Renewable electricity in computable general equilibrium models

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Outline

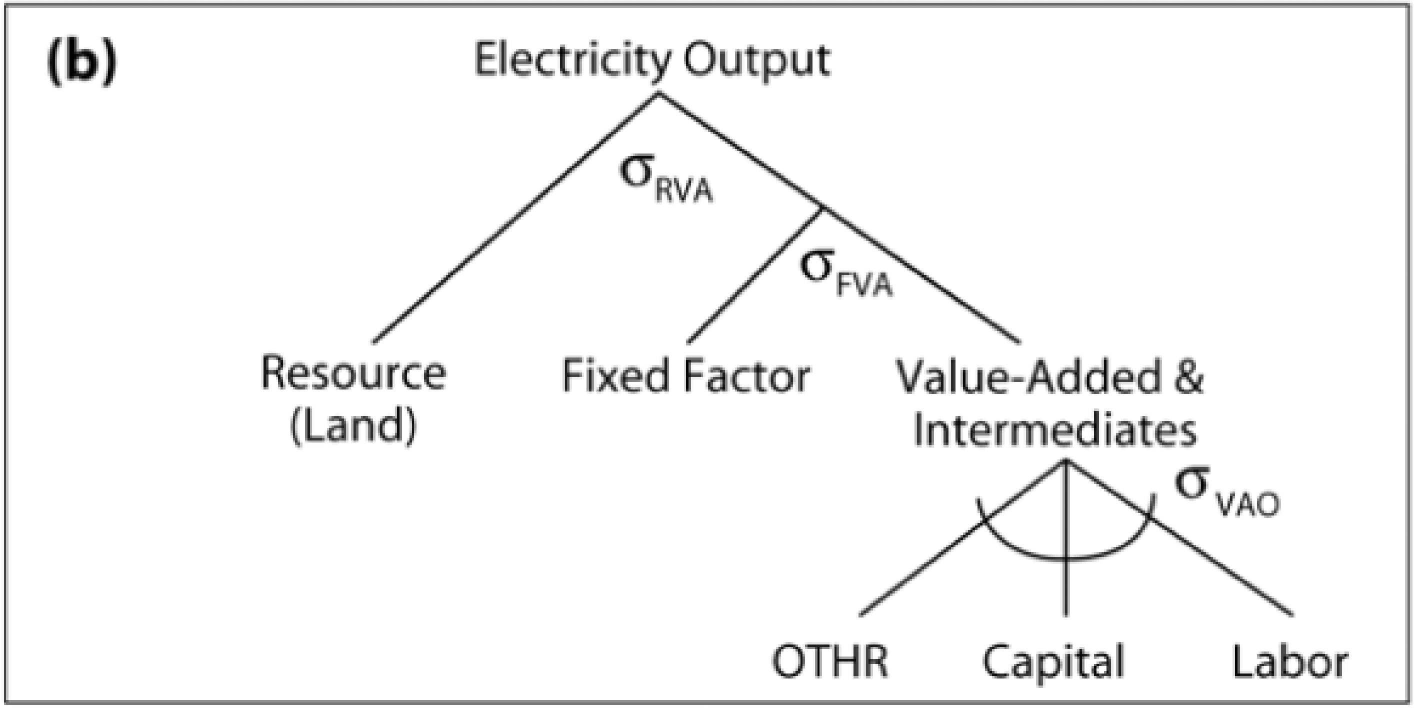
- The traditional (top-down) approach
- Top-down vs. bottom-up approaches
- Integrating top-down and bottom up approaches
- Comparing results from top-down and integrated models (preliminary)

The traditional (top-down) approach

- Electricity generation technologies are typically described by a nested constant-elasticity-of-substitution (CES) functions that combines energy, capital, labor and intermediate inputs from other sectors

