Analyzing Interactions Between Technological Change and Climate Change Mitigation Policies Using CGE Models

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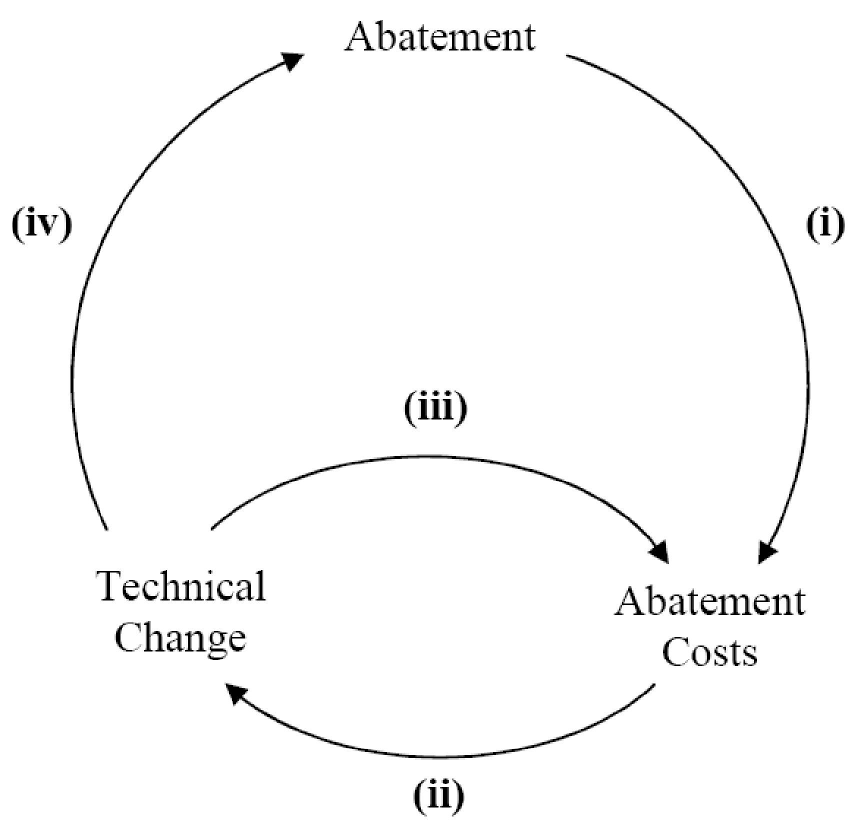
Plan of Talk

1. Introduction: climate-technology interactions
2. What is a CGE model?
3. How is technology represented in CGE models?
4. Methods of modeling technological change

Climate-Technology Interactions

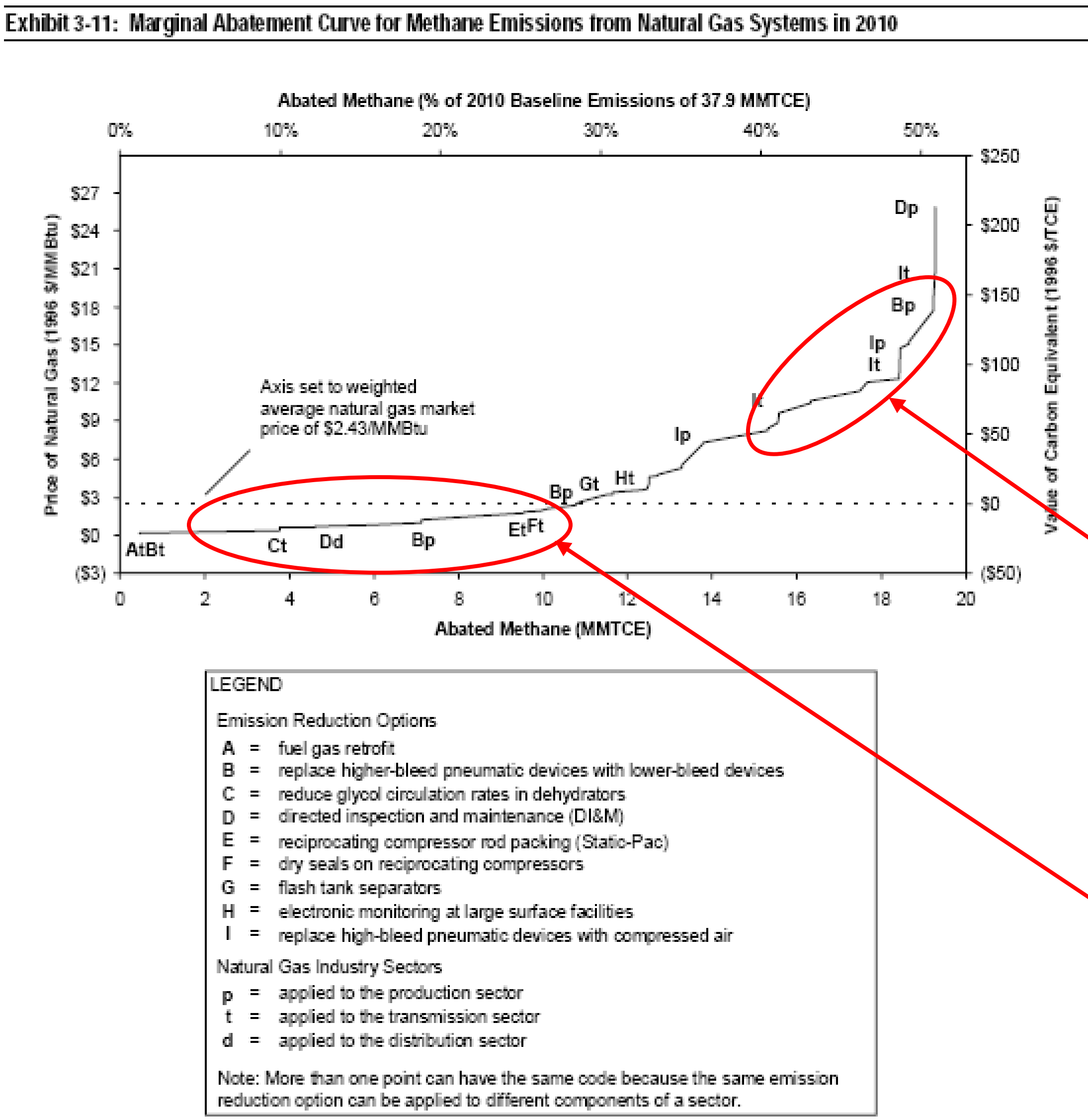


- Key processes:
  - (i) Direct effects of emission taxes/quotas on economy
  - (ii) Inducement of technological change
  - (iii) Economic and environmental consequences
  - (iv) Implications for optimal policy design
- Still need to understand mechanisms behind feedback loop (ii)-(iii)!

