Modeling Renewables: A Brief Survey of Key Issues in Integrating Bottom Up and Top Down

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Plan of Talk

- Motivation and model archetypes
- Investment
- Resources
- System operation impacts

Introduction

- Motivation: climate change impacts
  - What will be the effects on renewables?
  - (For US at least) Increasing extremes of temperature and humidity, increasing demand for summer cooling
  - Will—and if so, how—will these lead effects to a change in load shape?
  - Ultimately, will future increases in renewable penetration be able to provide the additional energy required, when needed, without increasing GHG emissions?

Bottom-Up: Electric Power/Energy System

[Objective: min pv of capacity + investment + variable input costs]

$$\min_{n_{i,t}, v_{f,i,t}, d_{\ell,t}} Z = \sum_t \beta^t \sum_i \left(c^X[x_{i,t}] + c^N[n_{i,t}] + \sum_f \sum_\ell \sum_r c_r^V[v_{f,\ell,r,i,t}] \right) \quad \text{s.t.}$$

[Production function based on parameters $\boldsymbol{\theta}_{\ell,r,i}$]

$$q_{\ell,i,t} = F[\mathbf{v}_{f,\ell,r,i,t}, x_{i,t}; \boldsymbol{\theta}_{\ell,r,i}]$$

[Demand response constraint based on parameters $\boldsymbol{\phi}_{\ell}$]

$$D_t \le G[\mathbf{d}_{\ell,t}; \boldsymbol{\phi}_{\ell}]$$

[Market clearance constraint by load segment]

$$d_{\ell,t} \le \sum_i q_{\ell,i,t}$$

[System operation feasibility constraints based on parameters $\boldsymbol{\psi}_{\ell,i}$]

$$S[\mathbf{q}_{\ell,i,t}; \boldsymbol{\psi}_{\ell,i}] = 0$$

[Capacity equation of motion]

$$x_{i,t+1} \le n_{i,t} + (1-\zeta_i) x_{i,t}$$

[Resource potential]

$$R_{f,\ell,r} \ge \sum_i v_{f,\ell,r,i,t}$$

Renewable Modeling Initiative

- Fundamental intellectual payoff is the response surface

$$\Delta Z=\Omega[\text{VRE Target},\boldsymbol{\theta}_{\ell,r,i},\boldsymbol{\phi}_{\ell},\boldsymbol{\psi}_{\ell,i},R_{f,\ell,r}]$$

  particularly the marginal response/envelope conditions

$$\partial\Delta Z/\partial\boldsymbol{\theta}_{\ell,r,i}\,,\ \partial\Delta Z/\partial\boldsymbol{\phi}_{\ell}\,,\ \partial\Delta Z/\partial\boldsymbol{\psi}_{\ell,i}\,,\ \partial\Delta Z/\partial R_{f,\ell,r}\ \Big|_{\text{VRE Target}}$$

- Observations from Monday's discussion
  - Recovering Ω is complicated by a key underdetermined aspect of the model intercomparison exercise: no standardization over connection between resource potentials and supply curves $c_r^V[v_{f,\ell,r,i,t}]$
  - Should the entire system cost premium ΔZ be entirely loaded back onto the VRE when the latter is being forced in <u>by fiat</u>?
  - Alternatively, if <u>not</u> forced—i.e., there is simply a change in technology or availability that facilitates increased renewable penetration—what will ΔZ be?
  - Economic interpretation of envelope conditions/ components of ΔZ attributable to different system components (cf Falko discussion)
  - Envisage using Ω to parameterize endogenous markup on VREs with increased penetration in IAMs—right idea but the <u>devil is in the details</u>!

Top-Down: Computable General Equilibrium (1)

- Circular flow of the economy $\Rightarrow$ conditions for GE to hold
  - Market clearance (*MC*): supply = demand for each reproducible good (e.g., electricity) or primary factor of production (e.g., labor)
  - Zero profit (*ZP*): each firm's output price = marginal cost of production
  - Income balance (*IB*): hholds' factor income from factor returns = expenditure on commodities
- A CGE model is merely an algebraic expression of the above
  - Parameters numerically calibrated on input-output economic accounts
  - System of equations solved for a set of goods prices (**P**), factor prices (**W**), industry activity levels (**A**), and household income levels (**I**)
- Key is to assume optimizing behavior by producers and hholds
  - Households minimize expenditure $\Rightarrow$ Final commodity demands(**P**, **I**)
  - Firms minimize costs $\Rightarrow$ Factor demands(**W**, **A**), Intermediate commodity demands(**P**, **A**)
- A CGE model combines circular flow conditions with the demand functions, KKT complementary slackness conditions

