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

Ian Sue Wing

Boston University
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]

$$\min \sum_{n} \{v_{f}, i, t, d, \ell, t\} = Z = \sum_{t} \beta t \sum_{c} X [x_{l}, t] + c_{N} [n_{l}, t] + \sum_{f} \sum_{r} \sum_{c} r_{V} [v_{f}, \ell, r, i, t]$$

s.t.

[Production function based on parameters $\theta_{l}, r, i$]

$$q_{l, i, t} = F[v_{f}, \ell, r, i, t, x_{l}, t; \theta_{l}, r, i]$$

[Demand response constraint based on parameters $\phi_{l}$]

$$D_{l, t} \leq G[d_{l, t}; \phi_{l}]$$

[Market clearance constraint by load segment]

$$d_{l, t} \leq \sum_{i} q_{l, i, t}$$

[System operation feasibility constraints based on parameters $\psi_{l, i}$]

$$S[q_{l, i, t}; \psi_{l, i}] = 0$$

[Capacity equation of motion]

$$x_{l, t+1} \leq n_{l, t} + (1 - \xi) x_{l, t}$$

[Resource potential]

$$R[f_{l}, f_{l}, r] \geq \sum_{i} v_{l} f_{l, r, i, t}$$
Renewable Modeling Initiative

• Fundamental intellectual payoff is the response surface

\[ \Delta Z = \Omega [ \text{VRE Target}, \theta \downarrow, r, i, \phi \downarrow, \psi \downarrow, i, R \downarrow f, \ell, r ] \]

particularly the marginal response/envelope conditions

\[ \partial \Delta Z / \partial \theta \downarrow, r, i , \partial \Delta Z / \partial \phi \downarrow , \partial \Delta Z / \partial \psi \downarrow, i , \partial \Delta Z / \partial R \downarrow f, \ell, r | \text{VRE Target} \]

• Observations from Monday’s discussion

– Recovering \( \Omega \) is complicated by a key underdetermined aspect of the model intercomparison exercise: no standardization over connection between resource potentials and supply curves \( c \downarrow f \uparrow V [ v \downarrow f, \ell, r, i, t ] \)

– Should the entire system cost premium \( \Delta Z \) be entirely loaded back onto the VRE when the latter is being forced in by fiat?

– Alternatively, if not forced—i.e., there is simply a change in technology or availability that facilitates increased renewable penetration—what will \( \Delta Z \) be?

– Economic interpretation of envelope conditions/ components of \( \Delta Z \) attributable to different system components (cf Falko discussion)

– Envisage using \( \Omega \) to parameterize endogenous markup on VREs with increased penetration in IAMs—right idea but the devil is in the details!
Top-Down: Computable General Equilibrium (1)

• Circular flow of the economy ⇒ 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 ⇒ Final commodity demands($P, I$)
  – Firms minimize costs ⇒ 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
  
  \( \textit{MC}: \) Factor endowment = \( \sum \) Factor demands(\( W, A \)),
  
  Goods supply(\( A \)) = \( \sum \) Intermediate goods demands(\( P, A \))
  
  \( + \sum \) Final goods demands(\( P, I \))

  \( \textit{ZP}: \) Goods price(\( P \)) \times \) Goods supply(\( A \)) =
  
  \( \sum \) \{Goods prices(\( P \)) \times \) Intermediate goods demands(\( P, A \))\}
  
  \( + \sum \) \{Factor prices(\( W \)) \times \) Factor demands(\( W, A \))\}

  \( \textit{IB}: \) \( \sum \) \{Goods prices(\( P \)) \times \) Final goods demands(\( P, I \))\}
  
  = \( \sum \) \{Factor prices(\( W \)) \times \) Factor endowments\}

- Solve for prices and quantities \textit{simultaneously}
  
  – Find commodity/factor prices industry/household activity levels
  
  which satisfy the system of equations

  \[ \textit{MC} \perp (P, W) \quad \textit{ZP} \perp A \quad \textit{IB} \perp I \]

  where “\( \perp \)” 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 transformation (≈ 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 economic value 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 economic logic of GE
    • Extent of physical resource base not so much of an issue for CGE models
    • Supply curve (cost) parameterization would appear to be much more important
An Archetypical Integrated Approach Using Nested CES Functions

Complementarity between total power supply and transmission

Technology-load mapping

Resource input determined by intersection of demand with exogenous supply curve
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 aggregate 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 $\Omega$ here...
Discussion of Potential Ways Forward?