Taxonomy of Simulation Models for Climate Change Policy Analysis

- Bottom-up models (e.g. MARKAL)
  - Engineering-based, activity analysis
  - Represent details of discrete technologies
  - Partial equilibrium (PE): domain restricted to energy system
  - Solve for quantities only (no prices)
  - Choose capacity to minimize system cost s.t. constraints of technology set, fixed demands for energy services
  - Assessment of technology portfolios to meet GHG constraints
- Top-down models (e.g. BEAR, MIT-EPPA)
  - Economic, **computable general equilibrium (CGE)**
  - Smooth, aggregative production functions
  - Macroeconomic, economy-wide in scope, multiple markets
  - Solve for prices, quantities <u>simultaneously</u>
  - Choose price vector s.t. supply = demand in all markets, firms make zero profits, hholds income = expenditure on final uses
  - Macroeconomic cost analysis of GHG limits/taxes

Why General Equilibrium Matters



Source: EPA (1999). U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions (EPA 430-R-99-013)

Key engineering cost assumptions: no mkt. interactions, fixed prices

...which can alter costs, rank-ordering of mitigation options up here!

BUT

actions taken down here can cause changes in prices of labor and capital, and demand for fuels...

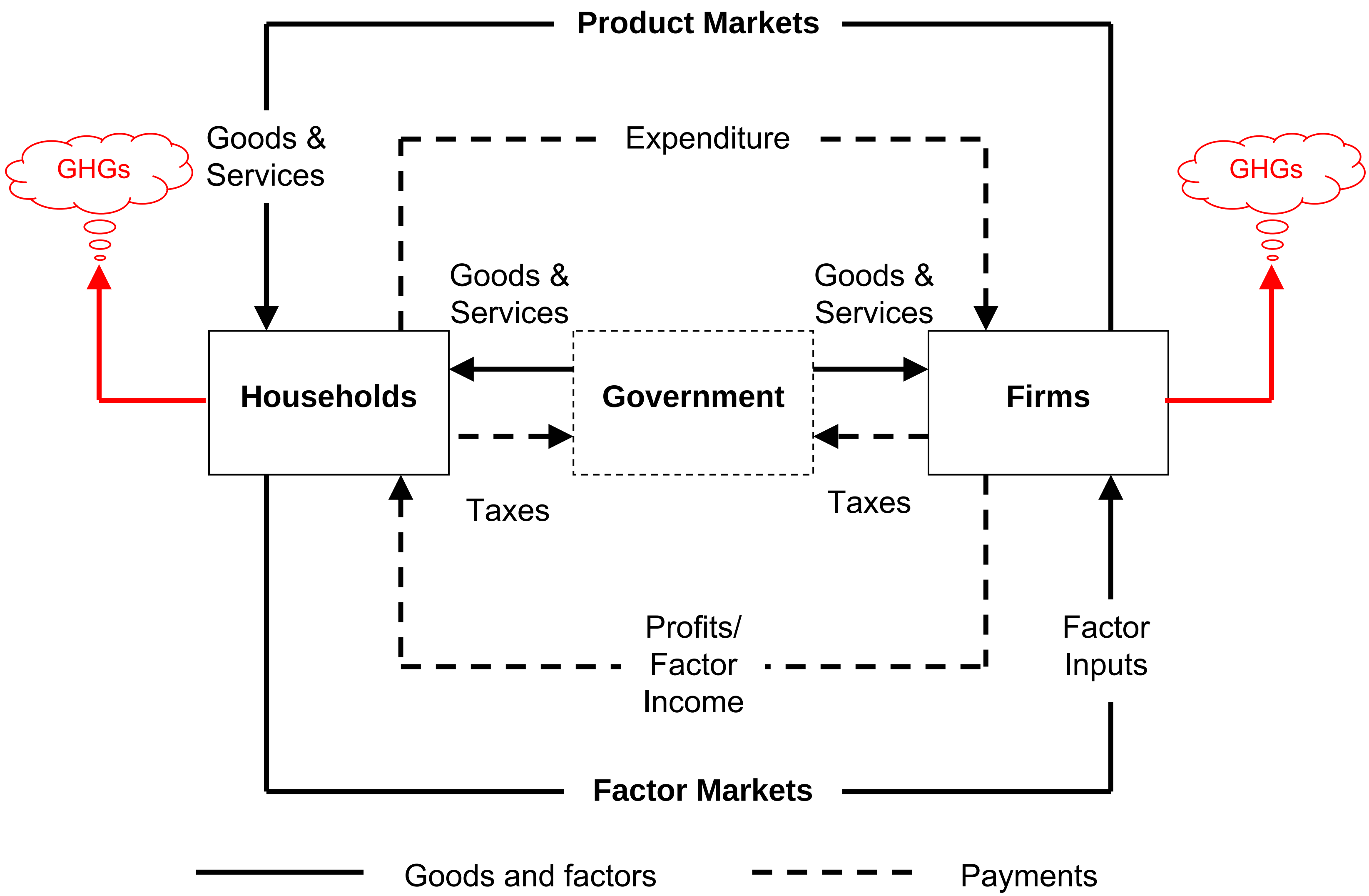
Induced Technological Change

- Biggest single imponderable in climate policy
- ITC first articulated by Hicks (1932)
  - "a change in the relative prices of factors of production is itself a spur to invention, and to invention of a particular kind—directed to economizing the use of a factor which has become relatively expensive". (p. 124)
- Attractive to policy makers
  - Advanced as the saving grace which will moderate economic cost of mitigating GHG emissions (e.g., Grubb 1997)
  - But controversial (e.g., Porter Hypothesis): economists don't like the idea of a "free lunch"
- Modeling requires innovation to be made endogenous
  - Exogenous TC in 90% of economic analyses!
  - Limited theoretical/empirical guidance: feedback loop (ii)-(iii)
  - Lots of ad-hockery, sensible formulations not very tractable

