Innovation, Renewable Energy, and Macroeconomic Growth

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Is the Energy Sector Under-investing in R&D?

Some Facts

- In early 80s energy companies were investing more in R&D than drug companies. By 2005 trend reversed.
- The US government proposed to spend $150B over the next 10 years on renewable energy R&D compared to the current $5B/year.
- Many empirical studies have determined that the optimal size of R&D in energy sector is 5 to 10 times the current level. (Kammen and Nemet (2005))
Should Government Subsidize R&D?

- The notion of "creative destruction"
  - Innovation often results in old technologies becoming obsolete
  - Energy companies may be reluctant to invest in R&D
- "Technological frontier" is reached
  - Given the existing state of knowledge, additional innovation may be very hard (Popp (2002))
Why Quantitative DGE Model

- Economic policies that affect the energy sector are seldom studied and evaluated in this way.
- DGE models are widely used to predict the effects of changes in economic policy and evaluate their impact on social welfare of the whole economy.
- It is needed to quantify the opportunity costs, as well as the intertemporal benefits.
- Compute equilibrium optimal paths of R&D investment in both the fossil fuel and renewable energy sectors.
- Determine the resulting length of the transition to a renewable-energy-based economy.
- Discuss how will the optimal paths and all the results be affected by imposing different tax/subsidy schemes.
The Macro Model – Basic Assumption

Goods and Service Production

- Per capita output of the good \( y = Ak \)
- Per capita stock of capital \( k \), while \( \dot{k} = i - \delta k \)
- \( y = R + B \)
  - R: Per capita energy derived from fossil fuel resources
  - B: Per capita energy derived from renewable technology
  - Fixed energy intensity
  - R and B are perfect substitute
The Macro Model – Basic Assumption

The marginal cost of fossil fuel extraction and conversion \( g(S, N) \)

- Total quantity of resources mined to date: \( S \), while \( \dot{S} = QR \)
- State of technological progress: \( N \), while \( \dot{N} = n \)
Experience Curves

- Describe how marginal costs decline with cumulative production
- Power Law: \( P_t = P_0 X^{-\alpha} \)
- where \( P_0 \) is the initial price, \( X \) is the cumulative production up to year \( t \), and \( 2^{-\alpha} \) is the progress ratio (PR)
The Macro Model – Basic Assumption

- Marginal cost of renewable energy: $p$
  
  
  $p = \begin{cases} 
  (\Gamma_1 + H)^{-\alpha} & \text{if } H \leq \Gamma_2^{-1/\alpha} - \Gamma_1 \\
  \Gamma_2 & \text{otherwise}
  \end{cases}$

- $\dot{H} = \begin{cases} 
  B(1 + \psi j) & \text{if } H \leq \Gamma_2^{-1/\alpha} - \Gamma_1 \\
  0 & \text{otherwise}
  \end{cases}$

- where $H$ is the stock of knowledge, and $j$ is the direct R&D expenditure

- Resource constraint: $c + i + j + n + g(S, N)R + pB = y$
The Macro Model – The Optimization Problem

- The general optimization problem:

$$\max \int_0^\infty e^{-\beta \tau} \frac{c(\tau)^{1-\gamma}}{1-\gamma} \, d\tau,$$

s.t. \( \dot{k}, \dot{H}, \dot{S}, \dot{N} \) differential equations and all the equations listed above.

- The current value Hamiltonian and Lagrangian:

$$\mathcal{H} = \frac{c(\tau)^{1-\gamma}}{1-\gamma} + \lambda [Ak - c - i - j - n - g(S, N)R - (\Gamma_1 + H)^{-\alpha} B] + \epsilon (R + B - Ak) + q(i - \delta k) + \eta B (1 + \psi j) + \sigma QR + \nu n + \mu j + \omega n + \xi R + \zeta B + \chi (\Gamma_2^{-1/\alpha} - \Gamma_1)$$
The Macro Model – The FONC and Co-state DE

- **First Order Conditions**

\[
\begin{align*}
\frac{\partial H}{\partial c} &= c^{−γ} − λ = 0 \\
\frac{\partial H}{\partial i} &= −λ + q = 0 \\
\frac{\partial H}{\partial j} &= −λ + ηψAk + μ = 0, μ ≥ 0, j ≥ 0 \\
\frac{\partial H}{\partial n} &= −λ + ν + ω = 0, ωn = 0, ω ≥ 0, n ≥ 0 \\
\frac{\partial H}{\partial R} &= −λg(S, N) + ε + σQ + ξ = 0, ξR = 0, ξ ≥ 0, R ≥ 0 \\
\frac{\partial H}{\partial B} &= −λ(Γ_1 + H)^{-α} + ε + η(1 + ψj) + ζ = 0, ζB = 0, ζ ≥ 0, B ≥ 0
\end{align*}
\]

