POTSDAM-INSTITUT FÜR KLIMAFOLGENFORSCHUNG

Integration of Variable Renewable Energy (VRE) in Integrated Assesment 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

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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

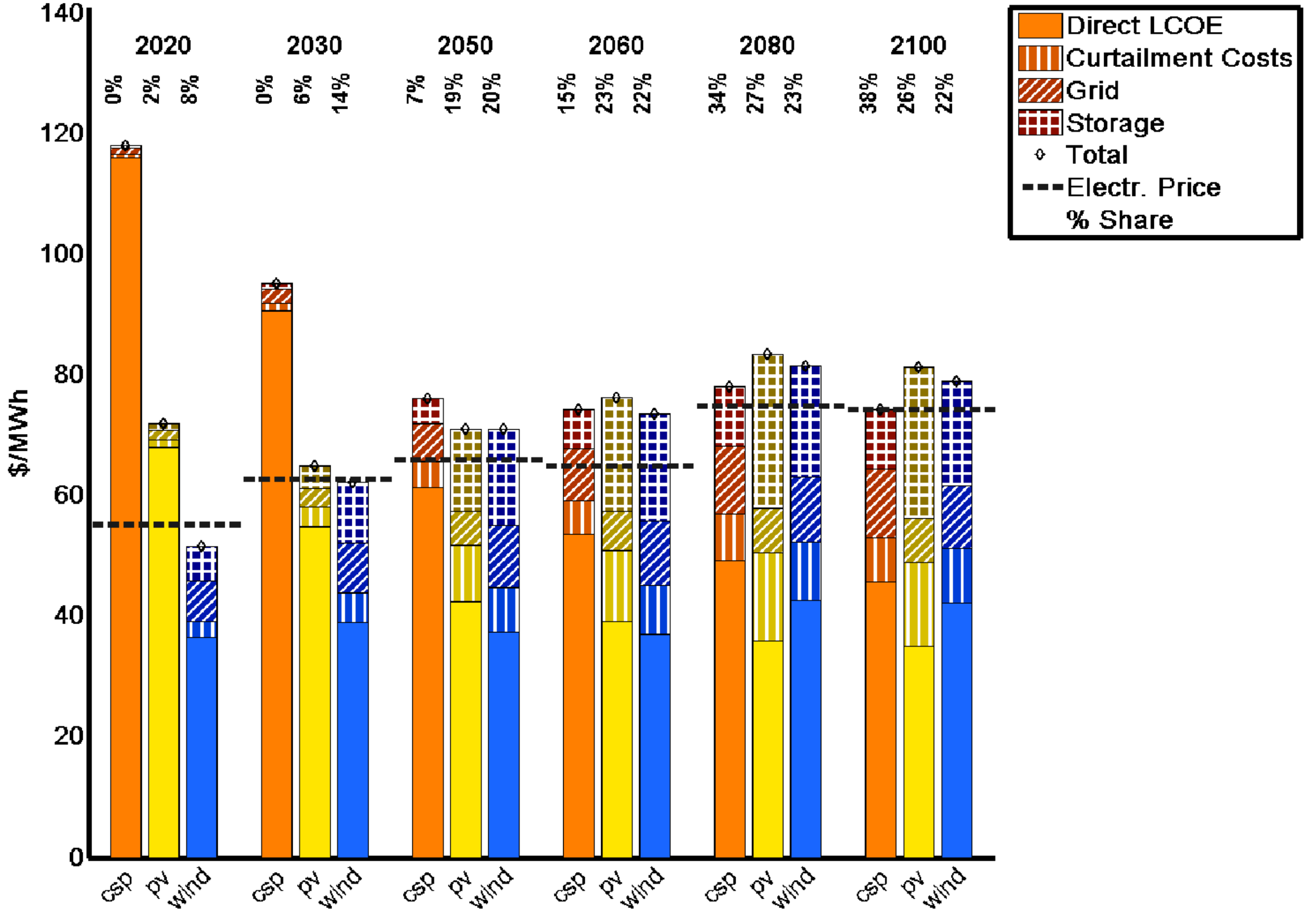
None/hard upper bound on RE: Too simple/unrealistic – should be discarded

- 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 convential 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