CGE Models

1. The circular flow of the economy
2. Social accounting matrices (SAMs)
3. Models as an extension of social accounting

The Circular Flow of the Economy



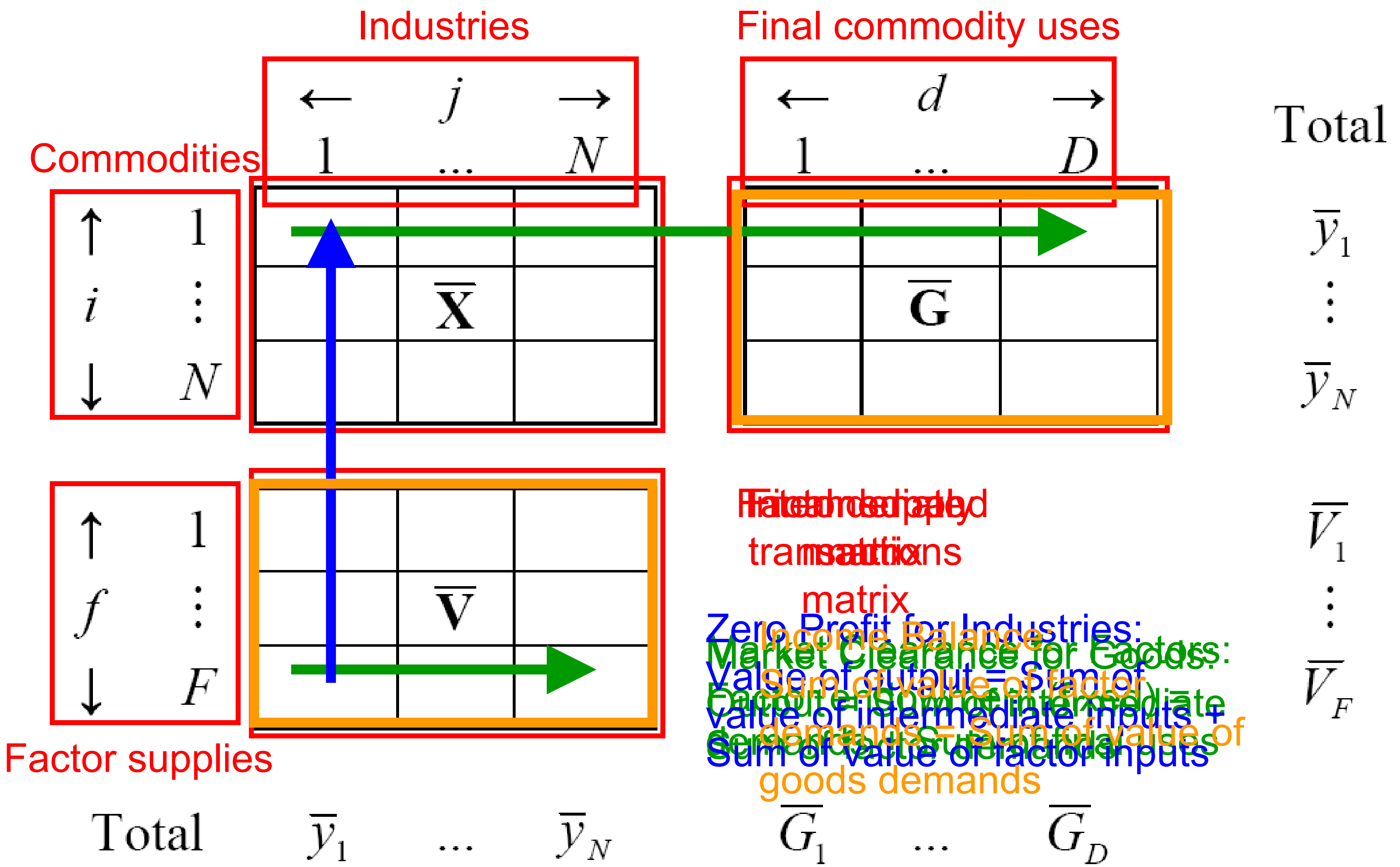
Foundations of Walrasian Equilibrium

- Conservation of product
  - Material balance
  - Every good or factor: Sum of sources = Sum of sinks
  - Physical $\Rightarrow$ holds even when not in equilibrium!
- Conservation of value
  - Budgetary balance
  - Value = price $\times$ quantity
  - Firms: Value of output = Sum of value of inputs
  - Households: Sum of value of expenditures on goods = Sum of value of incomes from factor rentals

General Equilibrium in a Nutshell

- Market clearance
  - Conservation of product for goods and factors
- Zero profit
  - Conservation of value for firms
  - Constant returns to scale production + perfectly competitive goods markets
- Income balance
  - Conservation of value for households
  - Constant returns to scale consumption + perfectly competitive factor markets

A Social Accounting Matrix



A Real SAM: California (2003)

	1	2	3	4	5 (Ref. Oil)	6	7	8 (Elec.)	9 (Nat. Gas)	10	11	12	13	14	Cons	Inv	Fed Gov	CA Gov	Loc Gov	Net Exp	Total
1	11.62	0.00	0.26	0.00	0.00	0.01	0.16	0.02	0.00	13.05	0.01	0.16	0.01	1.40	4.81	0.00	0.00	0.00	0.00	26.80	58.31
2	0.08	1.86	0.06	0.00	17.08	0.00	0.11	4.14	6.00	0.02	0.02	0.18	0.01	0.35	0.00	0.00	0.00	0.00	0.01	-16.52	13.42
3	2.56	0.20	2.19	0.08	0.16	0.27	0.47	0.88	0.01	1.40	0.09	0.21	0.52	0.59	0.82	1.33	0.00	0.00	0.00	4.93	16.70
4	0.01	0.01	0.01	0.08	0.04	0.00	0.06	0.01	0.00	5.02	0.46	0.17	0.07	1.07	0.00	0.00	0.01	0.06	0.17	-5.80	1.43
Ref. Oil 5	1.40	0.10	0.37	0.02	3.33	0.04	1.85	0.14	0.05	0.25	0.38	0.73	0.03	4.04	11.64	0.00	0.46	0.08	0.25	9.83	34.99
6	0.17	0.14	0.13	0.00	0.01	1.60	1.08	0.04	0.01	0.09	10.10	0.10	0.07	0.45	0.02	0.00	0.00	0.02	0.06	-7.98	6.10
7	0.21	0.00	0.05	0.00	0.03	0.02	0.24	0.21	0.02	0.20	0.51	0.13	0.03	6.79	4.20	69.33	1.65	4.33	2.55	2.33	92.84
Elec. 8	0.81	0.22	0.28	0.04	0.49	0.18	0.33	0.00	0.11	1.07	1.59	0.58	0.21	9.33	11.43	0.00	0.36	0.41	1.27	-10.87	17.84
Nat. Gas 9	0.06	0.03	0.03	0.03	0.56	0.07	0.08	0.01	0.09	0.49	0.62	0.26	0.16	2.22	4.70	0.00	0.06	0.09	0.28	12.36	22.19
10	4.75	0.02	0.13	0.09	0.12	0.03	2.74	0.09	0.04	25.19	8.82	2.17	0.15	34.24	83.64	6.18	1.80	2.02	6.17	-29.68	148.71
11	1.07	0.37	0.68	0.04	0.35	0.38	10.69	0.26	0.11	4.31	78.97	1.30	0.24	23.68	51.60	89.21	17.73	0.70	2.13	3.20	287.01
12	3.36	0.23	0.48	0.09	0.89	0.04	2.72	0.05	0.03	4.13	8.06	14.30	0.33	11.28	17.84	0.21	0.19	0.42	1.27	-2.42	63.51
13	0.10	0.04	0.09	0.00	0.15	0.08	3.42	0.06	0.04	0.81	1.01	0.30	0.91	1.64	0.64	0.00	0.06	0.13	0.39	-0.72	9.13
14	10.29	3.83	3.15	0.23	6.59	1.27	23.48	2.09	5.93	27.68	58.44	15.11	1.83	339.45	670.87	40.18	13.31	13.59	41.35	-18.98	1259.68
Labor	4.25	0.81	3.63	0.19	1.30	1.10	34.97	1.61	2.52	23.98	55.69	7.41	1.97	388.46							527.88
Capital	14.54	3.60	3.80	0.19	2.45	0.35	5.92	6.31	5.84	27.87	37.14	14.60	1.76	336.55							460.93
Net Tax	3.06	1.96	1.38	0.33	1.43	0.67	4.53	1.93	1.41	13.15	25.11	5.79	0.82	98.14							159.70
Total	58.31	13.42	16.71	1.43	34.99	6.10	92.83	17.84	22.19	148.71	287.01	63.51	9.13	1259.68	862.20	206.44	35.62	21.86	55.90	-33.52	

Units: Billion dollars
GDP = Value Added = $1.15 Trillion, Gross Output = $3.18 Trillion

1. Agriculture; 2. Crude Oil & Gas; 3. Pulp & Paper Mills; 4. Other Primary Industries; 5. Refineries; 6. Primary Metals; 7. Rest of Economy Aggregate; 8. Electric Power; 9. Gas Industrial & Distribution; 10. Nondurable Manufacturing; 11. Durable Manufacturing; 12. Chemicals Rubber & Plastics; 13. Non-metallic Mineral Products & Cement; 14. Services

Author's calculations using P. Berck et al. (2004). A SAM for California (http://are.berkeley.edu/~peter/Research/DRAM03B/).

