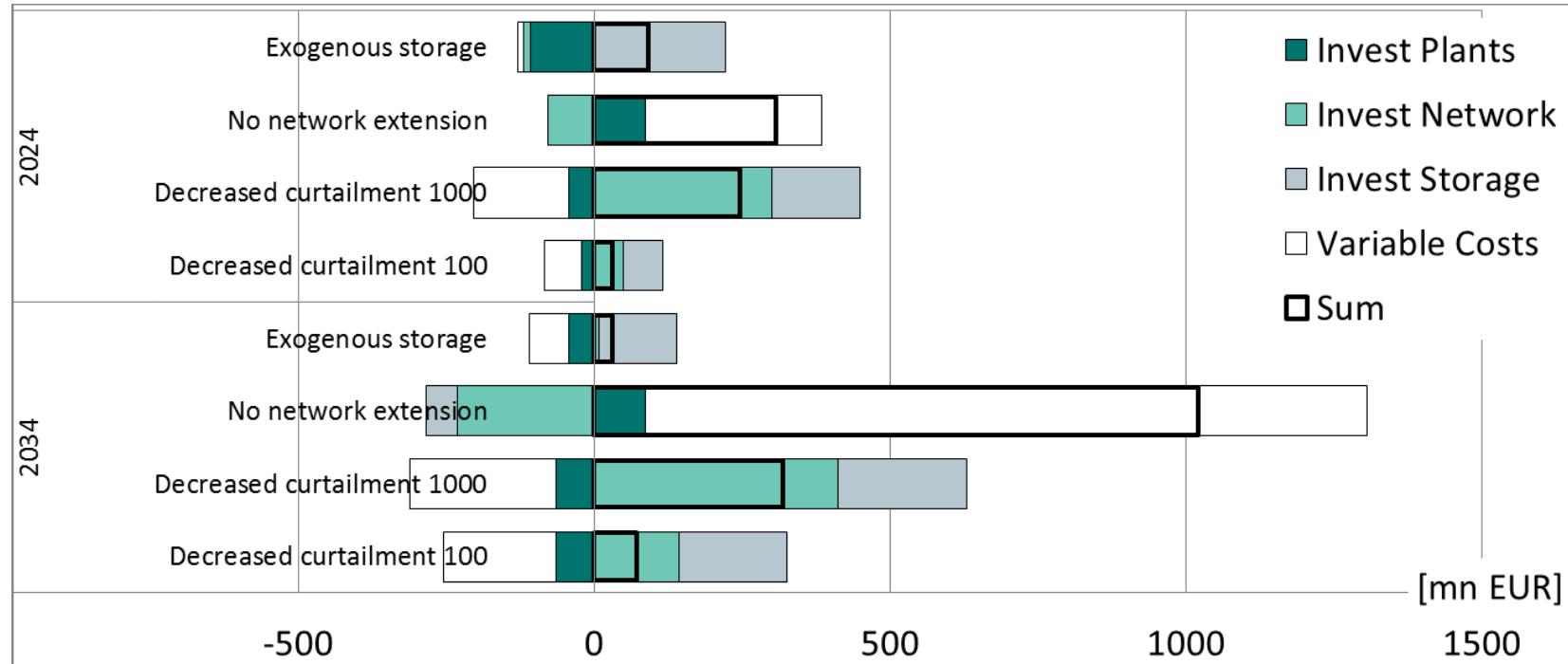


→ Focus on network and storage /
location plants less relevant

→ Largest thermal investments

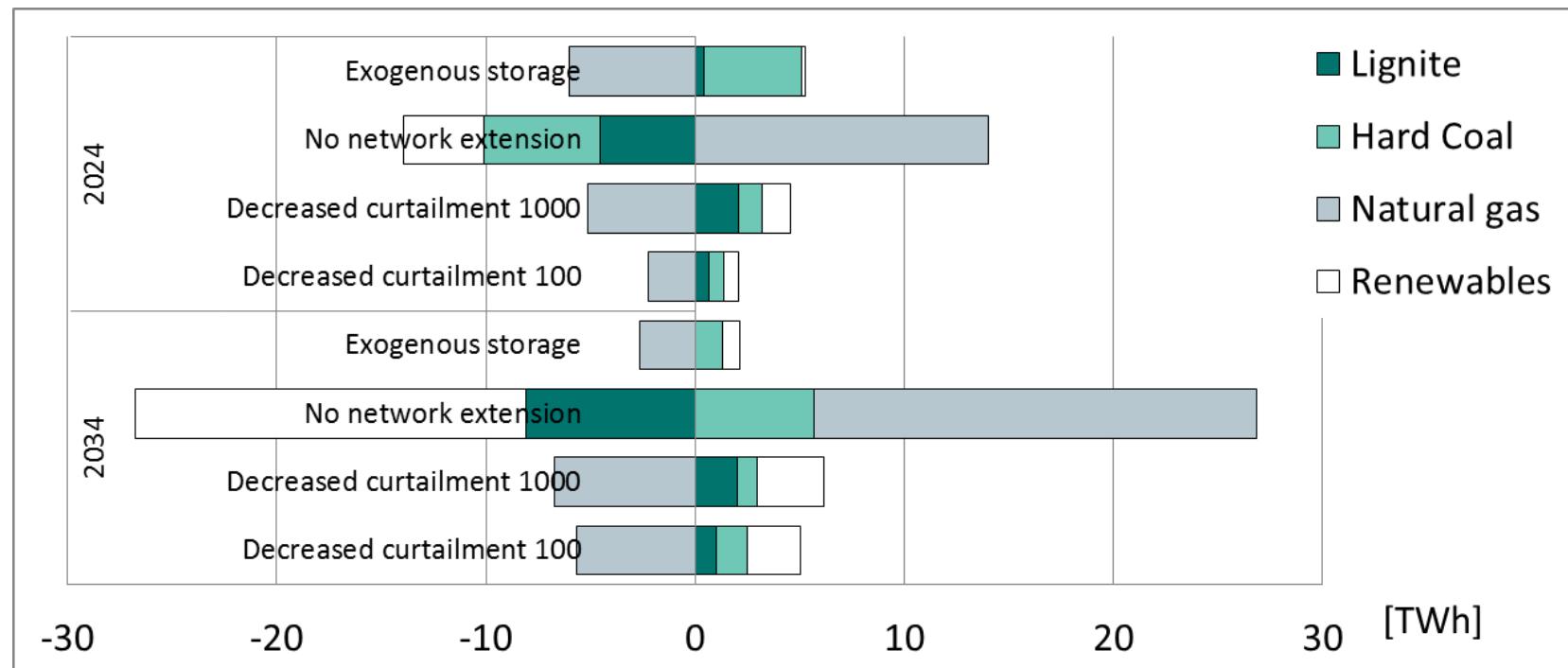
→ Partly substitution of thermal investments

Changes in system costs compared to reference scenario



- Highest costs in case without network extension
- Increasing marginal cost of decreased curtailment
- Network and storage complementary
- Exogenous storage capacities only slightly increase costs

Changes in power generation compared to reference scenario



- Without network extensions high RES curtailment
- Network investment increases coal generation
- Additional storage not only improves renewable integration, but also (temporarily) increases generation from coal

Discussion of limitations

- All assumed parameters are uncertain
- Selection of hours of a specific base year: representative?
- Neglected exchange with neighboring countries:
 - Effects on infrastructure investments hard to determine
 - Uncertain developments in other countries
 - Political relevance of domestic renewable integration
- Other flexibility options are neglected
- MILP: Optimality gap in same dimension as single investment projects
 - Analysis provides general tendency
 - No strong statements on specific projects!

Conclusions

- Renewable integration requires increasing infrastructure investments
- Gas-fired power plants, pumped storage, and networks are only partly substitutes, largely complements
- Mix of all options leads to least-cost solution
- Thermal investments:
 - Optimal location reduces network extension
 - How to ensure right placement
- Investments in storage appear to be a „no-regret“ option
- There are some line expansion opportunities that can foster renewable integration at very low costs
- Temporary increase of generation from coal is possible

Vielen Dank für Ihre Aufmerksamkeit.



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