

# Innovation, Renewable Energy, and Macroeconomic Growth: A Progress Report

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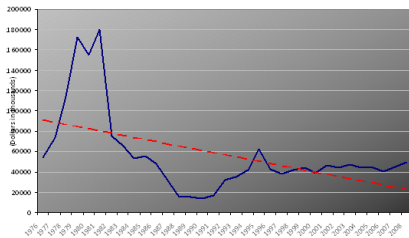
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- R&D in renewable energy as an engine of growth
- Most studies assume optimal size of R&D in (renewable) energy is 5 to 10 times the current level
- Proposal to spend \$150B/year in renewable energy R&D over next 10 years compared to current \$5B/year
- Our project:
  - Inform the policy discussion through rigorous modeling
  - Study effects of energy taxes/subsidies on the macroeconomy

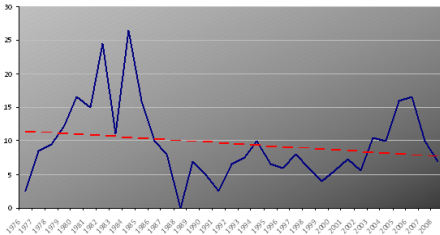
# Plan for the Presentation

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

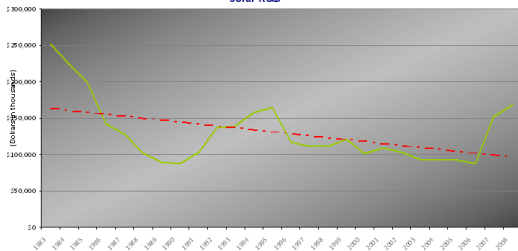
Wind R&D



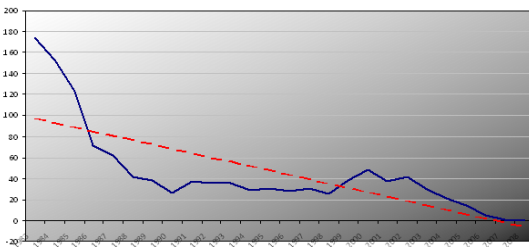
Wind Patents



### Solar R&D



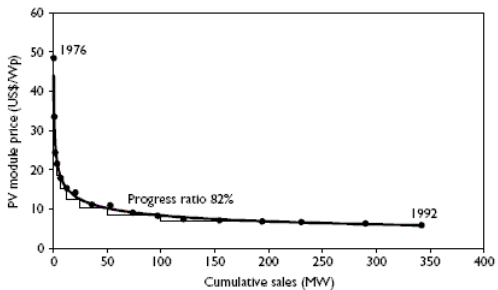
### Solar Patents



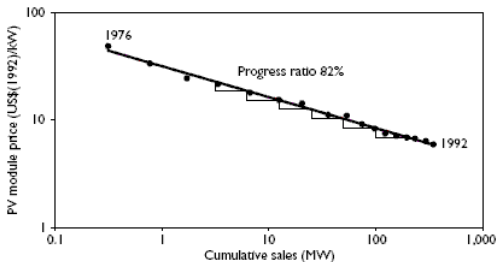
# Experience Curves

- 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



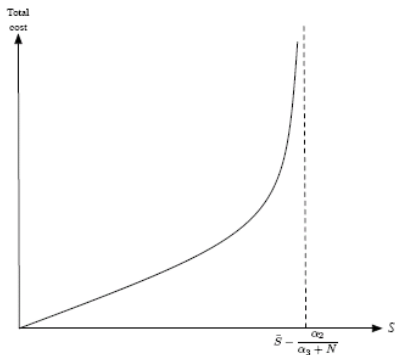
Experience Curve for Photovoltaic Modules, 1976-1992



# A Macro Model

- $c$ , per capita consumption
- Technology uses energy to produce output
- $R(B)$ , the per capita energy derived from fossil fuel(renewable) resources
- $Q$ , population; grows at constant rate
- $QR$ , 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
- Cost of extraction:  $g(S, N)$