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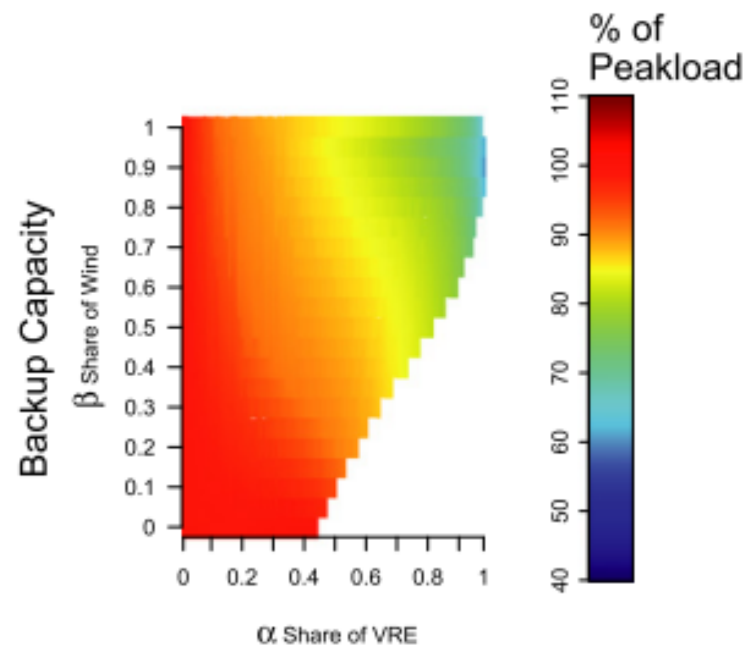
How to validate approaches?

- 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 cost**s

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,...)?

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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 Penalty	Y				Y		Y	Y				Y							
Storage		Y	Y		Y		Y								Y				
Backup/ Capacity constraint		Y	Y	Y	Y	Y		Y								Y			
Flexibility Requirement					Y		Y	Y											
Load Duration Curve / Time Slices		Y	Y	Y							Y			Y		Y			
Maximum share		15 %				Y				Y	Y				50 %	30 %	Y		Y
No Mechanism													Y					Y	

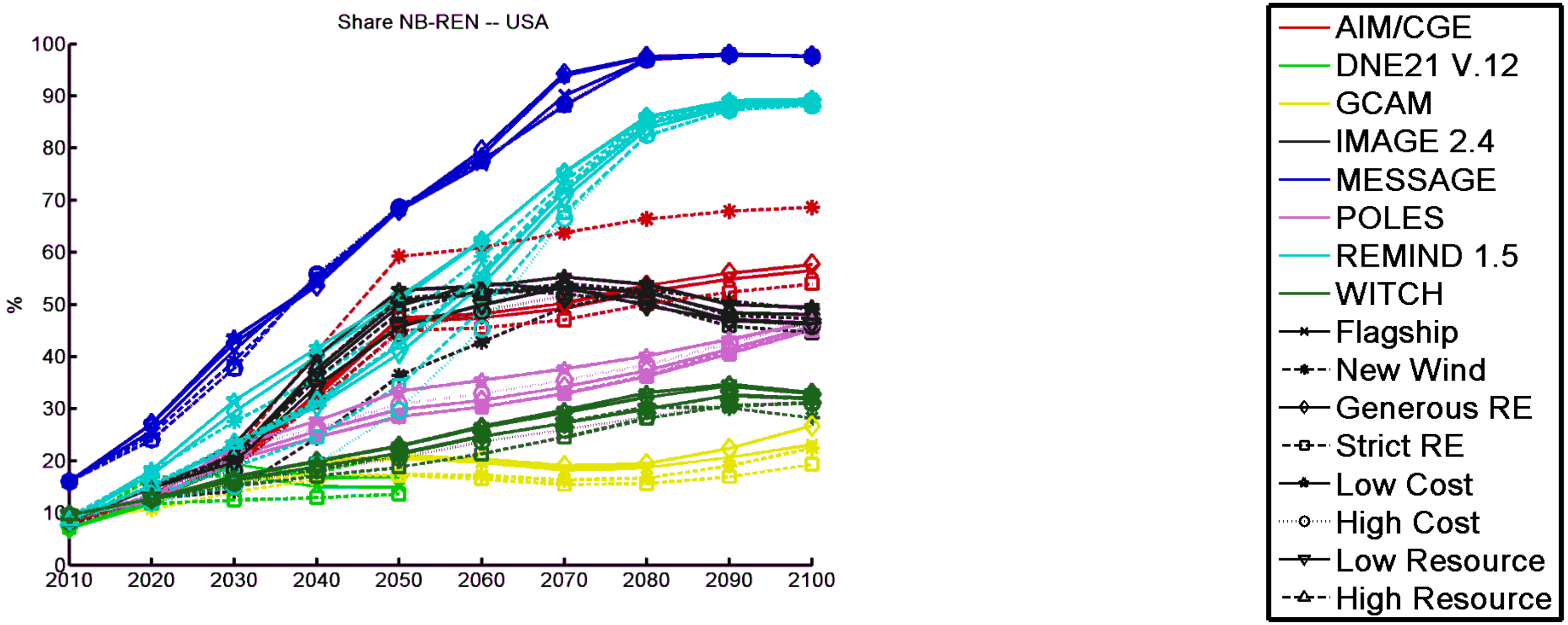
Part II: Integration scenarios for the RI workshop

