Photovoltaics and storage plants: Efficient capacities in a system view

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Motivation

- **Background and Problems:**
  - Political and societal objective of slowing down climate change
  - Massive expansion of renewable energy sources (RES)
  - Challenge to balance intermittent RES feed-in according to energy demand

  **Photovoltaics (PV)**
  - Highest potential besides wind
  - Established technology
  - Easy to install
  - Additional incentives in households

  **Storage Systems**
  - Partly established (PHS and Li-Ion)
  - Significant improvements expected (technical and costs)
  - Efficient in medium-term (expected)

- **Model:**
  - Simplified system model to investigate main interdependences between PV and storages
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Agenda

1. Motivation

2. Methods

3. Application

4. Conclusions
Efficient technology portfolio: Optimization Model

- **Cost function**

\[
\min \sum_{u_G} c_{uv,v,G}(u_G) \cdot K_G(u_G) + \sum_{t} \sum_{u_G} c_{uv,t,G}(u_G) \cdot y_{G,t}(t,u_G) + \sum_{u_S} (c_{uv,v,S}(u_S) \cdot K_S(u_S) + c_{uv,v,S}(u_S) \cdot V_S(u_S))
\]

- **Main restrictions (I/II)**
  - Cover energy demand
    \[
    \sum_{u_G} y_{G,c}(t,u_G) + \sum_{u_G} y_{G,R}(t,u_G) \cdot K_G(u_G) + \sum_{u_S} y_{S,dc}(t,u_S) = D(t) + S(t) + \sum_{u_S} y_{S,ch}(t,u_S) \perp \lambda_D(t) \geq 0
    \]
  - Storage level with self-discharge
    \[
    L_S(t+1,u_S) = L_S(t,u_S) + y_{S,ch}(t,u_S) \cdot \eta_S(u_S) - y_{S,dc}(t,u_S) - 0.5 \cdot (L_S(t+1,u_S) + L_S(t,u_S)) \cdot sd(u_S) \perp \lambda_{L_S}(t,u_S)
    \]
  - Cycle stability
    \[
    \sum_{t} y_{S,ch}(t,u_S) \cdot \eta_S(u_S) \leq V_S(u_S) \cdot cs(u_S)
    \]
Efficient technology portfolio: Optimization Model

- Main restrictions (II/II)
  
  - Minimal share of RES in power supply
    \[
    f_{\text{RE}} \cdot \sum_t D(t) \leq \sum_t \left( \left( \sum_{u^R \in u_R} y_{G,R}(t, u^R_G) \cdot K_G(u^R_G) \right) - S(t) + \left( \sum_{u_S} y_{S,dc}(t, u_S) - \sum_{u_{se}} y_{S,ch}(t, u_{se}) \right) \right) \perp \lambda_{\text{RE}} \geq 0
    \]
  
  - CO₂ emission bound
    \[
    \sum_t \sum_{u^C \in u_C} y_{G,C}(t, u^C_G) \cdot e_{\text{CO}_2}(u^C_G) \leq f_{\text{CO}_2} \perp \lambda_{\text{CO}_2} \geq 0
    \]
Efficient technology portfolio: Definition

- **Model Input**
  - Generation technologies $u_G$ characterized by
    - Investment costs $c_{inv,K,G}(u_G)$
    - Operational costs $c_{op,G}(t, u_G)$ - for RES zero
  - Storage technologies $u_S$ are characterized by
    - Investment costs $c_{inv,K,S}(u_S)$ for capacity and $c_{inv,v,S}(u_S)$ for volume
    - Efficiency $\eta_S(u_S)$, self-discharge $sd(u_S)$ and cycle stabillity $cs(u_S)$
  - Demand $D(t)$ and RES feed-in pattern $\gamma_{G,R}(t, u_R^{G})$
  - Political objectives:
    - Minimal share of RES in power supply $f_{RE}$
    - CO$_2$ emission bound $f_{CO2}$
  - Limitation by available sites especially for wind offshore and PHS
Efficient technology portfolio: Definition

- **Model Output**
  - Installed capacities $K_G(u_G)$ and $K_S(u_S)$
  - Storage volume $V_S(u_S)$
  - Power generation of conventional power plants $y_{G,C}(t, u_G)$
  - Storage operation with charging $y_{S, ch}(t, u_S)$ & discharging $y_{S, dc}(t, u_S)$ quantities and the corresponding storage level $L_S(t, u_S)$
  - Curtailed RES $S(t)$
  - Shadow prices of parameter related restrictions
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Reference Case: Input

- Scenario for Germany in 2040 based on hourly supply & demand (2011), no imports & exports
- Main input parameters
  - Realistic sites in Germany for wind offshore 54 GW and for PHS 2 TWh (IWES 2013)
  - 8,000 full cycles for Li-Ion technology
  - Minimal share of RES in power supply: 65%
  - CO₂ emission bound: 20% of 1990 level

