Optimal Infrastructure Investments for Renewable Energy Integration in Germany
Overview

1. Motivation and research questions
2. The model, input parameters, and scenarios
3. Results
4. Discussion of limitations
5. Conclusions
1. Motivation and research questions
Motivation

• German *Energiewende*:
  • Expansion of variable renewable power generation
  • Largely based on wind power and PV
  • Decrease of thermal generation

• Specific characteristics of wind and PV:
  • Fluctuating availability
  • Short-term deviations from forecasts
  • Spatial disparities: generation, load, existing networks

• Different infrastructure options for renewable integration:
1. Research question

- Preferable combinations of infrastructure options for renewable integration in Germany by 2024 / 2034?
  - Capacities and spatial distribution
  - Interactions between these options

- Infrastructure options included in the analysis:
  - Flexible gas-fired power plants (CCGT and OCGT)
  - Pumped hydro storage
  - Transmission upgrades (AC and DC)
  - Renewable curtailment (no investments)

Scenario-based planning perspective, not a forecast!
1. The model, input parameters, and scenarios
The optimization model

- Combined optimization of dispatch, transmission and investments
  - Minimization of total costs
  - DC load-flow approach
  - Integer investment variables → MILP

- Endogenous variables:
  - Investment
  - Dispatch
  - Load flow
The optimization model

- **Exogenous parameters:**
  - Baseline stock of thermal generation capacities
  - Baseline transmission network
  - Renewable capacities (fully exogenous)
  - Load (four weeks, every second hour)
  - Variable costs and specific investments

- Drawing on official NEP assumptions
2024: 10 GW planned (12%) // 2034: 20 GW planned (25%)
Investment options

- 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
## Investment scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Gas-fired plants</th>
<th>Transmission lines</th>
<th>Pumped hydro storage</th>
<th>Costs of RES curtailment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference scenario</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>0</td>
</tr>
<tr>
<td>Decreased curtailment 100</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>100 EUR/MWh</td>
</tr>
<tr>
<td>Decreased curtailment 1000</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>1000 EUR/MWh</td>
</tr>
<tr>
<td>No network extension</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>0</td>
</tr>
<tr>
<td>Exogenous storage</td>
<td>✓</td>
<td>✓</td>
<td>Exogenous (NEP)</td>
<td>0</td>
</tr>
</tbody>
</table>
1. Results
Results in the reference scenario

2024:
- 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%)

2034:
- 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%)
## Investments in other scenarios

<table>
<thead>
<tr>
<th>Year</th>
<th>Reference</th>
<th>Decreased curtailment 100 EUR/MWh</th>
<th>Decreased curtailment 1000 EUR/MWh</th>
<th>No network extension</th>
<th>Exogenous storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024</td>
<td><img src="image1" alt="Map 2024 Reference" /></td>
<td><img src="image2" alt="Map 2024 Decreased curtailment 100 EUR/MWh" /></td>
<td><img src="image3" alt="Map 2024 Decreased curtailment 1000 EUR/MWh" /></td>
<td><img src="image4" alt="Map 2024 No network extension" /></td>
<td><img src="image5" alt="Map 2024 Exogenous storage" /></td>
</tr>
<tr>
<td>2034</td>
<td><img src="image6" alt="Map 2034 Reference" /></td>
<td><img src="image7" alt="Map 2034 Decreased curtailment 100 EUR/MWh" /></td>
<td><img src="image8" alt="Map 2034 Decreased curtailment 1000 EUR/MWh" /></td>
<td><img src="image9" alt="Map 2034 No network extension" /></td>
<td><img src="image10" alt="Map 2034 Exogenous storage" /></td>
</tr>
</tbody>
</table>

- **2024**
  - High investments in DC lines
  - Larger thermal investments

- **2034**
  - High investments in DC lines
  - Larger thermal investments
Changes in power generation compared to reference scenario

Without network extensions: high RES curtailment

Additional storage not only fosters renewable integration, but also (temporarily) increases generation from coal
Changes in system costs compared to reference scenario

- Highest costs in case without network extension
- Increasing marginal cost of decreased curtailment
- Exogenous storage capacities only slightly increase costs
  → Compensated by additional system value?
1. Discussion of limitations
Discussion of model limitations