Top-Down: Computable General Equilibrium (2)

- CGE model in a nutshell

  MC: Factor endowment = ∑ Factor demands(**W**, **A**),
  Goods supply(**A**) = ∑ Intermediate goods demands(**P** , **A**)
  + ∑ Final goods demands(**P** , **I**)

  ZP: Goods price(**P**) × Goods supply(**A**) =
  ∑ {Goods prices(**P**) × Intermediate goods demands(**P**, **A**)}
  + ∑ {Factor prices(**W**) × Factor demands(**W**, **A**)}

  IB: ∑ {Goods prices(**P**) × Final goods demands(**P**, **I**)}
  = ∑ {Factor prices(**W**) × Factor endowments}

- Solve for prices and quantities *simultaneously*
  - Find commodity/factor prices industry/household activity levels which satisfy the system of equations

$$\underline{MC} \perp (\underline{\mathbf{P}}, \underline{\mathbf{W}}) \qquad \underline{ZP} \perp \underline{\mathbf{A}} \qquad \underline{IB} \perp \underline{\mathbf{I}}$$

where "⊥" indicates complementary slackness

Two Approaches to Integration

- Electric power sector represented by smooth functions, key issue: how to incorporate wealth of technical information embodied in system models into that abstraction
- Decomposition approach
  - Couple CGE with economic dispatch/capacity expansion, iteratively running models in tandem
  - CGE model uses elec. system model technology generation as a commodity endowment vector, computes prices, variable input quantities
  - Elec. system model uses supply/demand curves parameterized based on CGE price and input/output quantities, computes generation quantities by technology
- Integrated approach
  - Incorporate generation technologies as discrete options directly with CGE models' smooth production/cost functions (nested CES)
  - Calibration requires reconciling incommensurate input-output economic data with engineering data on technical characteristics of generation options, balance of system

Modeling Investment (1)

- Decomposition
  - A consistent approach would couple an intertemporal CGE model with a detailed intertemporal system model (incl. min. load constraints, ramp rates, security constraints, etc.)
  - Possible! RTI/ADAGE under development
  - Key issues to be addressed:
    - Need to map between system detail and coarse spatial/temporal resolution required to solve full intertemporal economic equilibrium
    - Nuances of setting up calibration to let system model compute capacity investment, hand off to CGE model. Avoids having to solve the computationally intractable *m*-capital stock multisectoral Ramsey model!
    - Most CGE models incorporate myopic dynamics—consistent linkages to intertemporal system models based on rolling capacity plans?

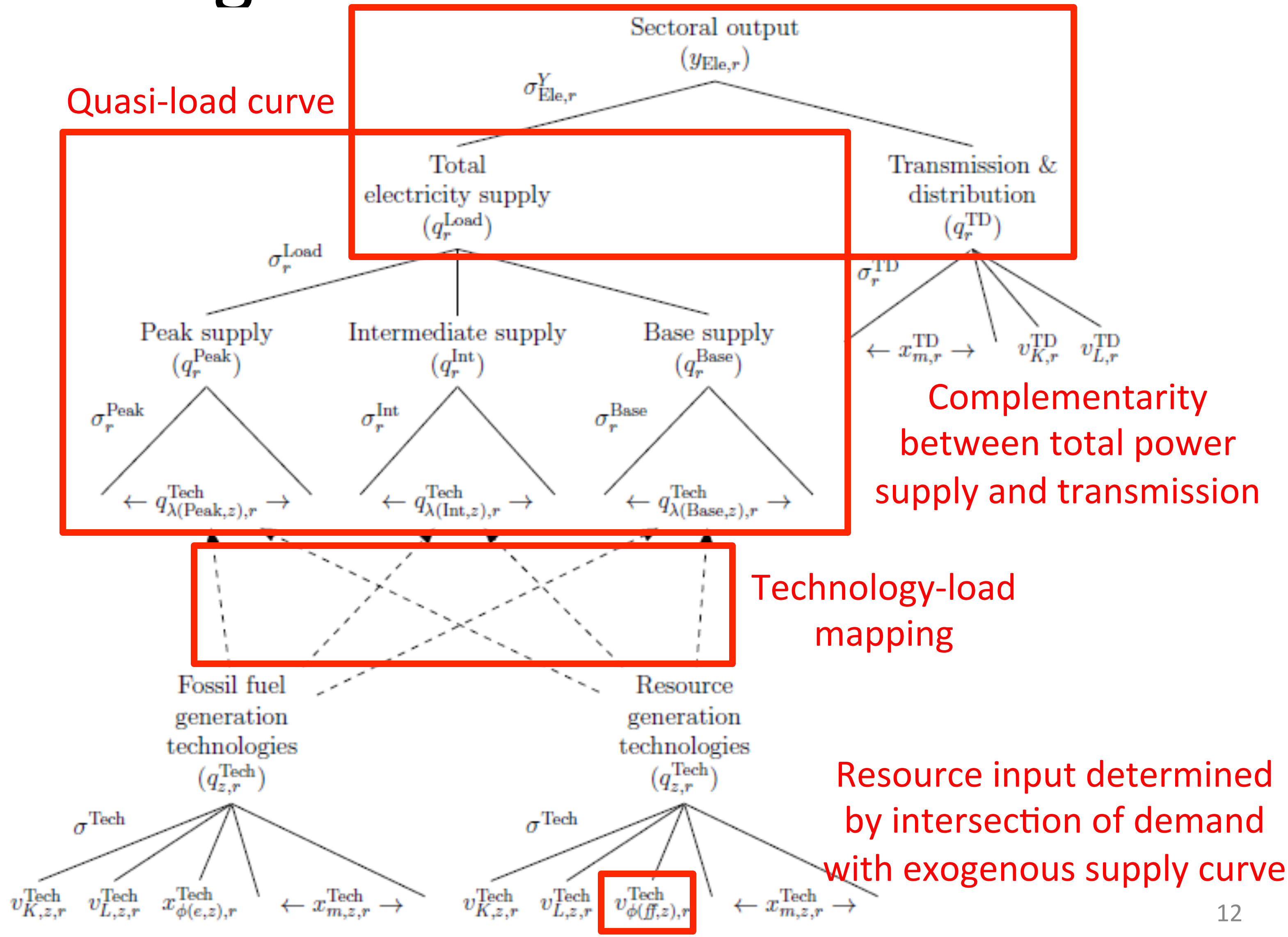
Modeling Investment (2)