From a SAM to a CGE Model

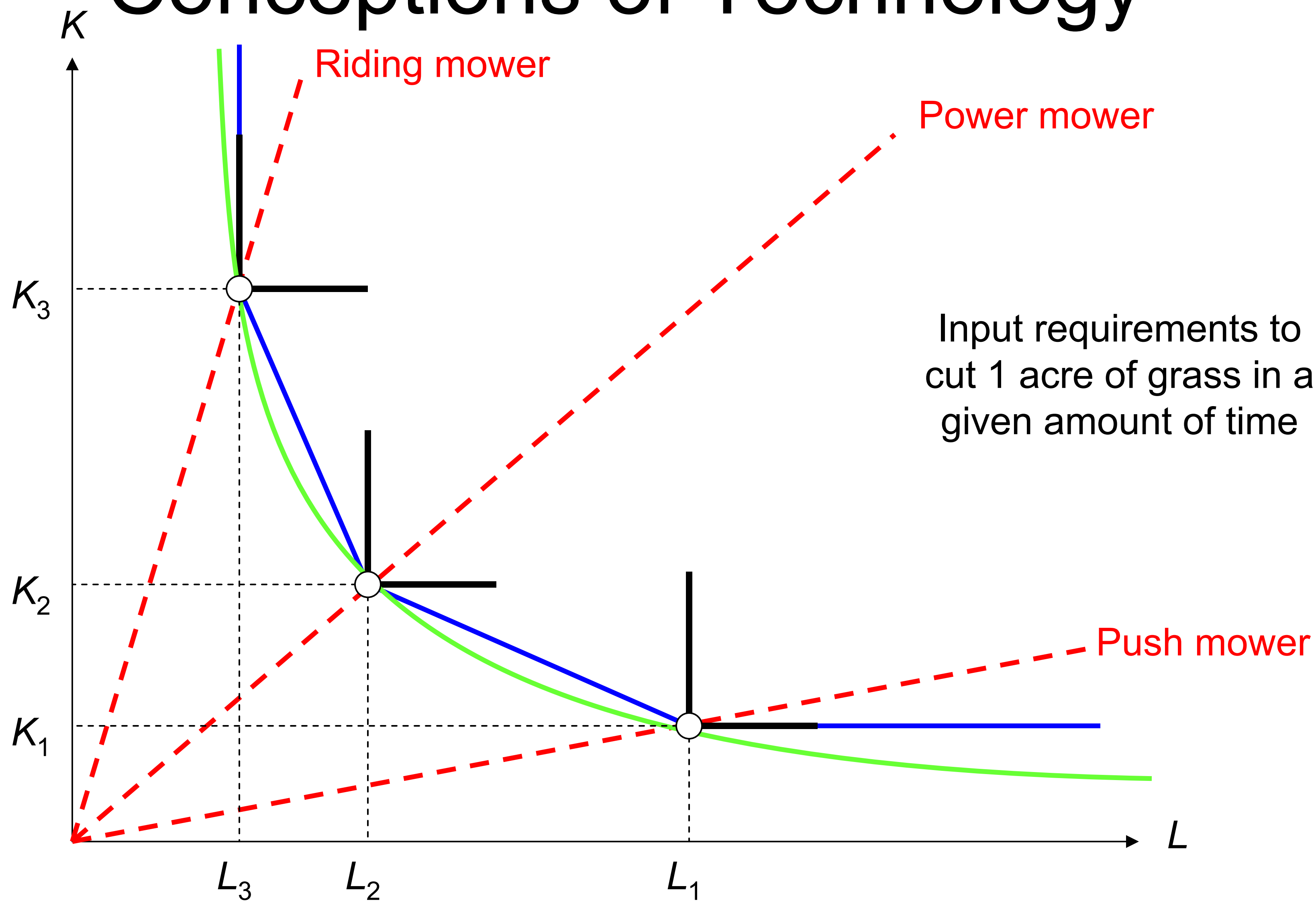
- CGE model
  - Algebraic expression of foregoing equilibrium conditions
  - Solves for vectors of prices, value flows that support equilibrium
- Fundamental assumptions from economic theory
  - Consumers max. utility $\Rightarrow$ demand for consumption goods, expenditure f'n
  - Producers max. profits $\Rightarrow$ demand for factors & intermediate goods, cost f'n
- Combine producer and consumer optimization w/. circular flow
  - Sum of factor demand f'ns = factor endowment
  - Sum of demand f'ns for each commodity = quantity of output produced
  - Price of each commodity = Producer's unit cost f'n
  - Price of numeraire good = Consumer's unit expenditure f'n
  - Income = Sum of value of factor demands + tax revenue
    = Sum of value of commodity demands
- "Model" = Multi-dimensional, nonlinear root-finding problem, solved using numerical methods:

✡(Goods prices, Factor prices, Activity levels) = 0

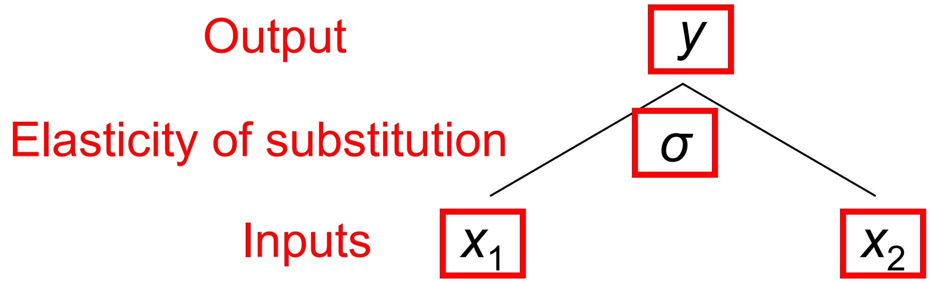
Technology in CGE Models

1. Production functions
2. Calibration
3. Substitution vs. technological change

Economic vs. Engineering Conceptions of Technology



Production and Cost Functions: Graphical Representation

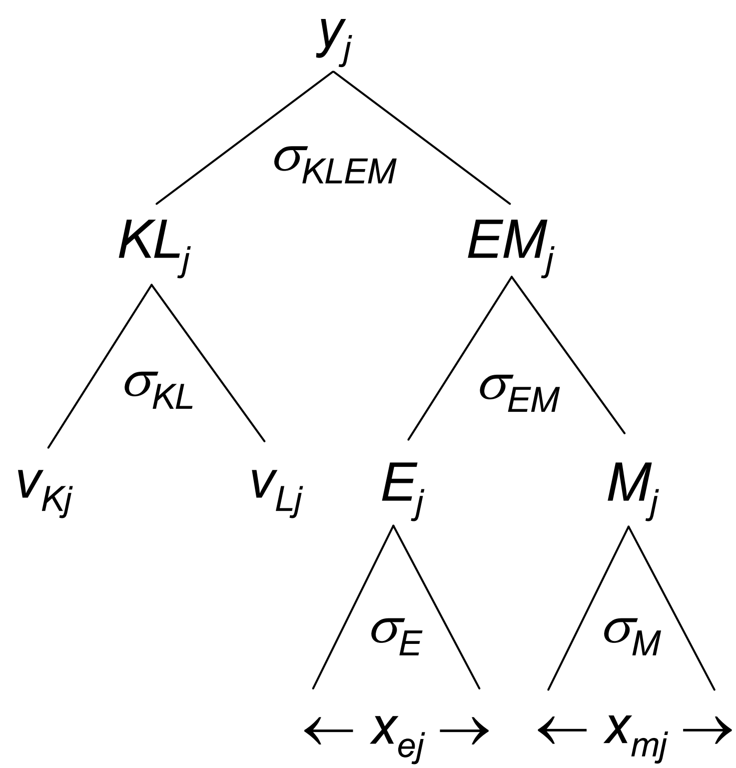


$$y = \left(a_1 x_1^{\frac{\sigma-1}{\sigma}} + a_2 x_2^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}$$

$$p = \left(a_1^{\sigma} p_1^{1-\sigma} + a_2^{\sigma} p_2^{1-\sigma} \right)^{\frac{1}{1-\sigma}}$$