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

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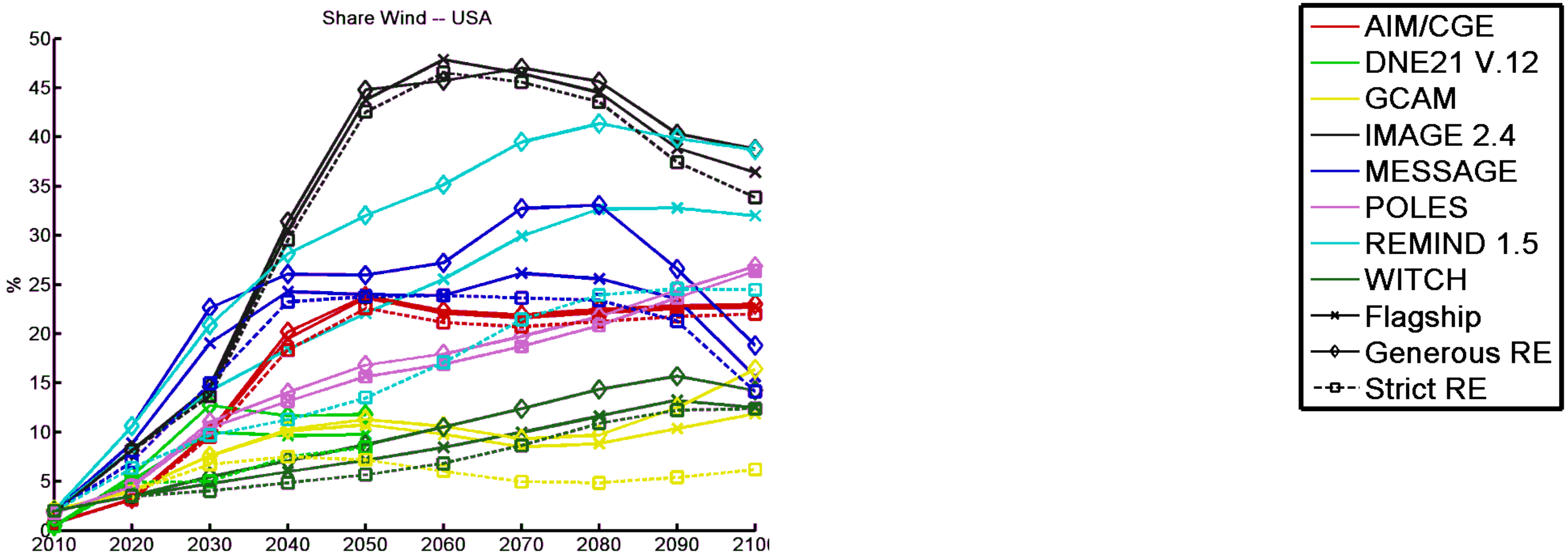
Integration Scenarios: Wind Shares



