Integration of Variable Renewable Energy (VRE) in Integrated Assessment Models

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Why focus on VRE modeling?

- Recent development says VRE could play much larger role than currently seen in IAMs:
  - Dedicated support has produced large deployment
  - Competitors are weak: nuclear, CCS
- On the other hand, recent growth has raised questions (and provided first answers) about system stability and integration costs

ADVANCE project has work package on VRE integration
Part I: General thoughts on VRE integration in IAMs
Possible objectives of IAM modeling:

• Develop cost estimations for climate targets
• Find the bottlenecks/crucial technologies for mitigation
• Produce plausible power system projections

What we need to get right to achieve these objectives:

• Power prices/emissions
• Get demand for resources (Coal/Gas/Nuclear/Biomass/VRE) right
  ➔ Understand the drivers/barriers for technology deployment
    • Resource potentials/ Technology costs/ Heterogeneity and integration challenges (Regional differences)

*Can this be achieved in IAMs, or do we need parameterizations from more detailed Bottom-Up models?*
VRE Integration mechanisms in IAMs:

• Basic: direct LCOE (no integration cost) vs. hard upper bound on share
• Varying level of complexity:
  – Implicit cost markups, e.g. CES function
  – Explicitly formulated cost markups
  – Capacity requirements
  – Flexibility requirements
  – Time slices/Load Curve
  – Residual load duration curve

⇒ Variety of options that partially overlap – are we still missing aspects?

• Impact depends strongly on the exact parameterization
• Crucial to estimate the strictness/plausibility of integration mechanisms
Discussion of VRE Integration mechanisms I

None/hard upper bound on RE: Too simple/unrealistic – should be discarded

• Implicit cost markup, e.g., through CES production function
  + „love of variety“ – prevents flip-flop effects, mix of power technologies
    - very coarse, difficult to parameterize
    - difficult to model paradigm shift/new technologies

• Explicit VRE cost markups:
  + full control over shape of the integration cost curve
  + easy to adjust to regional differences
  + can easily be compared to System LCOE derived from BU models
    - is completely parameterized/based on basic assumptions
    - does not influence the choice/costs of other generation technologies
Example of cost markups in REMIND

- Marginal integration costs increase linear with share in generation

⇒ At shares ~15%, PV integration costs become significant -> CSP takes over
Discussion of VRE Integration mechanisms II

Capacity Constraint/ Flexibility constraints

• Account for interactions between VRE capacities and reliability/flexibility of the non-VRE component of power supply (→ profile costs)
  – What are negative interactions if you have a model with fixed full load hours, which lead to fixed emissions/resource demands?
• Parameters tuned to one realization/scenario – can you really span a wide range of VRE shares with one parameter?
• How to determine the peak capacity requirement? How to include demand elasticity?
  – What are current experiences in capacity markets?
  – What are BU-models saying?
• Shadow price of constraints is an important measure to estimate possible implementation of new flexibility options
Discussion of VRE Integration mechanisms III

**Time slices/Load Curve/Residual Load Duration Curve:**
+ captures temporal heterogeneity of electricity
+ Integration costs increase with RE share
+ Explicit feedback of RE use on conventional power plant use
+ Allows explicit modeling – less need for parameterization

- RE incidence in different time slices is parameterized, thus data intensive: Needs full year time series of load & RE
- Numerically complex when you have many time slices?
- Difficult to implement storage and grid effects
How to validate approaches?

• Look at resulting integration costs:
  – Full/System LCOE: Very aggregated, easy to compare to BU calculations?
  – Shadow prices for flexibility and capacity, peak electricity prices?
• Ex-post validate individual scenarios by using capacities as input to a dispatch model
• Calculate a large range of scenarios with a detailed model and extract parameters for IAM repres

Example:
Schaber et al 2012: “Parametric study of variable renewable energy integration in Europe:
Advantages and costs of transmission grid extensions”
Data needs and other issues with validation

• Regional solar, wind and load time series – correlation between the three varies strongly from region to region
  – First step: try to come up with generalized region profiles, e.g. „good seasonal correlation between load and solar“, ...

• Need to cover a large parameter space on carbon prices, resource costs, VRE shares

• The bottom-up model needs to have all possible flexibility options included to prevent lock-in of the results into the current (thought) system
Brief recap: Flexibility options

- Dispatchable power plants (low capital intensity)
  - How well can you ramp CCS/ Nuclear/ Electrolysis?
- Short term storage: Pumped Hydro, Batteries, Demand Side Management
- Long-term storage: Pumped Hydro, Compressed Air, H2, Power2Gas
- Power2Heat (possibly large potential, but needs full system perspective)

→ we need better **aggregated** bottom-up knowledge on these options, not just single scenarios

→ Probably exact optimal flexibility option will vary, but we might extract **upper bounds on flexibility option costs**
Brief recap: Flexibility options II

- Do we need to model interaction to transmission expansion?
- Hypothesis: Grid expansion is usually a cheap long-term option, so best model each region like a copper plate
  ➜ we don’t need to model the trade-off