Technical coefficients: numerically calibrated using benchmark values of x_1, x_2 and y in SAM

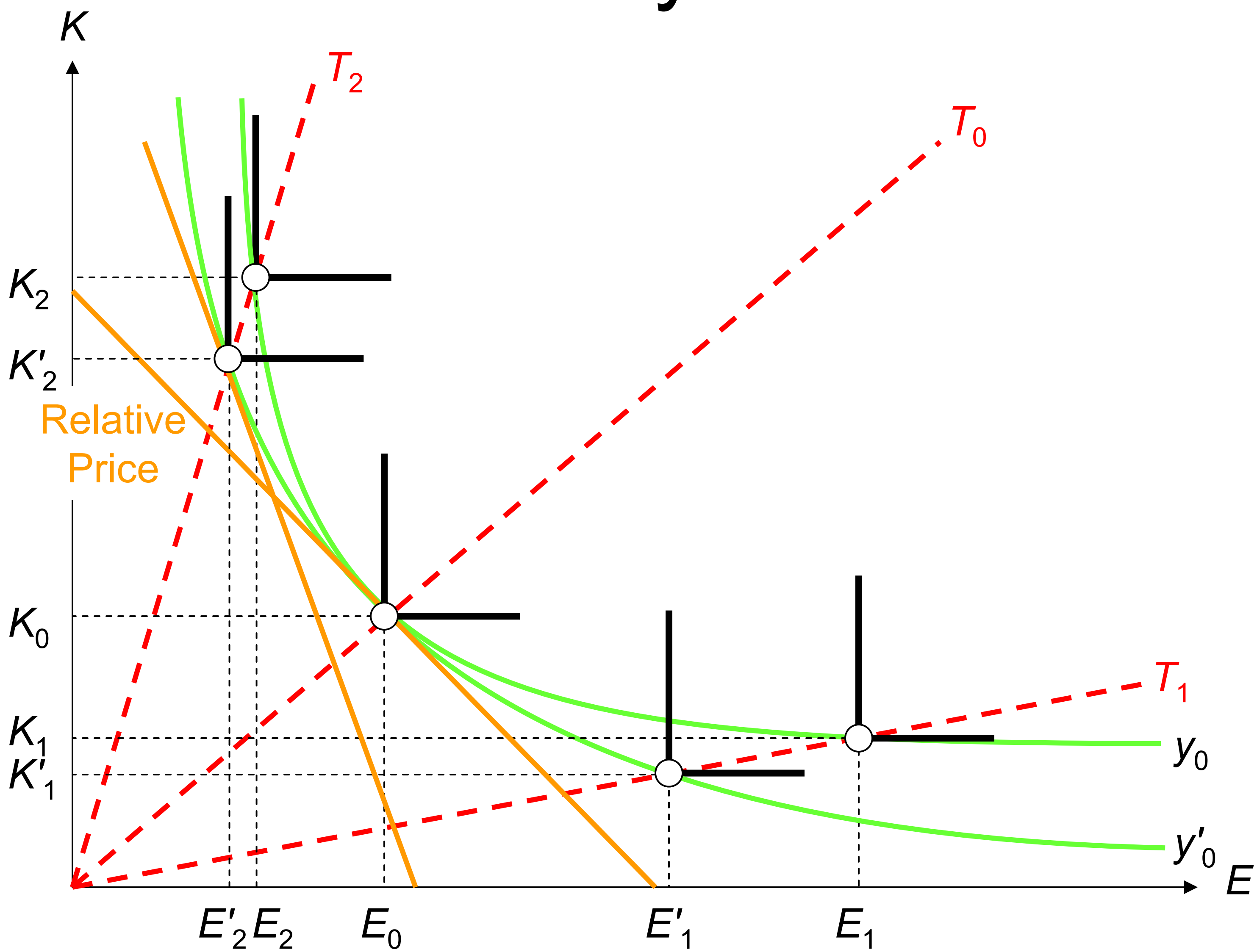
KLEM Nested CES Production Function (Bovenberg & Goulder 1996)



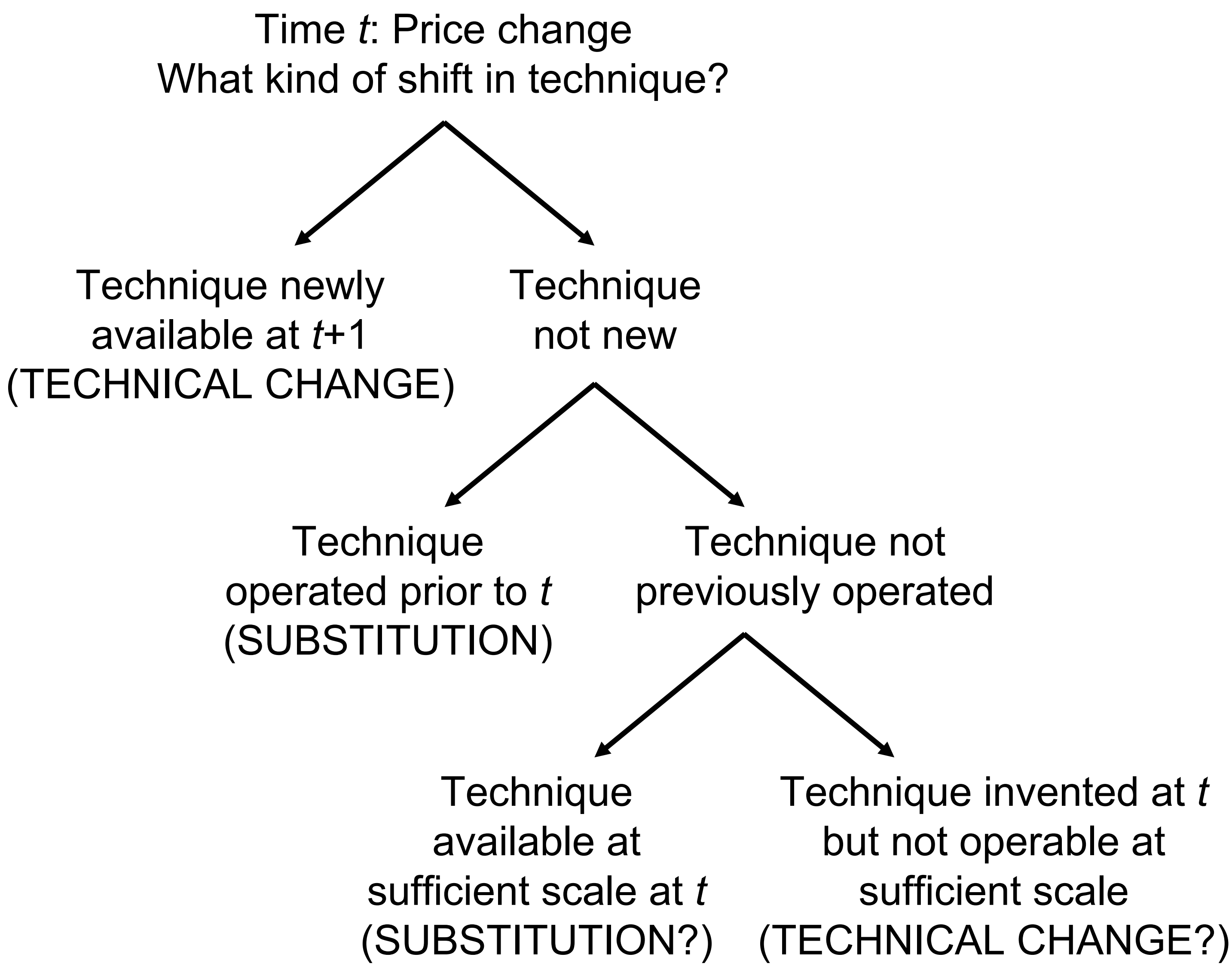
y_j = output of industry j; v_{Kj} = capital input to j; v_{Lj} = labor input to j

