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**

\[
\min \sum_{u_G} c_{inv,K,G}(u_G) \cdot K_G(u_G) + \sum_t \sum_{u_G} c_{op,G}(u_G) \cdot y_{G,c}(t, u_G) + \sum_{u_S} \left( c_{inv,K,S}(u_S) \cdot K_S(u_S) + c_{inv,V,S}(u_S) \cdot V_S(u_S) \right)
\]

- **Main restrictions (I/II)**
  - Cover energy demand

\[
\sum_{u_G \in u_G} y_{G,c}(t, u_G^C) + \sum_{u_G \in u_G} y_{G,R}(t, u_G^R) \cdot K_G(u_G^R) + \sum_{u_S} y_{S,dc}(t, u_S) = D(t) + S(t) + \sum_{u_S} y_{S,ch}(t, u_S) \perp \lambda^D(t) \geq 0
\]

  - Storage level with self-discharge

\[
L_S(t + 1, u_S) = L_S(t, u_S) + y_{S,ch}(t, u_S) \cdot \eta_S(u_S) - y_{S,dc}(t, u_S) - 0.5 \cdot \left( L_S(t + 1, u_S) + L_S(t, u_S) \right) \cdot sd(u_S) \perp \lambda^V_L(t, u_S)
\]

  - 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

  \[
  f_{RE} \cdot \sum_t D(t) \leq \sum_t \left[ \left( \sum_{u_G \in u_G^R} y_{G,R}(t, u_G^R) \cdot K_G(u_G^R) \right) - S(t) + \left( \sum_{u_S} y_{S,dc}(t, u_S) - \sum_{u_S} y_{S,ch}(t, u_S) \right) \right] \perp \lambda^{RE} \geq 0
  \]

  – CO₂ emission bound

  \[
  \sum_t \sum_{u_G^C \in u_G} y_{G,c}(t, u_G^C) \cdot e_{CO2}(u_G^C) \leq f_{CO2} \perp \lambda^{CO2} \geq 0
  \]
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>
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<tbody>
<tr>
<td>Lignite plant</td>
<td>1,500</td>
<td>0</td>
<td>40</td>
<td>49%</td>
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<td>(Hard) Coal plant</td>
<td>1,200</td>
<td>0</td>
<td>40</td>
<td>51%</td>
<td>23.9</td>
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<tr>
<td>CCGT</td>
<td>700</td>
<td>0</td>
<td>30</td>
<td>62%</td>
<td>50.5</td>
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<tr>
<td>OCGT</td>
<td>400</td>
<td>0</td>
<td>25</td>
<td>41%</td>
<td>76.3</td>
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<tr>
<td>Wind offshore</td>
<td>1,600</td>
<td>0</td>
<td>20</td>
<td>100%</td>
<td>0</td>
</tr>
<tr>
<td>Wind onshore</td>
<td>1,200</td>
<td>0</td>
<td>20</td>
<td>100%</td>
<td>0</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>800</td>
<td>0</td>
<td>25</td>
<td>100%</td>
<td>0</td>
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<tr>
<td>PHS</td>
<td>840</td>
<td>20</td>
<td>50</td>
<td>80%</td>
<td>0</td>
</tr>
<tr>
<td>Li-Ion</td>
<td>100</td>
<td>150</td>
<td>20</td>
<td>90%</td>
<td>0</td>
</tr>
</tbody>
</table>

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 €/t\( CO₂ \)
  - RES certificate price 46 €/MWh

### Capacities vs. Power Supply

<table>
<thead>
<tr>
<th>Demand</th>
<th>Capabilities</th>
<th>Power Supply</th>
<th>Amounts</th>
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<tbody>
<tr>
<td>90 GW</td>
<td>541 TWh</td>
<td>90 GW</td>
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<tr>
<td>Lignite</td>
<td>4 GW</td>
<td>24 TWh</td>
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<tr>
<td>Hard coal</td>
<td>0 GW</td>
<td>0 TWh</td>
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<tr>
<td>CCGT</td>
<td>45 GW</td>
<td>162 TWh</td>
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<td>OCGT</td>
<td>15 GW</td>
<td>3 TWh</td>
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<tr>
<td>Wind onshore</td>
<td>60 GW</td>
<td>97 TWh</td>
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<tr>
<td>Wind offshore</td>
<td>54 GW</td>
<td>172 TWh</td>
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<tr>
<td>Photovoltaic</td>
<td>74 GW</td>
<td>63 TWh</td>
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<tr>
<td>PHS</td>
<td>14 GW (29 h)</td>
<td>16 TWh</td>
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<tr>
<td>Li-Ion</td>
<td>4 GW (3 h)</td>
<td>3 TWh</td>
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<tr>
<td>Curtailment RES</td>
<td>61 GW</td>
<td>9 TWh</td>
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<tr>
<td>Load curtailment</td>
<td>2 GW</td>
<td>3 GWh</td>
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</table>
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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