<table>
<thead>
<tr>
<th>Unit</th>
<th>Capacity costs</th>
<th>Volume costs</th>
<th>Technical lifetime</th>
<th>Efficiency</th>
<th>Operational costs</th>
<th>Capacity costs</th>
<th>Volume costs</th>
<th>Technical lifetime</th>
<th>Efficiency</th>
<th>Operational costs</th>
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</thead>
<tbody>
<tr>
<td>Lignite plant</td>
<td>1,500 k€/MW</td>
<td>0 k€/MWh</td>
<td>40 years</td>
<td>49%</td>
<td>8.2</td>
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<tr>
<td>(Hard) Coal plant</td>
<td>1,200 k€/MW</td>
<td>0 k€/MWh</td>
<td>40 years</td>
<td>51%</td>
<td>23.9</td>
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<td>CGT</td>
<td>700 k€/MW</td>
<td>0 k€/MWh</td>
<td>30 years</td>
<td>62%</td>
<td>50.5</td>
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<tr>
<td>OCGT</td>
<td>400 k€/MW</td>
<td>0 k€/MWh</td>
<td>25 years</td>
<td>41%</td>
<td>76.3</td>
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<tr>
<td>Wind offshore</td>
<td>1,600 k€/MW</td>
<td>0 k€/MWh</td>
<td>20 years</td>
<td>100%</td>
<td>0</td>
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<tr>
<td>Wind onshore</td>
<td>1,200 k€/MW</td>
<td>0 k€/MWh</td>
<td>20 years</td>
<td>100%</td>
<td>0</td>
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<tr>
<td>Photovoltaic</td>
<td>800 k€/MW</td>
<td>0 k€/MWh</td>
<td>25 years</td>
<td>100%</td>
<td>0</td>
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<tr>
<td>PHS</td>
<td>840 k€/MW</td>
<td>20 k€/MWh</td>
<td>50 years</td>
<td>80%</td>
<td>0</td>
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<tr>
<td>Li-Ion</td>
<td>100 k€/MW</td>
<td>150 k€/MWh</td>
<td>20 years</td>
<td>90%</td>
<td>0</td>
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Source: based on data by IEA (2013), ISE (2013), RWTH Aachen (2013/2014), own analyses
Reference Case: Results

- **290 GW generation & storage capacities**
  - 64 GW conventional technologies
  - 188 GW RES
  - 28 GW storages

- **Demand coverage**
  - 65% by RES and 35% by conventional techn.
  - 91% of RES feed-in is used directly, 5% indirectly and 4% is curtailed or lost during storage process

- **System costs of 43 bn€**
  - Mean electricity price of 63 €/MWh
  - CO₂ emission price 76 €/tₐ₉O₂
  - RES certificate price 46 €/MWh

<table>
<thead>
<tr>
<th>Capacities</th>
<th>Power Supply</th>
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<tbody>
<tr>
<td>Demand</td>
<td>90 GW Peak-Load</td>
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<tr>
<td>Lignite</td>
<td>4 GW</td>
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<tr>
<td>Hard coal</td>
<td>0 GW</td>
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<td>CCGT</td>
<td>45 GW</td>
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<td>OCGT</td>
<td>15 GW</td>
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<td>Wind onshore</td>
<td>60 GW</td>
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<tr>
<td>Wind offshore</td>
<td>54 GW</td>
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<tr>
<td>Photovoltaic</td>
<td>74 GW</td>
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<tr>
<td>PHS</td>
<td>14 GW (29 h)</td>
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<tr>
<td>Li-Ion</td>
<td>4 GW (3 h)</td>
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<td>Curtailment RES</td>
<td>61 GW</td>
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<tr>
<td>Load curtailment</td>
<td>2 GW</td>
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Sensitivities PV Capacity – Investment Costs

- Investment costs variations (x-axis)
  - compared to the reference case
- Efficient PV capacity (y-axis)
- Main results
  - Continuous correlation
    - PV
    - Li-Ion as a complement
    - PHS as a substitute
Sensitivities Li-Ion Capacity – Investment Costs

- Investment costs variations (x-axis)
  - compared to the reference case
- Efficient Li-Ion capacity (y-axis)
- Main results
  - Monotonous dependency on Li-Ion and PHS costs
  - Non-monotonous dependency on PV costs beyond 37.5% variation
    - monotonous relation between ± 37.5%
    - substitution between Li-Ion and PHS in ± 50.0%
Sensitivities – CO₂ emission bound
Sensitivities – Minimal share of RES in power supply
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Conclusions

• Photovoltaics and storages will be part of the efficient portfolio

• High sensitivity to investment costs and political objectives

• Results do not provide a fully realistic picture of future capacities
  – simplified model –
  – Following important issues are not taken into account:
    • Connections to the surrounding countries
    • Limited grid capacity
    • Incentives for self-consumption for private households (and other customers)
    • No long term storage system like P2G (in future investigations)
Many thanks! – Questions?

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