x_{ej} = intermediate energy inputs to j; x_{mj} = intermediate non-energy inputs to j

Calibration, Technology Options and the Elasticity of Substitution



Substitution vs. Technical Change



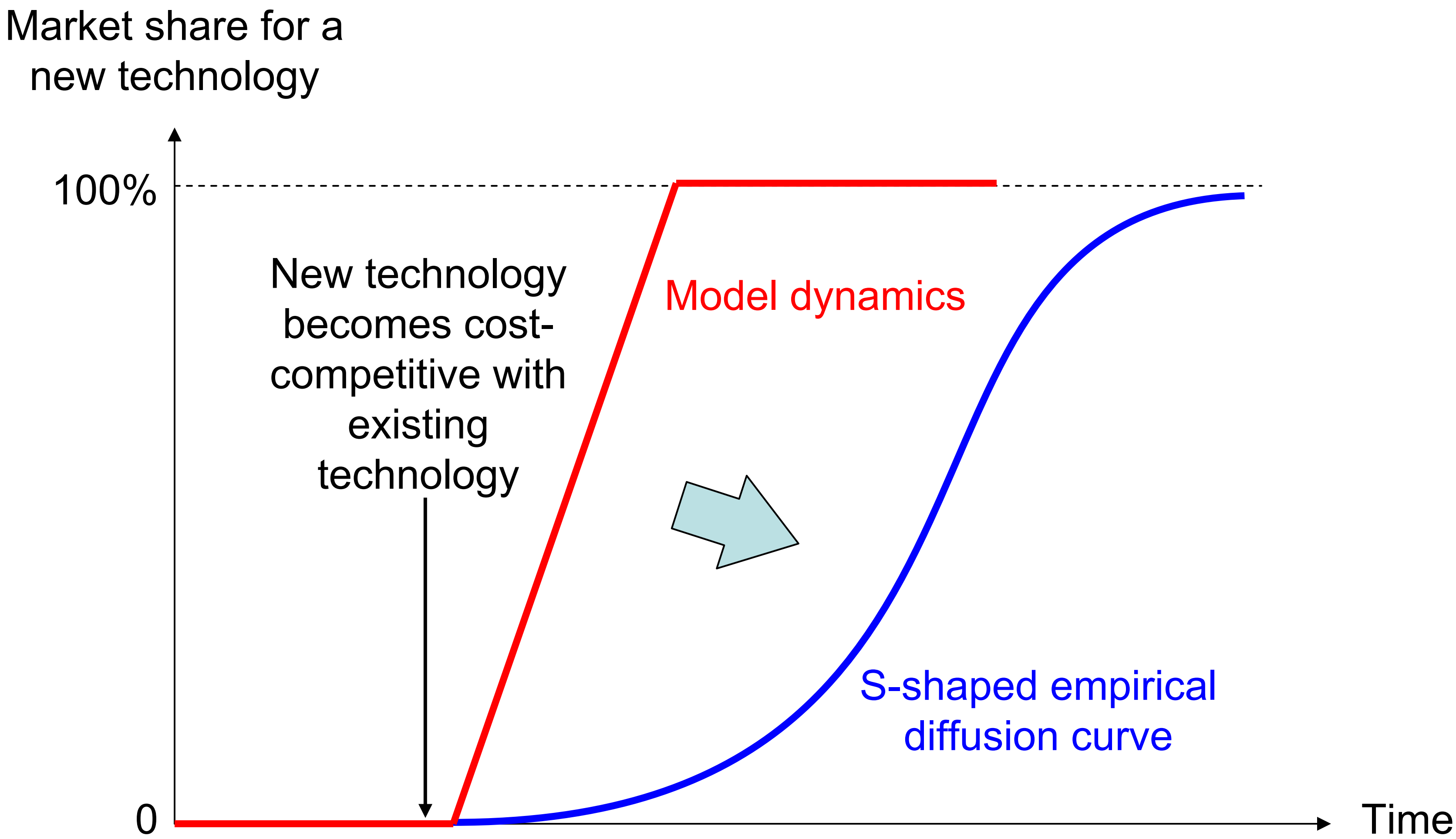
Modeling Technological Change

1. Backstop technologies
2. Learning by doing
3. The “stock of knowledge” approach

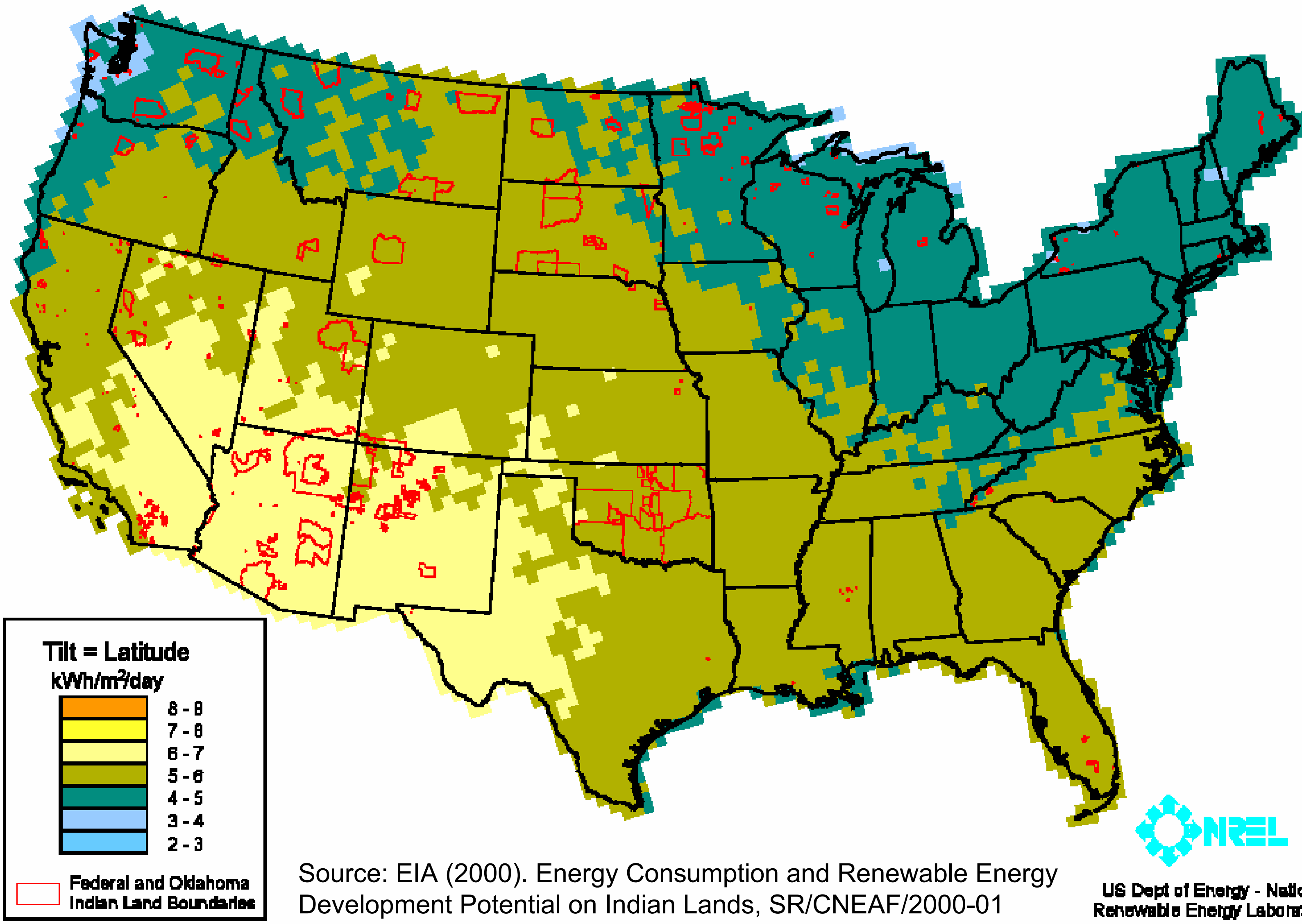
Backstop Technologies

- Radical, long-run technological progress
- New supply technologies not present/profitable in benchmark SAM
  - Represent generic energy transformation devices (e.g., wind, solar, etc.)
  - Originally infinite supply at constant (but high) marginal cost (e.g., plutonium breeder reactor—Nordhaus 1979)
- Easy to implement...
  - Production functions which “switch on” and are able to produce output after some exogenously-specified future time period