- General parameter uncertainty
- Selection of hours of a specific base year
- No exchange with neighboring countries:
  - Infrastructure demand should generally be overestimated
  - Uncertain developments in other countries
  - Political relevance of domestic renewable integration
- Other flexibility options are neglected (e.g., DSM)
- MILP: Optimality gap in same dimension as investment projects

→ Analysis provides general tendency
→ No strong statements on specific projects!
1. Conclusions
Conclusions

• Energiewende increasingly requires infrastructure investments
• Thermal plants, storage and networks are partly substitutes, partly complements
• Mix of all options leads to least-cost solution
• Thermal investments:
  • Optimal location reduces network extension
  • How to ensure right placement - market design?
• Pumped storage:
  • Moderate investments appear to be a „no-regret“ option
• Network expansion
  • Several projects can foster renewable integration at very low costs
Vielen Dank für Ihre Aufmerksamkeit.
A Model equations

Objective: Minimization of annualized system costs

\[
\begin{align*}
\min_{g_{p,t}, n_{s,t}, ps_{b,t}, i_{ac}, i_{dc}} & \quad \text{costs} = \left[ \sum_{p,t} (C_{p,t} \cdot g_{p,t}) + \sum_{cap,t} (V_{cap} \cdot g_{n,\text{cap},t}) \right] \cdot Y_h \\
& \quad + \sum_{n,\text{cap}} (FC_{cap} \cdot i_{cap}) \\
& \quad + \sum_{sto} (FC_{sto} \cdot i_{sto}) \\
& \quad + \sum_{ac} (FC_{ac} \cdot i_{ac}) \\
& \quad + \sum_{dc} (FC_{dc} \cdot i_{dc}) 
\end{align*}
\]

Variable generation cost
Investment costs generation capacity
Investment costs storage
Investment costs AC lines
Investment costs DC lines

Constraints:

\[
\begin{align*}
g_{p,t} & \leq \tilde{g}_{p,t} \\
|p_{f_{ac},t}| & \leq (\tilde{p}_{ac} + i_{ac} \cdot 1.7) \cdot TRM \\
|p_{f_{ac},t}| & = \sum_{n} (\theta_{nn} \cdot B_{nn}) \\
\theta_{n,t} & = \sum_{n} (\theta_{n,t} \cdot H_{ac,n}) \\
\theta_{n,t} & = 0 \\
g_{n,\text{cap},t} & \leq i_{cap} \cdot 0.5 \\
p_{sto_t} & \leq \overline{P}_{sto} \cdot i_{sto} \\
ps_{b,t} & \leq ps_{b} \\
ps_{b} & \leq \overline{P}_{b} \\
ps_{b} & = 0.75 ps_{b} \cdot ps_{b,1} + ps_{b,1} + ps_{b,2} \\
\Sigma_{p_{en}} g_{p,t} + \Sigma_{s} r_{n,s,t} + O_{n,t} & = \sum_{p_{en}} (\overline{ps}_{b,t} - ps_{b,t}) \\
& \quad + \sum_{cap} g_{n,\text{cap},t} \\
& \quad + \sum_{sto} (ps_{sto_t} - ps_{sto_t}) \\
& \quad + n_{i,t} + (\sum_{dc_{en}} n_{dc_t} \cdot Inc_{dc_t}) = 0
\end{align*}
\]
## Investment parameters

<table>
<thead>
<tr>
<th></th>
<th>Specific investments (mn EUR/km)</th>
<th>Life time in years</th>
<th>Efficiency in percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC transmission lines</td>
<td>1.4</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>DC transmission lines</td>
<td>1.4</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>AC transformer</td>
<td>4</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>DC converter</td>
<td>338</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>CCGT power plants</td>
<td>800</td>
<td>35</td>
<td>60</td>
</tr>
<tr>
<td>OCGT power plants</td>
<td>400</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>Pumped hydro storage</td>
<td>1200</td>
<td>40</td>
<td>80</td>
</tr>
</tbody>
</table>
Limitations with regard to storage

• Balancing of residual load:
  • Daily balancing (arbitrage)
  • Lower load gradients / lower ramping requirements
  • Contribution to peak load
  • Integration of RES surpluses

• System security:
  • Frequency control
  • Voltage control

• Congestion management

→ Some relevant applications are not included
→ Investments in storage may be underestimated