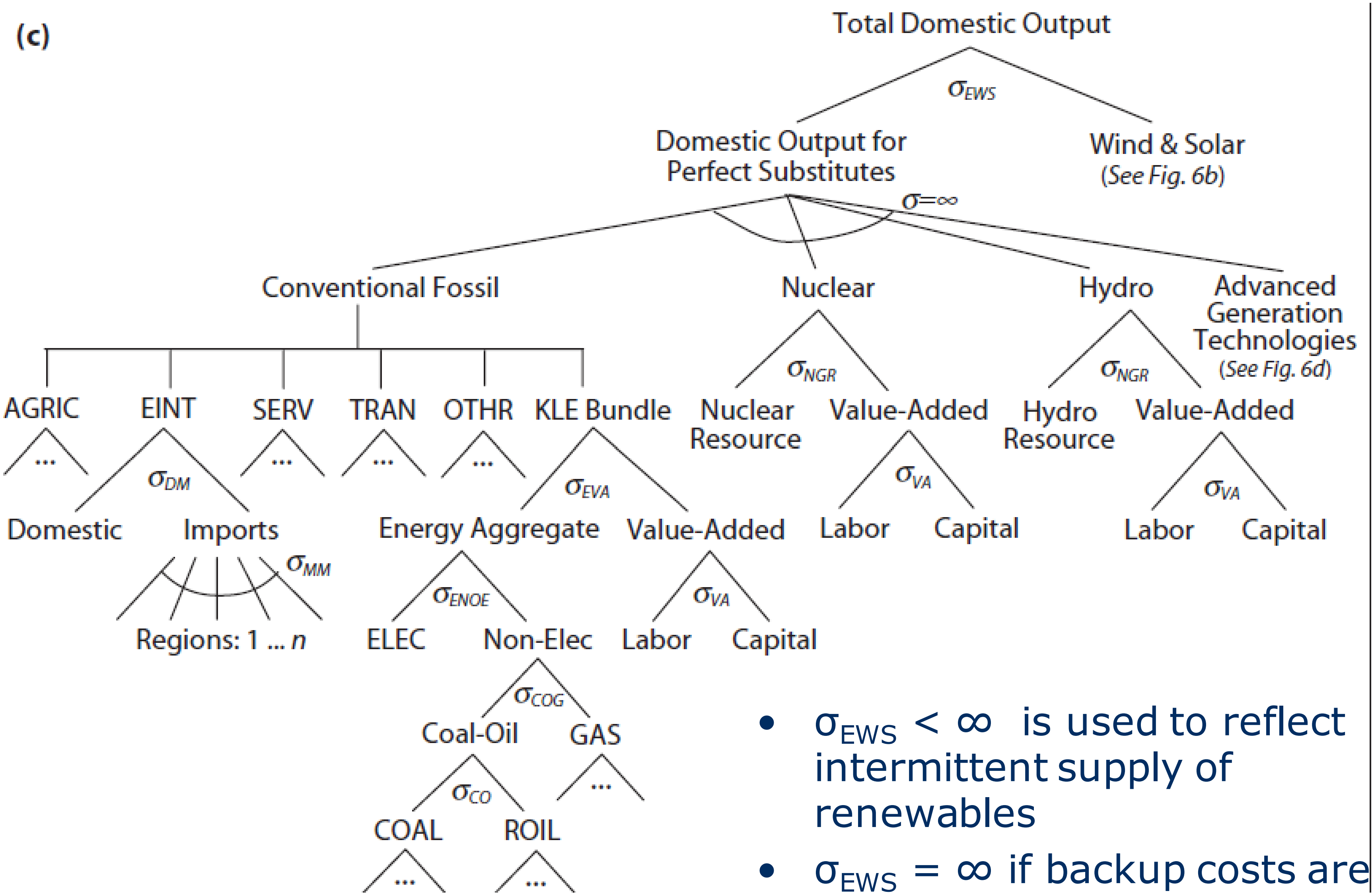
- Incorporate general equilibrium effects, but smooth functions are not well suited to capture the temporal and discrete nature of technology choice

Renewable electricity production



- The fixed factor and σ_{FVA} can be used to control penetration of the renewable technology

Electricity output



- $\sigma_{EWS} < \infty$ is used to reflect intermittent supply of renewables
- $\sigma_{EWS} = \infty$ if backup costs are considered

Top-down vs. Bottom-up

- Conventional **top-down (TD)** models:
  - Examine the broader economy and incorporate feedback effects between different markets triggered by policy-induced changes in relative prices and incomes
  - Limited technological detail of energy production or conversion
- Conventional **bottom-up (BU)** models:
  - Technological explicitness on supply and demand side
  - Typically lack macro-economic feedbacks and realistic representation of micro-economic decision making
- Both approached produce similar results when focusing on conventional fossil-based electricity generation technologies, but there can be significant differences when large-scale electricity generation from intermittent renewable energy sources are considered

Limitations for top-down Modeling of Electricity in CGE Models

- Aggregate, smooth production functions to represent electricity sector technology competition
- Computational complexity and conceptual framework limit detail that can be incorporated
- Modeling challenges are particularly critical for representing renewable energy in electricity sector comprising e.g.:
  - Limited number of technologies; no storage
  - Characterization of renewable resources and electricity demand at sufficiently resolved regional and temporal scales
  - Capacity investment decisions including back-up for intermittent generation
  - Access to and the cost of transmission

Limitations for “Bottom-up” Energy/ Electricity Sector Models

- No feedback from other sectors to the electric sector, and limited ability to handle feedback from the demand-side of electricity
- Not able to address broad economic effects of electricity sector policies (e.g., welfare, income, labor, government transfers)

Taxonomy of Hybrid Modeling Approaches

1) "Soft-link" approach to couple two existing TD and BU models
   - Models are solved independently and "some" information between models is exchanged
2) One model type complemented by "reduced-form" representation of the other
   - Integrate "some" technology detail in TD models
3) "Hard-link" approach fully integrates TD and BU models within a single consistent framework