  - Technical characteristics based on engineering data, assumptions
- ... BUT, can be difficult to control!
  - “Bang-bang” vs. sigmoid empirical diffusion profile (Nakicenovic & Grubler, 1998)
  - Imperfect substitutability w/. conventional sources of supply
  - Malleability of technology-specific capital (Sue Wing, forthcoming)
  - Input requirements: complementary infrastructure, natural resources
- Resource considerations → renewables no panacea
  - Finite technical potential, non-homogeneous graded structure → increasing cost
  - Opportunity costs of extraction: alternative uses for land under PV arrays, windmills, energy crops

An Illustration of “Bang-Bang”



Solar Resource Potential



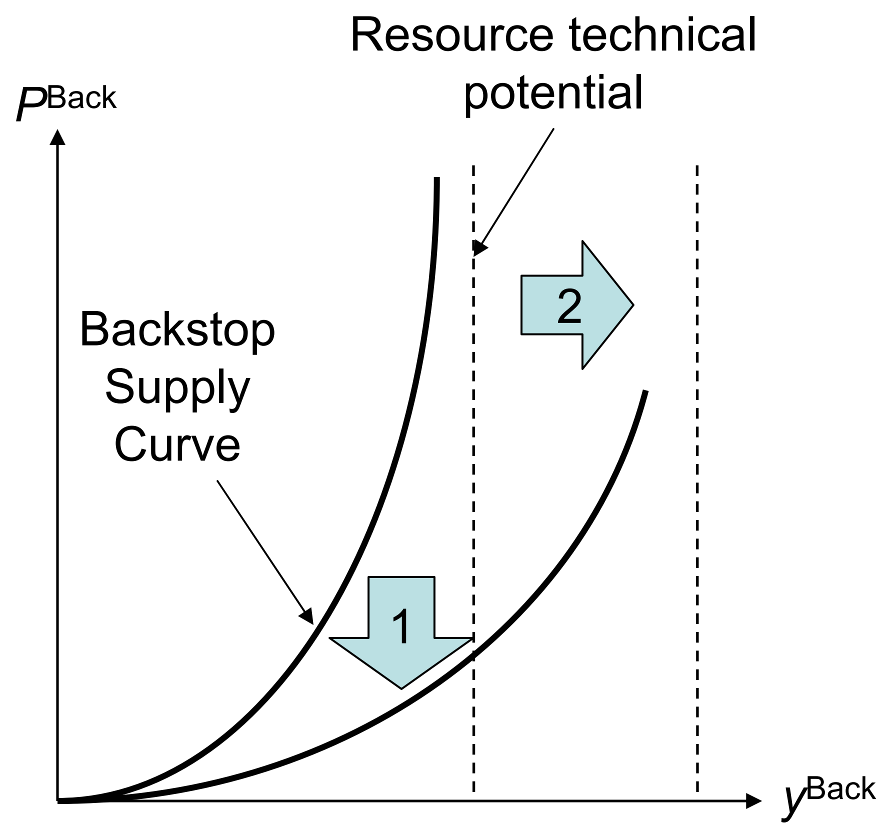
Source: EIA (2000). Energy Consumption and Renewable Energy Development Potential on Indian Lands, SR/CNEAF/2000-01