- Integrated
  - Minimum requirement: avoid implausible “bang-bang” technology behavior, achieve via imperfect capacity substitution in short-run equilibrium
  - Sue Wing (2006): punt on investment entirely!
    - Treat capital as a homogeneous intersectorally mobile “jelly” factor
    - Transform capital input to electric power sector into technology-specific capital, using a CET function with low elasticity of tranformation (~ 0.5)
  - Full *m*-capital intertemporal GE problem computationally intractable, fallback ⇒ myopic dynamics
    - BUT, requires specification of an ad-hoc investment demand function for technology-specific capital
    - Scope for doing this based on empirically estimated relationships?

Modeling Resources

- Decomposition
  - Burden falls on BU model per Monday's discussion
  - Need to work out <u>economic value</u> of VRE resource endowments, and a way to represent their use, given that the system model short-circuits the connection between the two in the top-down model
- Integrated
  - Need markups of technologies inactive in the benchmark in terms of LCOG + BOS costs (cf Falko/Robert discussion)
  - Need representation of resources and their use that is consistent with the <u>economic logic</u> of GE
    - Extent of <u>physical</u> resource base not so much of an issue for CGE models
    - Supply curve (<u>cost</u>) parameterization would appear to be much more important

An Archetypical Integrated Approach Using Nested CES Functions



Differentiating Load, Matching Technologies (1)

- Key weakness of the integrated approach is treatment of electricity as a homogeneous good on the demand side
  - Largely unavoidable, given monolithic character of I-O data, lack of information on distribution of different consumers' electricity demand among different load classes
  - Holy grail is a row disaggregation of electricity demand in I-O table into load segments, but this is possible only where data are available (e.g., Dias & Linares, 2010; EPRI???)
  - In any case need a procedure to divide <u>aggregate</u> load into classes, specify load class demands for generation technologies' outputs
  - Data constraints mean current parameterization usually based on judgment and assumptions
    - Aggregate load = CES1(Base load, Intermediate load, Peak load)
    - Base, Intermediate or Peak load = CES2(different technology outputs)

Differentiating Load, Matching Technologies (2)

- Aforementioned procedure makes it simple to introduce new “backstop” VRE generation technologies that do not exist in benchmark calibration dataset
  - A key issue is modeling renewable penetration in poorer developing regions
  - Two basic calibration options
    - Recalibrate CES1() to accommodate additional inputs
    - Retain CES1() but specify output of VRE technology as a perfect substitute for an extant conventional technology
  - In either case competition between VRE and conventional technology options constrained by 2 critical factors which determine penetration rate/extent
    - Resource supply schedule
    - Markup of non-extant technology over average cost of existing alternatives
  - Key questions is how to employ something like Ω here...

Discussion of Potential Ways Forward?