Combining the strengths of both modeling paradigms through development of an integrated model framework

- Building on work by Lanz and Rausch (2011), Rausch and Mowers (2012) integrate the MIT US Regional Energy Policy (USREP) model and NREL's Renewable Energy Deployment System (ReEDs) model

Integration of an Economy-wide Model with an Electricity Sector Optimization Model to Assess the Economic Impacts of U.S. Climate Policy

MIT USREP model

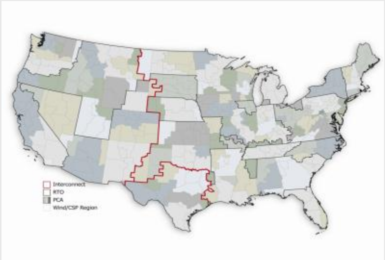
- Computable General Equilibrium (CGE) model of the U.S. economy
- Representation of integrated economic-energy system at state/regional and detailed sectoral level

INTEGRATED MODEL FEATURES

- ➢ Full integration of both models using state-of-the-art numerical techniques
- ➢ Combines macroeconomic framework with technology-rich representation of electricity sector including detailed treatment of renewable energy
- ➢ Enables economic assessment of climate policies with significant electric sector role

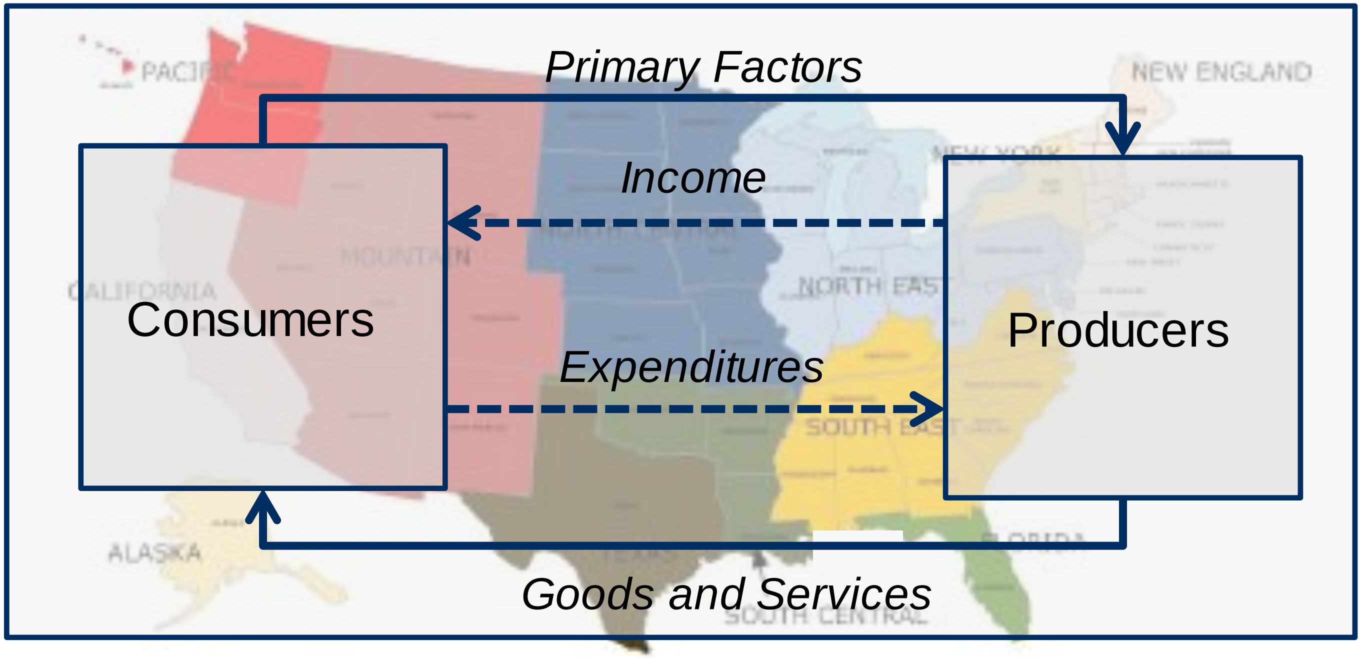
NREL's ReEDS model

- Capacity expansion & dispatch linear programming model for the US electricity sector including all major generator types
- High spatial and temporal resolution to represent renewable resources and transmission expansion



Rausch and Mowers (2012)