US Dept of Energy - National Renewable Energy Laboratory

Modeling BackstopR&D

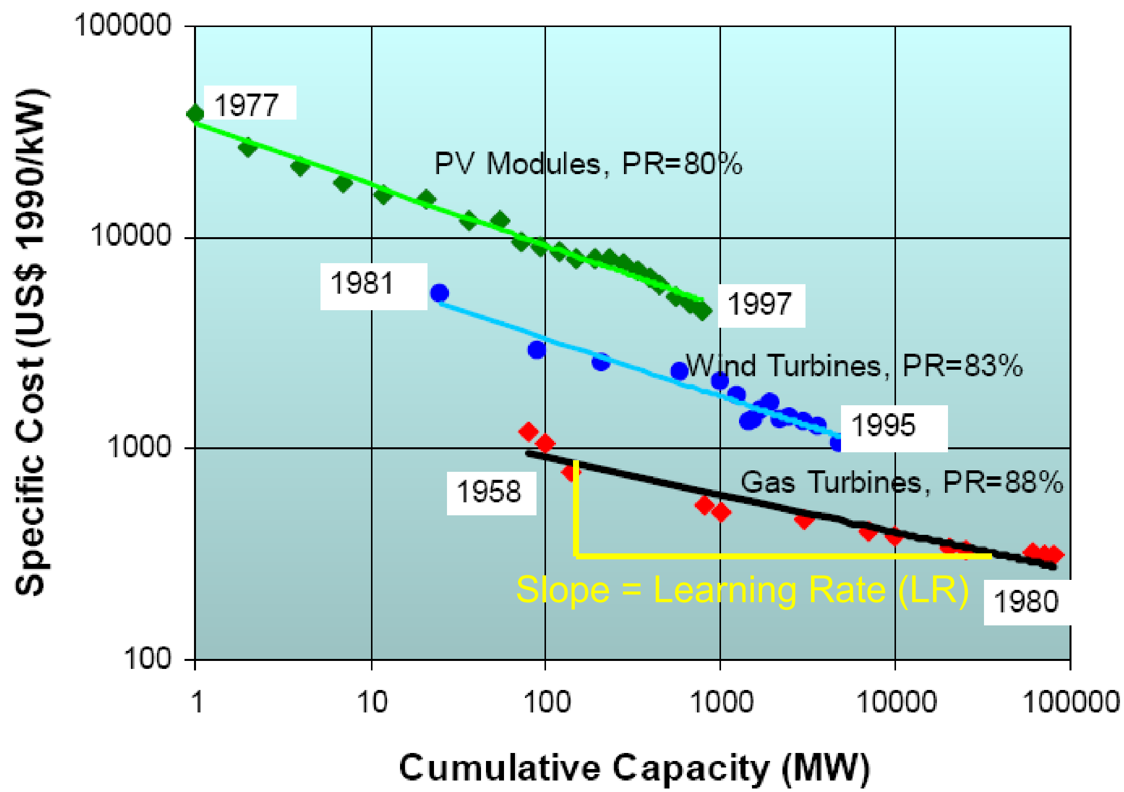
Key question: how much potential for research to moderate resource limits on new technologies?

- What does R&D do?
  1. Increase productivity: more backstop energy output for given resource supply
     - e.g. higher efficiency wind turbines
  2. Reduce opportunity costs of renewable resources: expand endowments
     - e.g. rooftop PV designs permit multiple land uses
- Punch line
  - Need an <u>intertemporal</u> CGE model!
  - Must be able to simulate how potential future cost savings create demand for R&D today



Learning-by-Doing

- Unit costs of capacity fall with cumulative investment
  - Pervasive empirical phenomenon
  - Fundamentally increasing returns
  - Focused on individual, specific technologies
  - More applicable to backstops than aggregate CGE model sectors
- Implications (intertemporal models)
  - Rapid early investment in low-carbon technologies
  - Dramatic reduction in mitigation costs relative to no-learning case



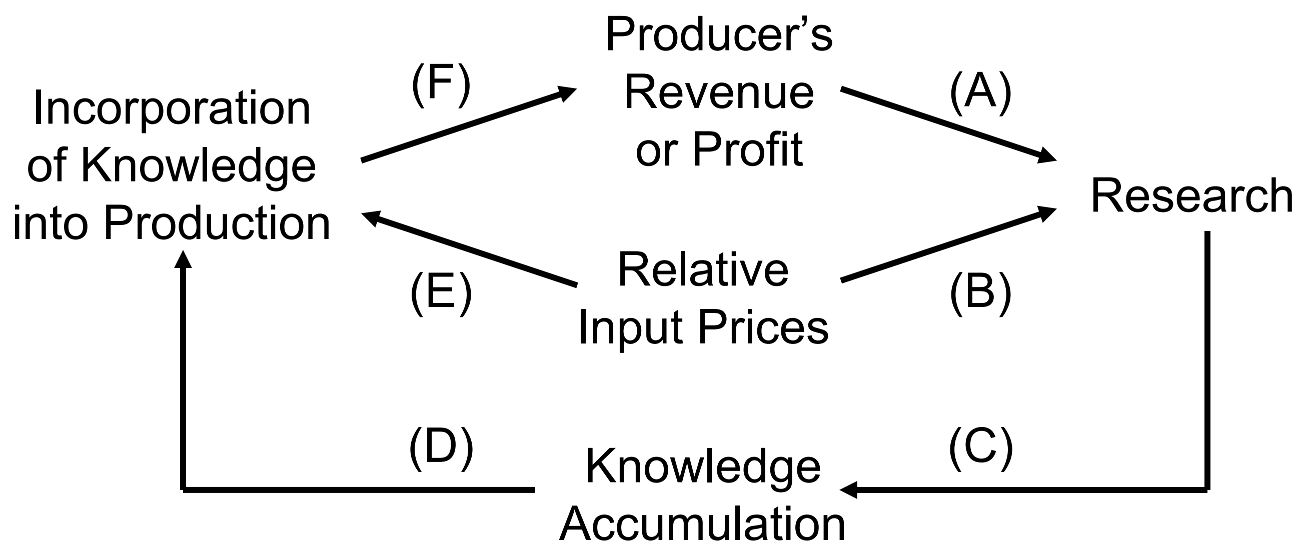
Progress Ratio (PR) = 2^{-LR}

Unit Cost $\propto$ (Cumulative Capacity)$^{-LR}$

Skeptical Thoughts on LBD

- Issues
  - LBD mechanistic: a free and <u>inevitable</u> by-product of capital investment
  - Learning rates used in models often not a product of rigorous econometric analysis (e.g., McDonald & Schrattenholzer 2001; exception: Isoard & Soria, 2001)
  - LBD cannot go on forever: no empirical guidance on LR unit cost “floor”
  - PE vs. GE models: resource constraints?
  - Non-convexity associated w/. increasing returns → numerical instability, need for ad-hoc bounds to enable models to solve
- Assessment
  - By judicious choice of learning rate, analyst can get any answer he/she wants
  - Unbundling the learning curve: insights into <u>mechanisms</u> underlying cost reductions, feedback of abatement on technical progress
  - Why not explicitly model deliberate, costly search for improvements through R&D?
  - Little value as a <u>predictive</u> tool

The Stock of Knowledge Approach



(A) Current pool of resources for research
(B) Price inducement of R&D
(C) R&D creates new knowledge (intangible)
(D) Expansion of economy's aggregate endowment of knowledge over time
(E) Intangible services allocated among producers according to relative prices
(F) Enhancement of productivity/profit

- Increased efficiency of production
- Facilitating the substitution of knowledge for relatively costly tangible inputs

Modeling Issues

- By far the most difficult method of representing technical change
  - Major challenge: essential unobservability of knowledge
  - BUT big payoff: understanding the factors affecting inducement
- Data: estimation of knowledge in SAM
  - Have information on R&D by industry
  - Much more difficult problem to empirically estimate returns to knowledge
  - Calibration of dynamic models with multiple capital stocks: forefront of research (Sue Wing & Popp 2006)

Insights from Explicitly Modeling Knowledge

- Crowding out important (Popp 2004, 2004)
  - No free lunch: more “environment-saving” R&D = less “economy-growing “ R&D
- Timing of R&D
  - Cumulative nature of knowledge → no need for “crash” program
  - Opposite result from LBD
  - Uncertainty over role of increasing returns
- Spillovers important
  - Source of increasing returns in R&D → faster knowledge accumulation
  - Enhances intersectoral mobility of knowledge
- Like capital, “malleability” of knowledge important
  - Bulk of ITC’s impact in its ability to diffuse to sectors w/. highest marginal return (Sue Wing 2003)

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