But: how to account for non-cost related barriers to grid expansion (conservation, lack of incentives for power companies, effect on regional electricity prices,...)?
# Current situation (between EMF27 & ADVANCE)

|                        | AIM/CGE | DNE 21 | GCAM | IMAGE | MESSAGE | POLES | REMIND | WITCH | Mod 1 | Mod 2 | Mod 3 | Mod 4 | Mod 5 | Mod 6 | Mod 7 | Mod 8 | Mod 9 | Mod 10 |
|------------------------|---------|--------|------|-------|---------|-------|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| **Generalized Cost**   | Y       | Y      | Y    | Y     | Y       |       | Y      |       | Y     |       |       |       |       |       |       |       |       |       |
| **Penalty**            |         |        |      |       |         |       |        |       |       |       |       |       |       |       |       |       |       |       |
| **Storage**            | Y       | Y      | Y    | Y     | Y       | Y    | Y      |       | Y     |       |       |       |       |       |       |       |       |       |
| **Backup/ Capacity**   | Y       | Y      | Y    | Y     | Y       | Y    | Y      |       | Y     |       |       |       |       |       |       |       |       |       |
| **constraint**         |         |        |      |       |         |       |        |       |       |       |       |       |       |       |       |       |       |       |
| **Flexibility**        | Y       | Y      | Y    | Y     | Y       | Y    | Y      |       | Y     |       |       |       |       |       |       |       |       |       |
| **Requirement**        |         |        |      |       |         |       |        |       |       |       |       |       |       |       |       |       |       |       |
| **Load Duration**      | Y       | Y      | Y    | Y     | Y       | Y    | Y      |       | Y     |       |       |       |       |       | Y     | Y     | Y     |       |
| **Curve / Time Slices**|         |        |      |       |         |       |        |       |       |       |       |       |       |       |       |       |       |       |
| **Maximum share**      | 15 %    | Y      | Y    | Y     | Y       |       | Y      |       | Y     |       |       |       |       |       |       |       |       |       |
| **No Mechanism**       |         |        |      |       |         |       |        |       | Y     |       |       |       |       |       |       | Y     |       |       |

**Note:** The green squares indicate the presence, while the yellow squares indicate the absence of the feature in the respective module.
Part II: Integration scenarios for the RI workshop
RI Scenarios to understand VRE deployment

• Carbon tax scenarios with fixed variation (+/- 30-50%) of
  a) integration constraints
  b) capital costs
  c) resource potential
  for wind energy to analyze and compare impacts on wind and VRE deployment.

• Additionally, one scenario with noNuclear&noCCS forces high renewable shares in most models
RI Scenarios: Non-Biomass RE Shares

- Each model has a clear “signature“ Non-Bio RE use
- Wind variation scenarios have little effect on Non-Bio RE use, except for EU
- Limitations:
  - Not all models ran all variations
  - Resource potentials matter for AIM in USA & EU, MESSAGE in China
Integration Scenarios: Wind Shares

- Very different wind shares between the models
- Very different reactivity to variation of integration constraint
### Integration Scenarios: Wind Shares

<table>
<thead>
<tr>
<th>USA</th>
<th>relative change</th>
<th>absolute change in percentage points</th>
<th>average wind share</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Generous</td>
<td>Strict</td>
<td>Generous</td>
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<tr>
<td>AIM/CGE</td>
<td>2%</td>
<td>-4%</td>
<td>0%</td>
</tr>
<tr>
<td>DNE21 V.12</td>
<td>20%</td>
<td>-22%</td>
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<td>-32%</td>
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<tr>
<td>IMAGE 2.4</td>
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<td>-3%</td>
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<tr>
<td>MESSAGE V.4</td>
<td>17%</td>
<td>-9%</td>
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</tr>
<tr>
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<td>5%</td>
<td>0%</td>
<td>1%</td>
</tr>
<tr>
<td>REMIND 1.5</td>
<td>35%</td>
<td>-30%</td>
<td>8%</td>
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<tr>
<td>WITCH</td>
<td>18%</td>
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- Is it plausible that wind shares change by <5% if generation constraints are changed by +/- 30-50%?
- Difficult to answer – to what costs markups does it translate?
  - Full LCOE that include integration costs?
  - Peak electricity prices? Capacity prices?
Indirect Integration cost measure: LCOE over Price?

- From average direct LCOE values, integration cost markups seem to be in the range of 80% for most models (AIM ~30%, MESSAGE ~150%)
- Marginal direct LCOE values should be the more relevant cost metric – but only few models currently report them
Integration effect vs. Cost effect:

<table>
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<th>Lo Cost</th>
<th>Hi Cost</th>
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• Several models also show little reaction to cost variations +/- 30-50%

=> what drives RE deployment in the IAMs?
Effect on Electricity Prices?

- Very different electricity prices across models, quite different across regions
- Integration constraint has little effect on electricity prices
- Relatively large effect for AIM – plausible, as AIM seems resource-constrained
Forcing RE: Scenario without CCS/Nuclear

• Strong increase of wind&solar share in GCAM, AIM – less so in WITCH, IMAGE, POLES, REMIND
• Large electricity price increases in POLES, GCAM, WITCH, less so in IMAGE, AIM, no real effect on REMIND & MESSAGE

⇒ Why so little VRE in POLES and WITCH although prices are high?
Main Questions for VRE Modeling

• Have we understood the drivers for VRE deployment?
• How much can we model inside IAMs, what needs to be parameterized?
• Even if bottom-up models cannot (yet) give us clear answers about optimal flexibility options, maybe they can give us upper limits to integration costs?
• What are suitable metrics to validate integration constraints?
Thank you!