MIT USREP Model: Overview

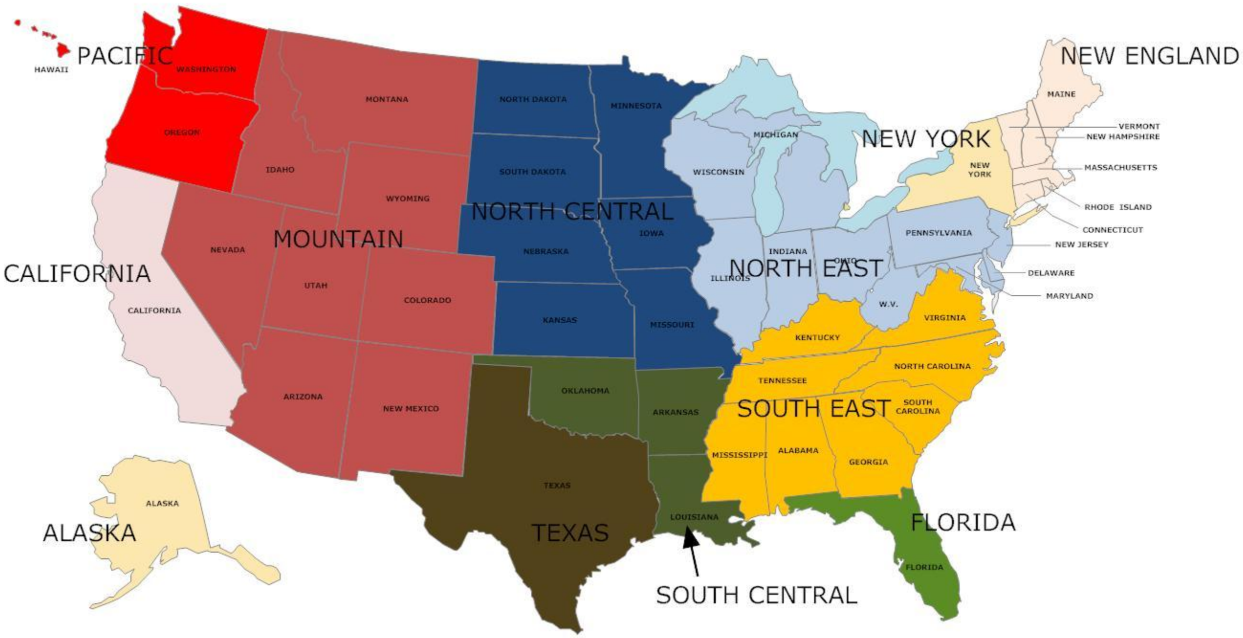


MODEL FEATURES

- Multi-region, multi-sector recursive-dynamic general equilibrium model
- State-level economic (IMPLAN) and energy (EIA) data
- Regional emissions for “Kyoto” greenhouse gases
- 5 energy and 5 non-energy sectors
- Heterogeneous consumers within regions
- Federal and state government taxes and transfers

Spatial and Social Output Aggregation

- **Income Classes**: Total U.S. population is grouped by nine annual income classes allowing for the evaluation of policy impacts on different social classes
- **Regions:** State-level dataset allows flexible regional aggregation



Sample Sectoral Aggregation

Sectors	Ener[...]	[...]duction Factors
Non-energy sectors	**Ener[...]**	
Agriculture	*Fuel*	
Services	Co[...]	[...]ces
Other energy intensive sectors	Na[...]	[...]resources
Manufactured and processed goods	Cr[...]	[...]sources
Transportation	Re[...]	
Paper Products	Elec[...]	
Chemical products		
Non-metallic minerals		
Iron and steel		
Non-ferrous metals		

Model with top-down representation of technologies

Advanced energy technologies

Fuel substitutes:

- Coal Gasification
- Shale Oil
- Biomass Liquids

Electricity generation:

- Biomass Electricity
- Intermittent Wind
- Wind with gas backup
- Wind with biomass backup
- Natural Gas Combined Cycle
- Natural Gas Combined Cycle with CCS
- Integrated Coal Gasification Cycle CCS
- Advanced Nuclear

- Aggregation based on 57 [...] Project (GTAP) data

NREL's ReEDS Model

ReEDS (Regional Energy Deployment System) model has been developed by NREL's Strategic Energy Analysis Center (Short et. al, 2009)

