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

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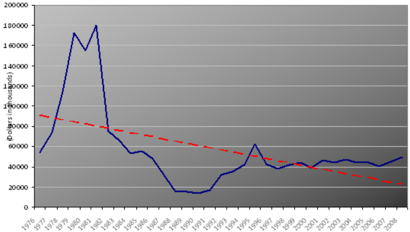
Introduction

- 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

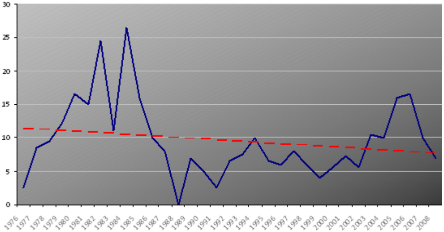
Plan for the Presentation

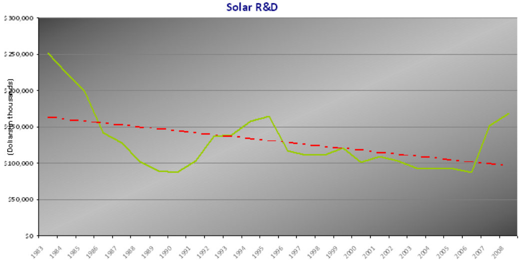
- Measures of R&D Output:
  - (Cited) Patents
  - Experience Curves
- Imbed version of experience curves into macroeconomic model
- Compute equilibrium
- Calibration
- Policy scenarios

Wind R&D



Wind Patents




Solar R&D
(Dollars in thousands)
$300,000
$250,000
$100,000
$50,000
$0
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
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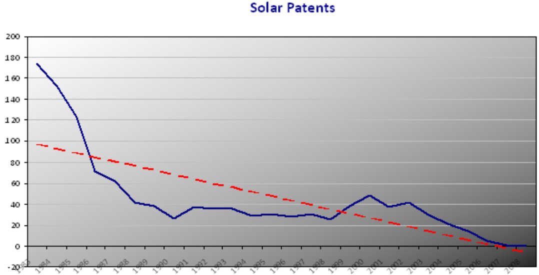
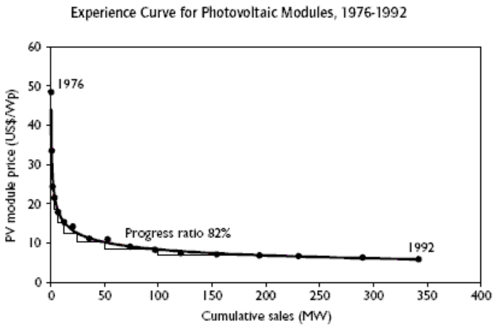
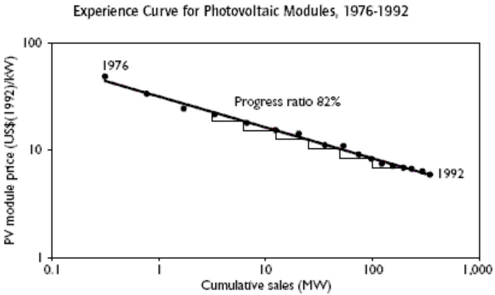
2004
2005
2006
2007
2008


Solar Patents
200
180
160
140
120
100
80
60
40
20
0
-20

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:

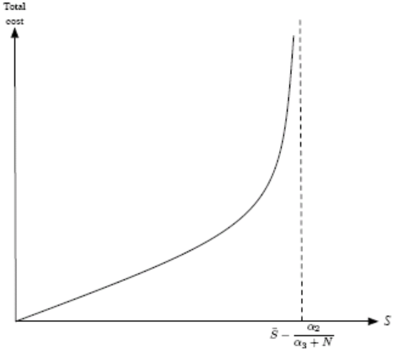

Experience Curve for Photovoltaic Modules, 1976-1992
PV module price (US$/Wp)
Cumulative sales (MW)
1976
1992
Progress ratio 82%
60
50
40
30
20
10
0
0
50
100
150
200
250
300
350
400


Experience Curve for Photovoltaic Modules, 1976-1992
PV module price (US$(1992)/kW)
Cumulative sales (MW)
1976
1992
Progress ratio 82%
100
10
1
0.1
1
10
100
1,000

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: $g(S, N)$



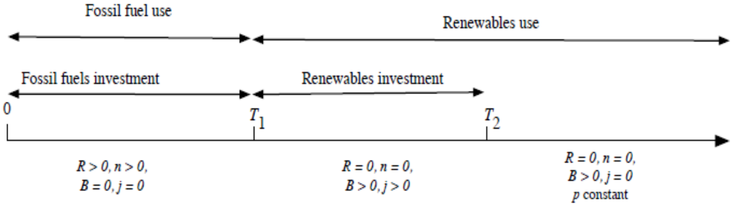
- k, capital stock; output: $y = Ak$
- Energy needed to produce output (energy supplies in efficiency units)
- Ratio of energy to capital inputs fixed
- y proportional to $R + B$

- p, marginal cost of the energy produced using renewable technology
    - $\downarrow$ as knowledge gained through experience/investment in research
- Γ_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: $\max \int_0^{\infty} e^{-\beta\tau} u\left(c(\tau)\right)\, d\tau$
- 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:



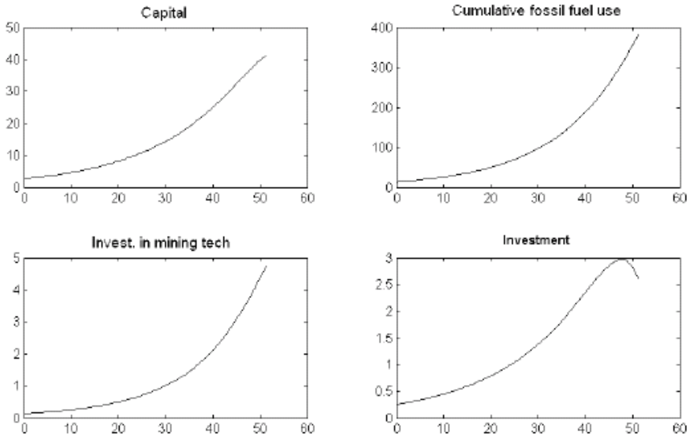
Calibration

- 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

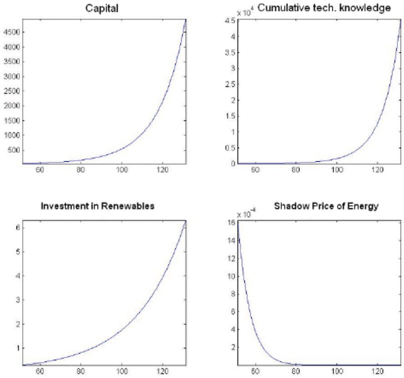
- Data sources:
    - *Food And Agriculture Organization of the UN*
    - *Energy Information Administration (EIA)*
    - *Survey of Energy Resources, World Energy Council (WEC)*
    - *Center for Global Trade Analysis, Purdue University*
    - *Cambridge Energy Research Associates (CERA, 2009)*
    - *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:



Capital
4500
4000
3500
3000
2500
2000
1500
1000
500
60
80
100
120
x 10^4 Cumulative tech. knowledge
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
60
80
100
120
Investment in Renewables
6
5
4
3
2
1
60
80
100
120
Shadow Price of Energy
x 10^-4
16
14
12
10
8
6
4
2
60
80
100
120

Policy Scenarios

- 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