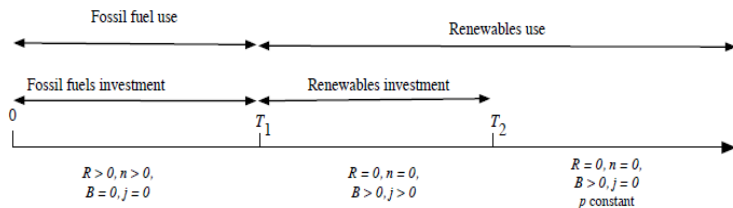
- $k$ , capital stock; output:  $y = Ak$
- Energy needed to produce output (energy supplies in efficiency units)
- Ratio of energy to capital inputs fixed
- $y$  proportional to  $R + B$

- $p$ , marginal cost of the energy produced using renewable technology
  - $\downarrow$  as knowledge gained through experience/investment in research
- $\Gamma_2$ , lower limit for  $p$
- $H$ , stock of knowledge about renewable energy production:  
 $p = (\Gamma_1 + H)^{-\alpha}$ ;  $\alpha = .37$
- $j$ , direct investment necessary for accumulating knowledge
  - $\dot{H} = j(1 + \psi B)$
  - Direct R&D twice as productive as learning-by-doing:  $\psi = .5$

- Objective:  $\max \int_0^{\infty} e^{-\beta\tau} u(c(\tau)) d\tau$
- 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

# Equilibrium Regimes

- Depending on parametrization:



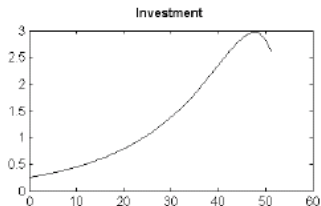
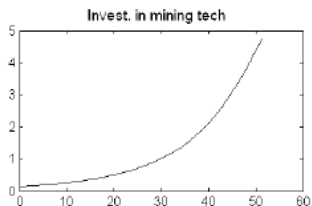
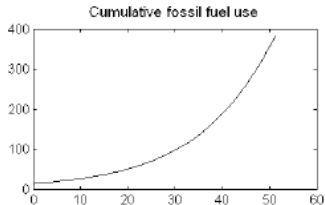
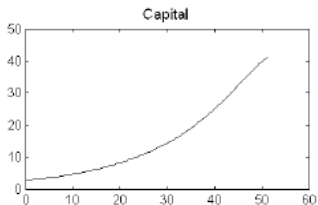
- Taking model to data: Kydland and Prescott, 1982 (Nobel prize, 2004)
- Assign numerical values to parameters so that model consistent with actual world economy
- Not the best method for prediction (aggregate data, no industry detail)
- Allows rigorous study of effects of policy across different sectors

- Data sources:

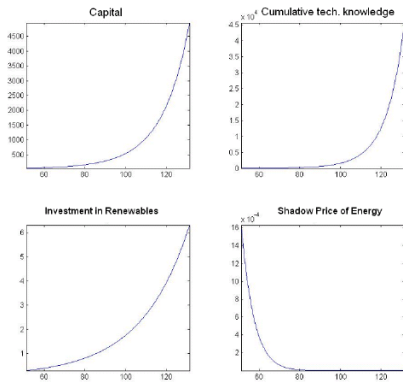
- *Food And Agriculture Organization of the UN*
- *Energy Information Administration (EIA)*
- *Survey of Energy Resources, World Energy Council (WEC)*
- *Center for Global Trade Analysis, Purdue University*
- *Cambridge Energy Research Associates (CERA, 2009)*
- *National Energy Technology Laboratory (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
- Average decline rates for oil production from existing fields (*CERA*): 6% per year

- $T_1 = 51$ ;  $T_2 = 131$
- 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

# Summary

- Experience curves: useful measure of technological progress
- Calibrated macro model incorporating experience curves
- Many possible extensions/applications to policy evaluation
- Analysis does not consider *emissions/climate change* or *energy independence* issues