Modeling system integration of variable renewable energies for long-term climate objectives: the role of electric grid and storage

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VRE penetration and modeling in IAMs

• Decarbonization of the energy system →
  - Energy efficiency
  - Nuclear
  - Carbon Capture and Storage (CCS)
  - Renewables (especially Variable Renewable Energies, VREs, i.e. wind and solar PV)

• VREs
  → variability and non-dispatchability, in contrast with the requirement that the load be instantaneously equalized by the generation
  → problems in terms of management of the electrical grids

• Integrated Assessment Models (IAMs)
  → objective: simulate the evolution of electricity demand and mix over the next decades
  → mandatory to properly model VRE system integration, although inevitably in a simplified / aggregated form (different spatial and temporal scales)
WITCH: Introduction

WITCH – World Induced Technical Change Hybrid

- Climate-energy-economic IAM (Integrated Assessment Model) → Socio-economic impacts of climate change
- Hybrid: aggregated, top-down, inter-temporal optimal-growth model + disaggregated description of the energy sector

Modeling the European power sector evolution: low-carbon generation technologies (renewables, CCS, nuclear), the electric infrastructure and their role in the EU leadership in climate policy
The limitation to VRE penetration into the electrical grid was (mainly) modeled in WITCH through:

• a constraint on the **flexibility** of the power generation fleet
• a constraint on the installed **capacity** of the power generation fleet

WITCH: Flexibility constraint (old version)

<table>
<thead>
<tr>
<th>Power technology</th>
<th>Flexibility coefficient (f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>-0.1</td>
</tr>
<tr>
<td>Wind</td>
<td>-0.08</td>
</tr>
<tr>
<td>PV</td>
<td>-0.05</td>
</tr>
<tr>
<td>CSP</td>
<td>0</td>
</tr>
<tr>
<td>Nuclear</td>
<td>0</td>
</tr>
<tr>
<td>Coal</td>
<td>0.15</td>
</tr>
<tr>
<td>Oil</td>
<td>0.3</td>
</tr>
<tr>
<td>Biomass</td>
<td>0.3</td>
</tr>
<tr>
<td>Gas</td>
<td>0.5</td>
</tr>
<tr>
<td>Hydro</td>
<td>0.5</td>
</tr>
<tr>
<td>Storage</td>
<td>1</td>
</tr>
</tbody>
</table>

\[ \sum_i Q_{EL}(t,n)_i \cdot f_i + Q_{EL\_TOT}(t,n) \cdot f_{LOAD} \geq 0 \]

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WITCH: Capacity constraint (old version)

Firm generation capacity \( \geq (1.5-2) \cdot \) Annual average load

Non-variable capacity + “weighted” variable capacity (wind and PV)

\[
\sum_i K_{EL}(t,n)_{i, non\_VRE} + \sum_i K_{EL}(t,n)_{i, VRE} \cdot CF_i \cdot CV_i \text{ (share)} + K_{ELstor} \cdot CV_{stor} \geq c(n) \cdot Q_{EL\_TOT}(t,n)/\text{yearly\_hours}
\]

- \( CV_{stor} = 0.85 \)
- \( CF_i \cdot CV_i \text{ (share)} \)
WITCH: Grid (old version)

Grid requirement (depending on power capacity)

\[
K_{\text{EL,GRID}}(t, n) = \sum_{jel|\text{non\_VRE}} K_{\text{EL}}(jel, t, n) \\
+ \sum_{jel|\text{VRE}} \sum_{\text{distance}} K_{\text{EL\_D}}(jel, t, n, \text{distance}) \times \frac{\text{transm\_cost}(jel, \text{distance})}{\text{grid\_cost}} \\
+ \sum_{jel|\text{VRE}} K_{\text{EL}}(jel, t, n) \times \left(1 + \text{SHARE\_EL}(jel, t, n)^b\right)
\]
WITCH: VRE integration (old version) – Main weaknesses

- The flexibility and the capacity constraints are quite aggregated tools to model VRE system integration. In particular:
  - the coefficients are poorly parameterized and documented
  - they have been calibrated on the US power system (but: regional variability)
  - the flexibility coefficients might change with VRE penetration
- No curtailment of VRE electricity generation is considered.
- Storage and grid are modeled quite rudimentarily.

These issues have been addressed in the new model version.
WITCH: New VRE integration – Reference


Indirect implementation of the Residual Load Duration Curves (RLDC) to the MESSAGE model, i.e. to a framework based on the following main points:

- Electricity treated as a homogeneous good
- Flexibility constraint
- Capacity constraint
Residual Load Duration Curves (RLDC)

Residual Load Duration Curves (RLDC) – VRE effects

MESSAGE – Data/parameters derived from the RLDCs

CURTAILMENT

• Introduction of short-term and seasonal curtailment

FLEXIBILITY CONSTRAINT

• Load flexibility coefficients (differentiated by region)
• VRE flexibility coefficients (variable with VRE share)

CAPACITY CONSTRAINT

• Firm capacity requirement variable over time (already differentiated by region)
• Capacity values (variable with VRE share differentiating by region)
WITCH: New grid modeling

- Differentiation between transmission and distribution
  - Same linear proportion with generation capacity, but grid capacity expressed in [km] instead of [GW]
- Introduction of grid losses
- Regional grid requirement
- Introduction of grid pooling and smartening effects
  - Integration of grid into the flexibility constraint
### WITCH: New storage modeling – Technologies

<table>
<thead>
<tr>
<th>Type of storage</th>
<th>Technology</th>
<th>FlexC</th>
<th>CapC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-term</td>
<td>Pumped Hydroelectric Storage (PHES)</td>
<td>0.75</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Compressed Air Energy Storage (CAES)</td>
<td>0.75</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Lithium-ion batteries (LiB)</td>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td>Seasonal</td>
<td>Alkaline electrolyzer → hydrogen → Polymer Electrolyte Membrane Fuel Cells (PEMFC)</td>
<td>0.9</td>
<td>1</td>
</tr>
</tbody>
</table>
Modeling the European power sector evolution: low-carbon generation technologies (renewables, CCS, nuclear), the electric infrastructure and their role in the EU leadership in climate policy
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WITCH: Results – Comparison with IAMs (VRE share)
WITCH: Results – Comparison with IAMs (storage)

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