

Innovation, Renewable Energy, and Macroeconomic Growth

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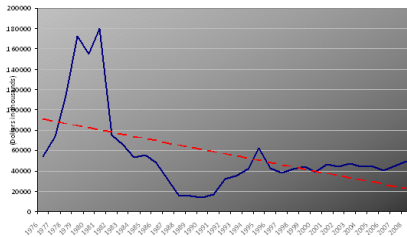
Introduction

- Most studies assume optimal size of R&D in (renewable) energy is 5 to 10 times the current level
- In early 80s energy companies were investing more in R&D than drug companies. By 2005 trend reversed
- Proposal to spend \$150B/year in renewable energy R&D over next 10 years compared to current \$5B/year
- *Research plan*: tech. progress in renewable energy as an engine of growth
- Effects of taxes/subsidies

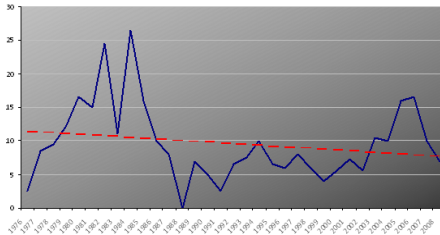
Plan for the Presentation

- Measures of R&D Output:
 - (Cited) Patents
 - Experience Curves
- Imbed version of experience curves into macroeconomic model
- Compute equilibrium
- Calibration
- Policy scenarios

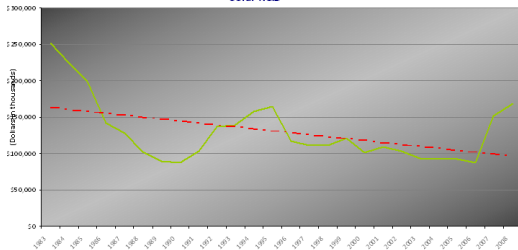
Wind R&D



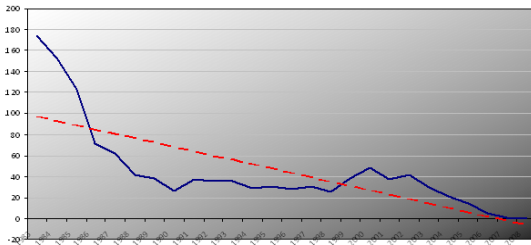
Wind Patents



Solar R&D



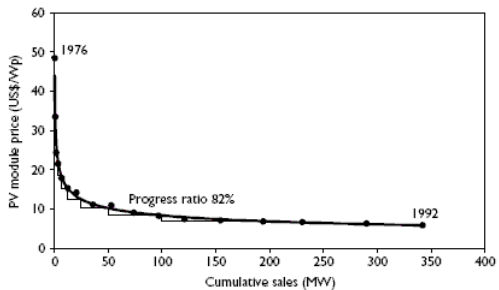
Solar Patents



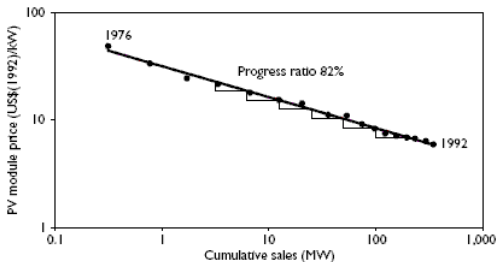
Experience Curves

- Describe how costs decline with cumulative production
- $P_t = P_0 X^{-\alpha}$ “power law”
 - P_0 , the initial price (*\$ cost of first MW of sales*)
 - X , cumulative production in year t
 - $2^{-\alpha}$, Progress ratio (PR)
 - For each doubling of cumulative production (sales), price \downarrow to $PR\%$ of its previous value
- Rewrite as: $\ln P_t = \ln P_0 - \alpha \ln X$; straight line in a log – log plot:

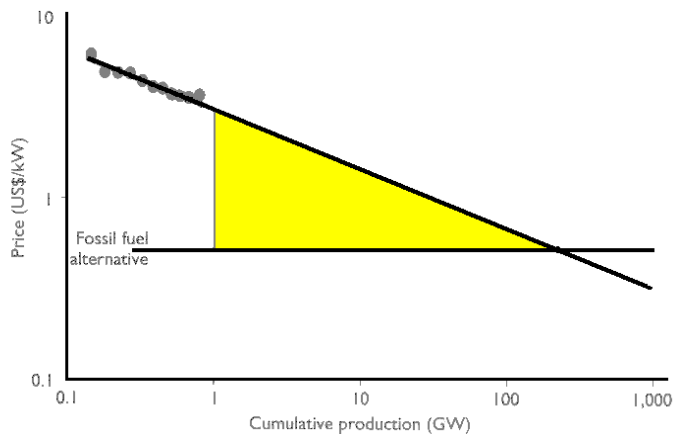
Experience Curve for Photovoltaic Modules, 1976-1992



Experience Curve for Photovoltaic Modules, 1976-1992



Experience Curves as Policy Tools

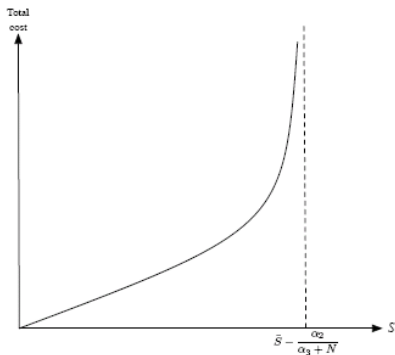


- Area in triangle: “cost needed to reach break-even point” ...
- ... but not the only cost:
 - Abandoning existing technologies
 - Opportunity costs of subsidies
 - Learning-by-doing takes time, not just volume
- Need macro model to quantify costs/effects on other sectors

A Macro Model

- Cts. time, representative household
- c , per capita consumption
- Technology uses energy to produce output
- R , the per capita energy derived from fossil fuel resources
- Q , population; grows at the constant rate π
- QR , total fossil fuel used; $S = \int_0^T QRdt$
- Most easily-mined/richest fields exhausted first \rightarrow Marginal costs of extraction increase in S

- Allow for technical change in mining exploration
- N , technical knowledge
- n , investment in mining technology leads to an accumulation of knowledge: $\dot{N} = n$
- Cost of extraction: $g(S, N)$



- Output: $y = Ak$
- Energy needed to produce output (energy supplies in efficiency units)
- Ratio of energy to capital inputs fixed
- R and B perfect substitutes: $R + B = y$
- k , “capital” stock, $\dot{k} = i - \delta k$

- p , marginal cost of the energy produced using renewable technology
 - \downarrow as knowledge gained through experience/investment in research
- Γ_2 , lower limit for p
- H , stock of knowledge about renewable energy production:

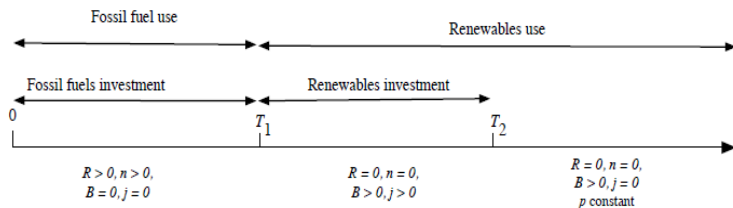
$$p = \begin{cases} (\Gamma_1 + H)^{-\alpha}, & \text{if } H < \Gamma_2^{1/\alpha} - \Gamma_1; \\ \Gamma_2, & \text{otherwise.} \end{cases} \quad ; \alpha = .37$$

- j , direct investment necessary for accumulating knowledge
 - $\dot{H} = j(1 + \psi B)$ (also trying: $\dot{H} = B(1 + \psi j)$)
 - Direct R&D twice as productive as learning-by-doing: $\psi = .5$

- Objective: $\max \int_0^{\infty} e^{-\beta\tau} \frac{c(\tau)^{1-\gamma}}{1-\gamma} d\tau$
- Constraint: $c + i + j + n + g(S, N)R + pB = y$
- Maximize subject to initial conditions $S(0) = S_0 > 0$, $k(0) = k_0 > 0$, $H(0) = 0$, feasibility constraint, definitions of output, energy input, evolution of costs of energy
- Control variables: c, i, j, R, n, B
- State variables: k, H, S, N