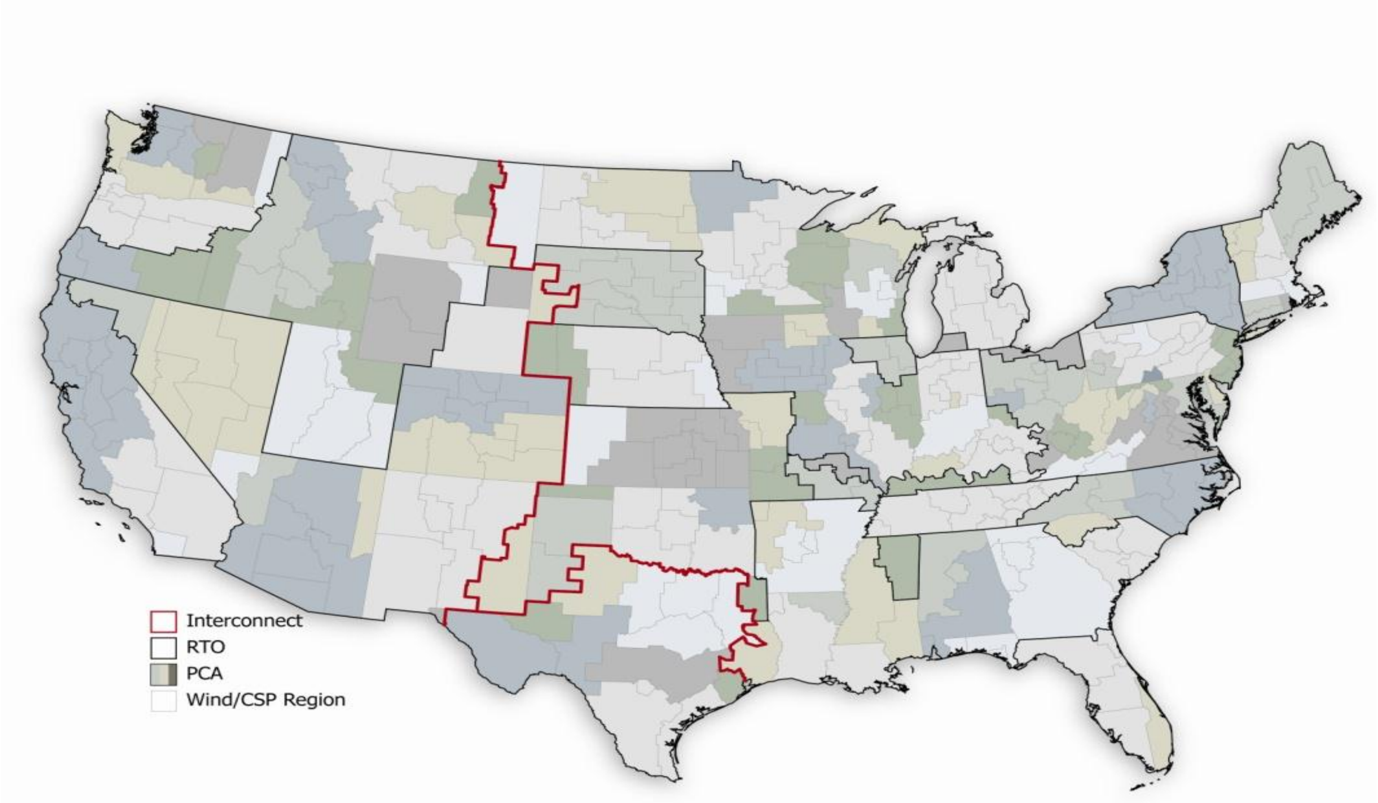
- Capacity expansion & dispatch linear programming model for the continental US electricity sector including transmission & all major generator types
- Minimize total system cost in each 2-year investment period until 2050
  - All constraints (e.g. balance load, reserves, etc.) must be satisfied
- Multi-regional (356 wind/solar resource regions, 134 power control areas)
  - Enables transmission capacity expansion
  - Enables treatment of the variability of wind/solar
- Temporal resolution
  - 17 time slices in each year
  - Statistical treatment of variability and uncertainty of wind & solar

ReEDS uses a system-wide least cost optimization to estimate the types and locations of electricity generators, storage, and transmission infrastructure; and the overall cost of electricity supply, while ensuring a balance of supply and demand.

ReEDS Resources/Technologies

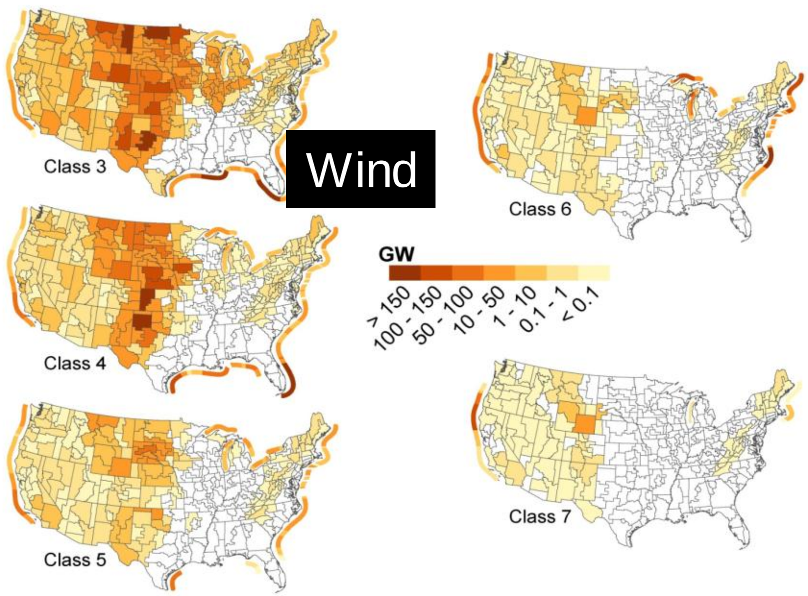
- **Conventionals** (fossil & nuclear):
  - Coal (pulverized, IGCC, & IGCC-CCS)
  - Natural Gas (combustion turbine, combined cycle, & CC-CCS)
  - Oil
  - Nuclear
- **Renewables:**
  - Biomass (dedicated, cofired, & landfill-gas/MSW)
  - Geothermal (hydrothermal & EGS)
  - Hydropower
  - Marine Hydrokinetic
  - Solar (concentrating solar power & PV)
  - Wind (onshore & offshore)
- **Storage:** pumped hydropower storage, CAES, batteries
- **Demand-side techs:** plug-in hybrid/electric vehicles (PHEVs), thermal energy storage in buildings, interruptible load