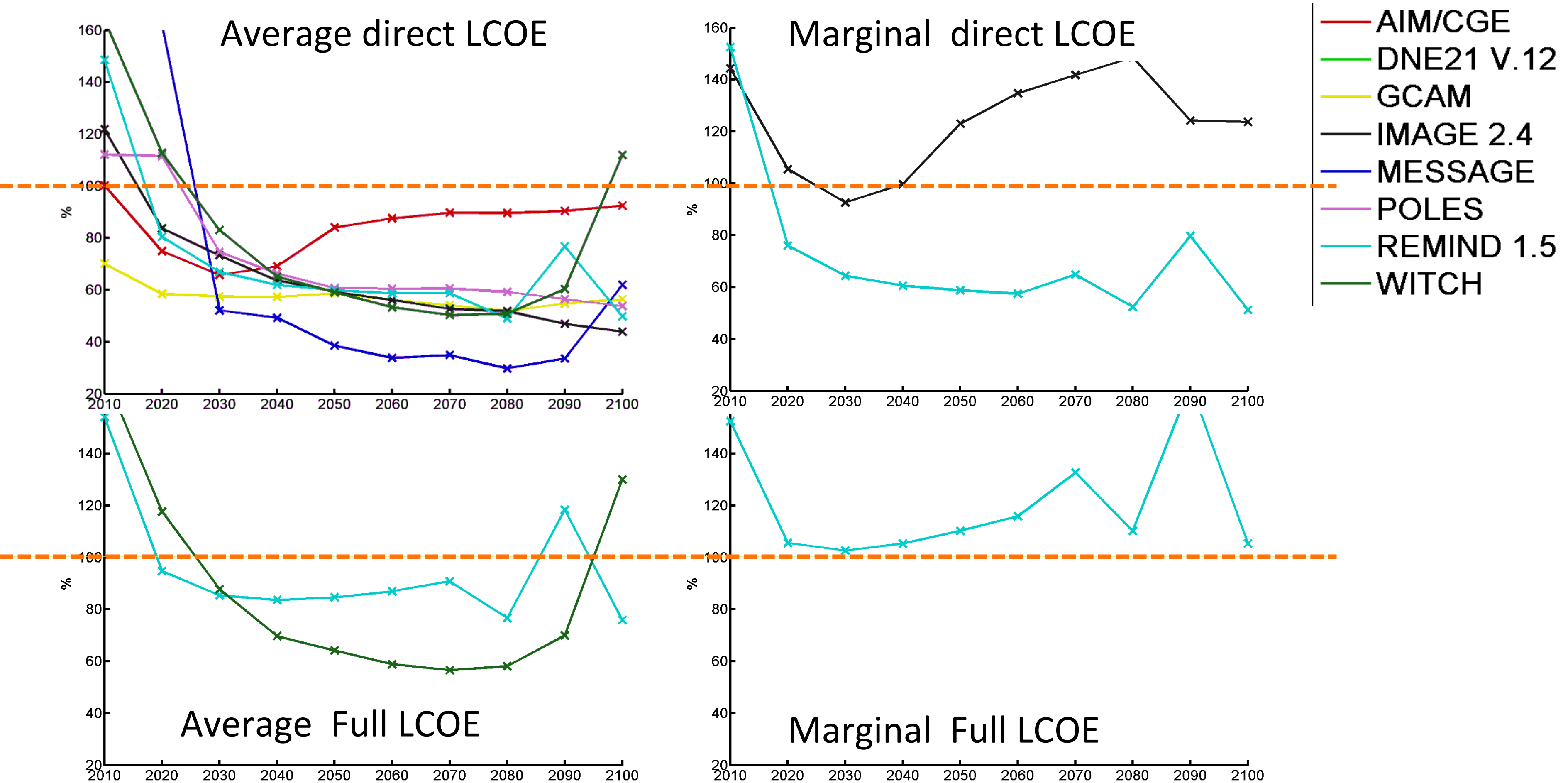
- Very different wind shares between the models
- Very different reactivity to variation of integration constraint

Integration Scenarios: Wind Shares

USA	relative change		absolute change in percentage points			average wind share	
	Generous	Strict	Generous	Strict		2010-2050	2010-2100
AIM/CGE	2%	-4%	0%	-1%		10%	16%
DNE21 V.12	20%	-22%	2%	-2%		7%	NaN
GCAM 3.0	11%	-32%	1%	-3%		6%	8%
IMAGE 2.4	2%	-3%	1%	-1%		17%	31%
MESSAGE V.4	17%	-9%	4%	-2%		15%	19%
POLES	5%	0%	1%	0%		8%	15%
REMIND 1.5	35%	-30%	8%	-7%		12%	21%
WITCH	18%	-11%	2%	-1%		4%	8%