Equilibrium Regimes

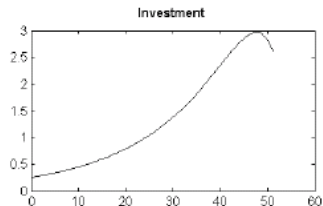
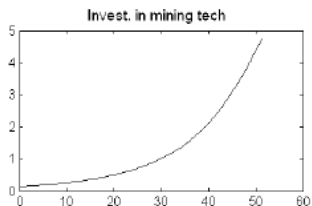
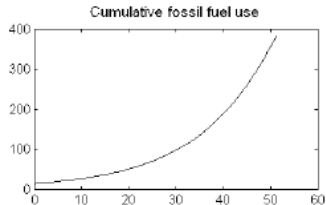
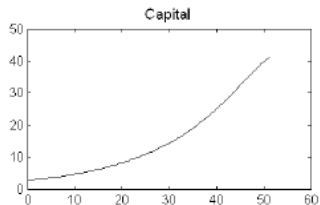
- Depending on parametrization:



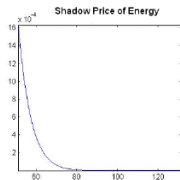
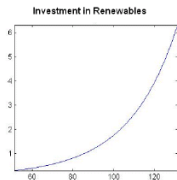
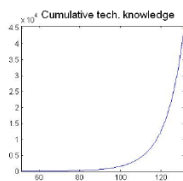
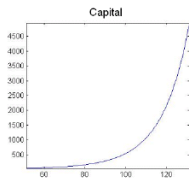
- Assign numerical values to parameters so that model consistent with actual world economy
- Data sources:
 - *Food And Agriculture Organization of the UN*
 - *Energy Information Administration (EIA)*
 - *Survey of Energy Resources, World Energy Council (WEC)*
 - *Center for Global Trade Analysis, Purdue University*
 - *Cambridge Energy Research Associates (CERA, 2009)*
 - *National Energy Technology Laboratory (NETL)*
 - *United States Geological Survey (USGS)*
 - *Energy Information Administration (EIA)*

- R : world wide production of oil, natural gas, coal in 2004 (*EIA*): 392.689 quads
- S : total resources of coal, oil, extra heavy oil, natural bitumen, oil shale, natural gas (*WEC*): 115.2 quintillion BTU (300 times the 2004 annual worldwide production)
- Taking into account methane hydrates (*NETL, USGS*): 719.6 quintillion BTU. $S = 834.8$ quintillion BTU

- $T_1 = 51$; $T_2 = 131$
- Regime 1:



- Regime 2:



- Tax on Fossil Fuel Energy (n)

Table 1: Values of key variables with fossil fuel taxes

	$\tau_n = 0$	$\tau_n = 0.02$	$\tau_n = 0.05$	$\tau_n = 0.2$
T_1	51.2249	46.3859	45.19	39.9463
$N(T_1)$	64.6412	58.0567	57.5293	55.1507
$S(T_1)$	382.9009	350.9142	348.3918	334.1527
T_2	131.4168	126.5756	125.347	120.1413

- Taxing fossil fuels accelerates adoption of renewable energy
- Fossil fuel reserves used less intensively
- Total extraction of fossil fuels declines
- Tax creates wedge between equilibrium and socially optimal investment

- Subsidy for Renewable Energy (j)

Table 2: Values of key variables with renewable investment subsidies

	$\tau = 0$	$\tau = 0.02$	$\tau = 0.05$	$\tau = 0.2$
T_1	51.2218	34.9859	28.7297	17.6351
$N(T_1)$	64.6412	95.4224	113.4596	126.0906
$S(T_1)$	382.9009	516.5132	585.6372	629.2025
T_2	131.4168	105.0398	94.7115	77.2363

- Subsidy accelerates adoption of renewable energy
- Appears to be more effective than tax on fossil fuels
- Fossil fuel reserves used more intensively under subsidy
- Intuition: opportunity cost of using fossil fuel in the short run declines

- 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