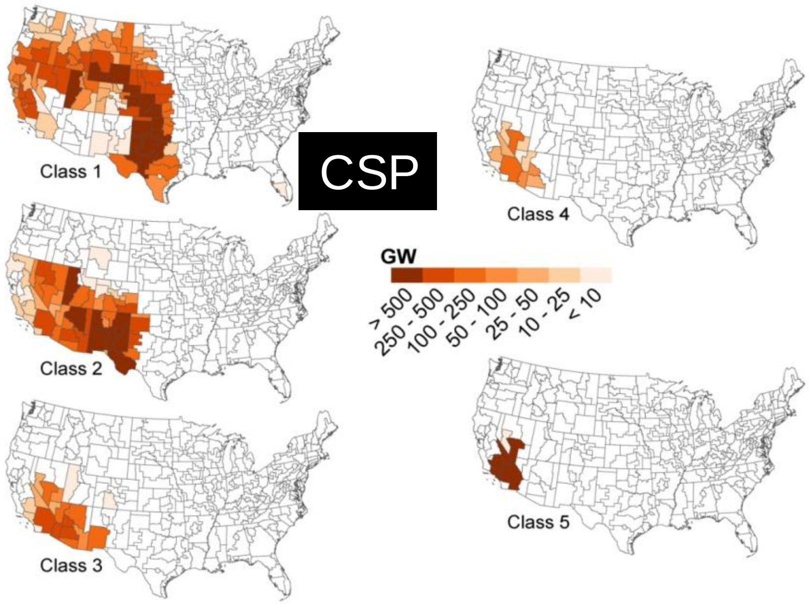
ReEDS Regions

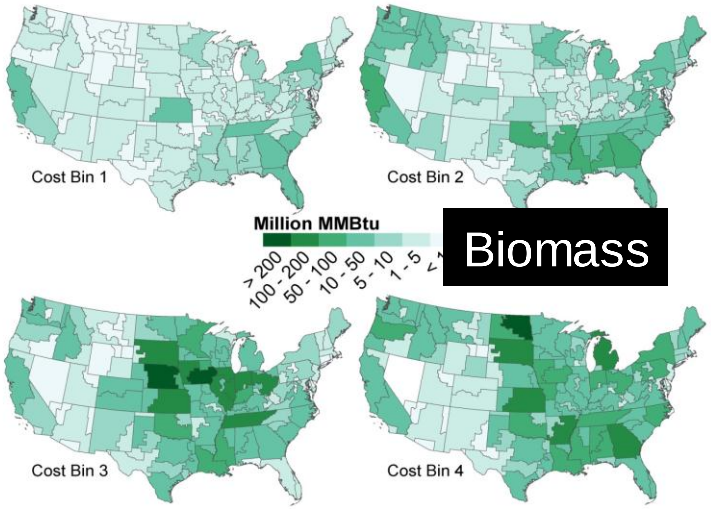


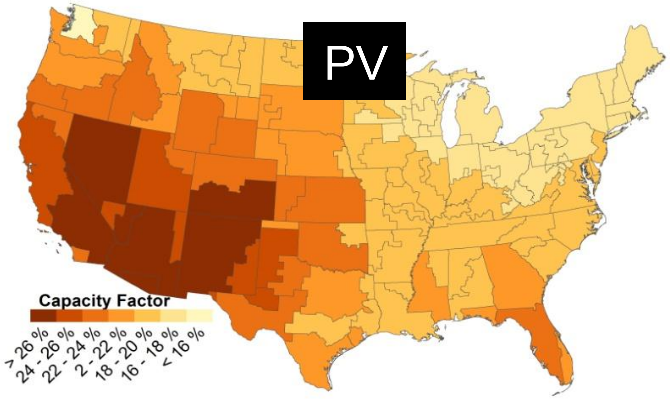
- 356 CSP/Wind resource regions: level at which CSP/Wind capacity expansion occurs and resource limitations are considered
- 134 Power Control Areas (PCA): level at which demand requirements must be satisfied
- 21 RTOs: level at which reserve requirements must be met
- 3 asynchronous interconnects