- 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

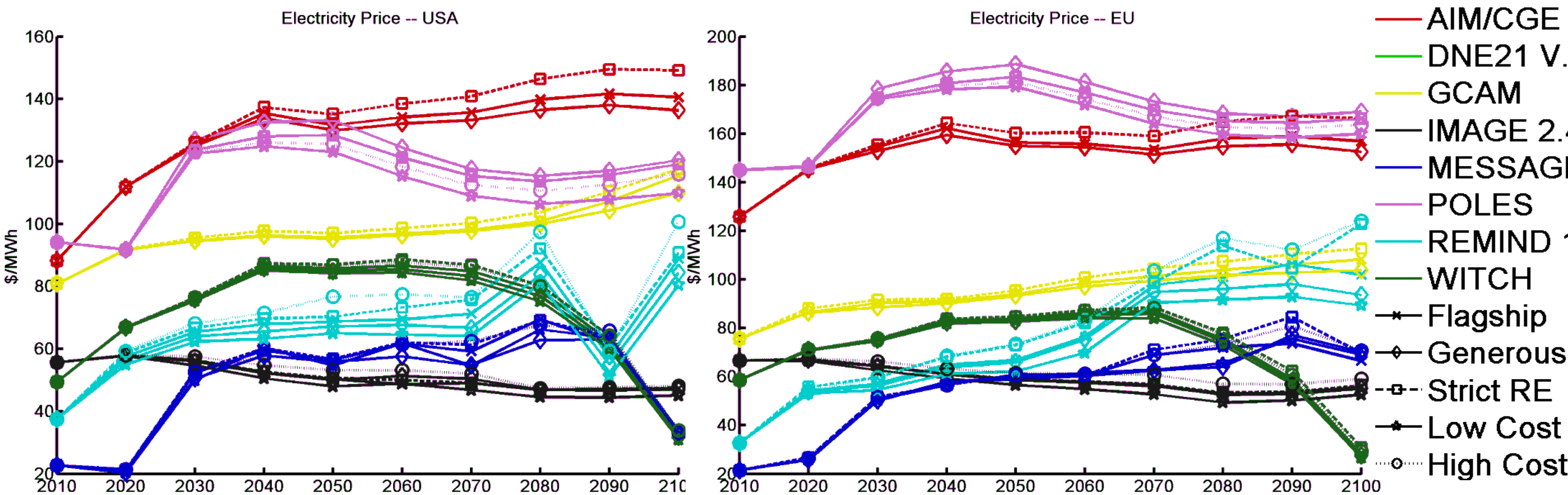
Integration effect vs. Cost effect:

	absolute change in percentage points			
	Generous Integration	**Strict Integration**	**Lo Cost**	**Hi Cost**
AIM/CGE	0%	-1%		
DNE21 V.12	2%	-2%		
GCAM 3.0	1%	-3%		
IMAGE 2.4	1%	-1%	3%	-3%
MESSAGE V.4	4%	-2%	2%	-2%
POLES	1%	0%	4%	2%
REMIND 1.5	8%	-7%	9%	-11%
WITCH	2%	-1%	2%	-1%

- 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 accross regions
- Integration constraint has little effect on electricity prices
- Relatively large effect for AIM – plausible, as AIM seems resource-constrained

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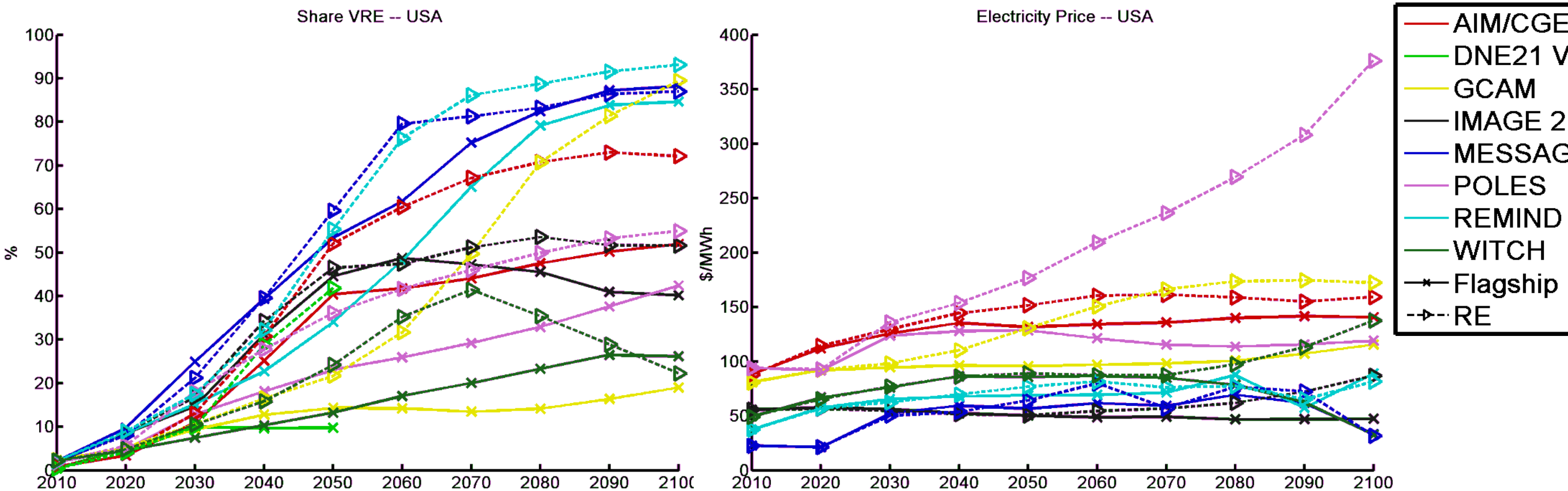
Forcing RE: Scenario without CCS/Nuclear



- 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!