- **Co-State Differential Equations**

\[
\begin{align*}
\dot{q} &= (β + δ)q − λA + εA \\
\dot{η} &= βη − λα(Γ_1 + H)^{-α−1}B + χ, χ(Γ_2^{-1/α} − Γ_1 − H) = 0, χ ≥ 0, H ≤ Γ_2^{-1/α} − Γ_1 \\
\dot{σ} &= βσ + λ \frac{∂g}{∂S} R \\
\dot{ν} &= βν + λ \frac{∂g}{∂N} R
\end{align*}
\]
The Macro Model – Calibration

- Assign numerical values to parameters so that model consistent with actual world economy

- Data sources:
  - Food And Agriculture Organization of the UN
  - Energy Information Administration (EIA)
  - Survey of Energy Resources, World Energy Council (WEC)
  - Center for Global Trade Analysis, Purdue University Cambridge Energy Research Associates (CERA, 2009)
  - National Energy Technology Laboratory (NETL)
  - United States Geological Survey (USGS)
  - Energy Information Administration (EIA)
The Macro Model – Algorithm

- Five regimes of the economy:
  - $[0, T_1]$, the initial fossil fuel economy, $R > 0, n > 0$
  - $[T_1, T_2]$, the economy with renewables, direct investment in R&D is zero, $B > 0, j = 0$
  - $[T_2, T_3]$, the economy with renewables, direct investment in R&D is positive, $B > 0, j > 0$
  - $[T_3, T_4]$, the economy with renewables, direct investment in R&D is zero, $B > 0, j = 0$
  - $[T_4, \infty]$, the long run endogenous growth economy, $B > 0, j = 0, p = \Gamma_2$
The Macro Model – Algorithm

- Define boundary conditions at each transition time
- Solve differential equation systems in a backward order
- 3 initial guesses: $T_4$, the constant in the analytical solution of $k_{T_4}$, and $S_{T_1}$
- 3 targets: $S_0 = N_0 = 0$ and $k_0$
The Macro Model – Tentative Results

- \([0, T_1]\), the initial fossil fuel economy, \(R > 0\), \(n > 0\), \(i > 0\)
The Macro Model – Tentative Results

- \([T_2, T_3]\), the economy with renewables, direct investment in R&D is positive, \(B > 0, j > 0\)
The Macro Model – Policy Scenarios

- Tax on $n$ during the fossil fuel regime
  - Resource Constraint:
    \[ c + i + (1 + \tau_n)n + g(S, N)R = y + T, \text{ where } T = \tau_n n \]

- Subsidy for $j$ during the renewable energy regime
  - Resource Constraint:
    \[ c + i + (1 - \tau_j)j + pB = y - T, \text{ where } T = \tau_j j \]

- Find the results for different policy scenarios
  \[ \tau = 2\%, 5\% \text{ and } 20\% \]

- Implication for policy

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The Multi-type Capital Model – Basic Assumption

- Per capita output of the good $y = Ak$
- Total energy input into goods production $e = Fk$, where $F$ is a linear decreasing function of investment $i_F$
- $k$: capital stock for goods
- $k_R$: capital for fossil fuel extraction and conversion
- $k_B$: capital for renewable energy sector
- Energy Production functions:
  - $R = \mu_R k_R$, where $\mu_R$ is a constant
  - $B = \mu_B k_B$ where $\mu_B$ is a linear increasing function of cumulative knowledge $H$
The Multi-type Capital Model – Basic Assumption

- Marginal cost of $R$: $g(S, N)$
- Marginal cost of $B$: a constant $m$, which is the operation and maintenance cost
- Energy market equilibrium: $F_k = \rho \mu_R k_R + \mu_B k_B$
- $\rho$: utilization variable, 0 or 1
- Resource constraint:
  
  $$c + i + i_R + i_B + i_F + j + n + g(S, N)R + mk_B = y$$
The Multi-type Capital Model – Regimes of the Economy

- Investment in end-use capital \((i > 0)\)
- Investment in end-use fuel intensity \((i_E > 0)\)
- Investment in renewables capital \((i_R > 0)\)
- Increase in renewables efficiency via learning by doing
- Investment in renewables R&D \((j > 0)\)
- Fossil fuel use is positive \((p > 0)\)
- Investment in mining and conversion efficiency \((n > 0)\)
- Investment in fossil fuel capital \((i_F > 0)\)

Regime 1: \(T_1\)  Regime 2: \(T_2\)  Regime 3: \(T_3\)  Regime 4: \(T_4\)  Regime 5: \(T_5\)  Regime 6: \(T_6\)  Regime 7: \(T_7\)  Regime 8: \(T_8\)  Analytical Solution
Experience curves: useful measure of technological progress
Calibrated DGE model incorporating experience curves
Many possible extensions/applications to policy evaluation
Analysis does not consider emissions/climate change or energy independence issues