ReEDS Resource Resolution

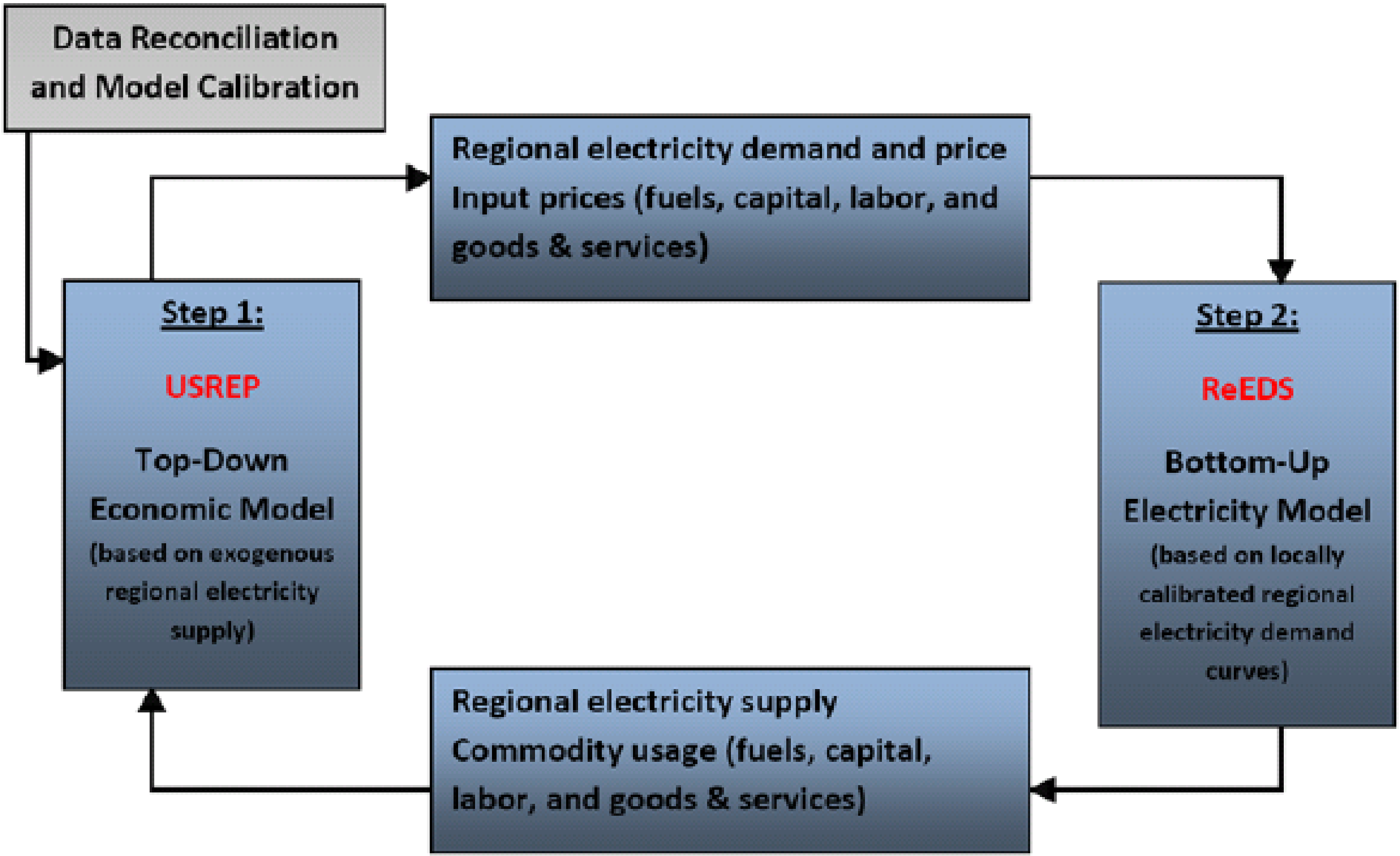








Integrating USREP and ReEDS



- Employ a decomposition approach (Boehringer and Rutherford, JEDC, 2009) to overcome dimensionality problem
- Iterative solution approach allows ReEDS and USREP tp be solved separately

Comparing TD and integrated results

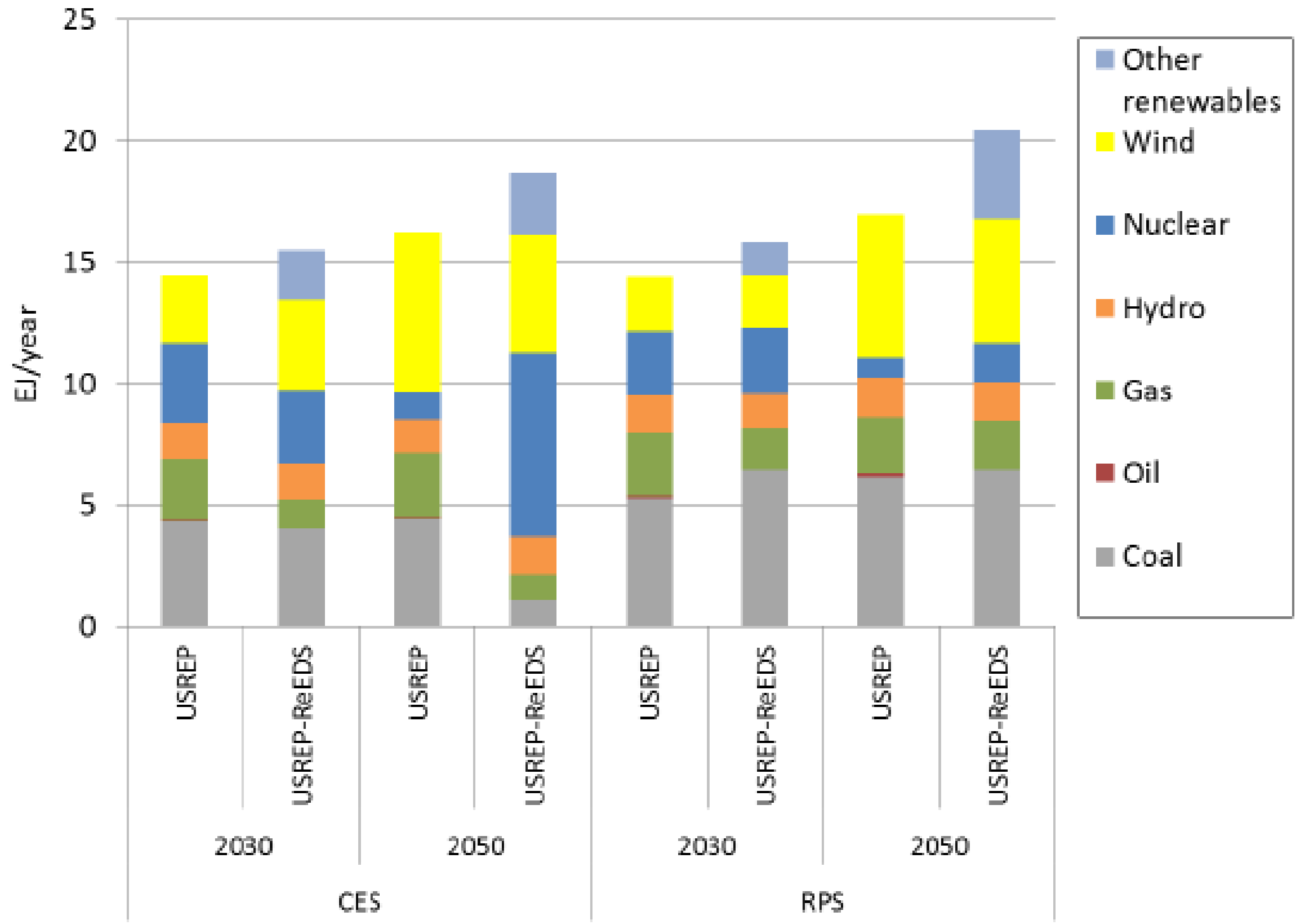
- **RPS:** A federal renewable portfolio standard for electricity which mandates that 20% by 2020 and 50% by 2050 of electricity is produced from renewable energy (including hydropower), and that all new coal power plants capture and store more than 90% of their CO_2 emissions

- **CES:** A federal clean energy standard for electricity under which all renewable energy sources and nuclear receive full credit while fossil electricity with CCS technologies are credited at 90% and natural gas at 50% with targets defined as linearly increasing from reference levels in the 2012 to 50% by 2020 and 90% by 2040 and thereafter

Summary results

	USREP		USREP-ReEDS	
	RPS	**CES**	**RPS**	**CES**
Net present value welfare costs ($trillions)	1.6	2.1	0.91	2.0
Cumulative CO_2 emissions reduction (%)	8.4	10.6	7.1	17.0
Elec. price increase relative to baseline (%)				
Year 2030	6.0	7.3	0.7	5.3
Year 2050	4.7	10.0	7.1	13.6

Electricity generation



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- Lanz, B. and S. Rausch, 2011. "General Equilibrium, Electricity Generation Technologies and the Cost of Carbon Abatement: A Structural Sensitivity Analysis." *Energy Economics*, 33: 1035–1047.
- Rausch, S. and M. Mowers, 2012. "Distributional and Efficiency Impacts of Clean and Renewable Energy Standards." MIT Joint Program on the Science and Policy of Global Change Report No. 225.