Integrated assessment in a multi-region world with multiple energy sources

John Hassler, Per Krusell, and Michael Reiter
IIES, IIES, and IHS, respectively

Macroeconomics of Climate Change, December 2012

Background

Two closely related projects:

- Construction of global IAM with (extremely) high regional resolution. Main features:
  - DSGE: microeconomic foundations, amenable to full policy and welfare analysis.
  - Climate and carbon cycle modeling along the lines of Nordhaus's DICE and RICE.
  - Quantitative focus, numerical solution based on recent advances in macroeconomic modeling.
- Construction of analytically much more tractable "toy version" of the above (HK [Hassler and Krusell (2012)]).
  - Shortcuts needed for tractability not so crazy (surprisingly!), so quantitatively relevant.
  - Builds on GHKT [Golosov, Hassler, Krusell, and Tsyvinski (2011)], a one-region (DICE) model with tractability.

This paper

Further work:

- continuing development of HK (richer framework than we first expected!)
- in particular develops energy sector.

Key focus:

- oil and coal treated separately, allow green energy source too
- different regions face different costs of coal production
- taxing oil vs. taxing coal
- taxes in parts of the world (EU) vs. global taxes
- new today: endogenous technical progress in energy use

Model basics

- 4 oil-consuming regions, significant heterogeneity:
  - in climate sensitivities and damages
  - in level of income/development/productivity
  - in income/climate/weather outcomes
  - energy input from oil, coal (heterogeneous production costs), and green
- oil-producing countries, all alike
- no trade across regions, except in oil at common world price
- no capital flows across regions
- exogenous labor input
- 100% depreciation of capital

Oil consumers

- In all regions, preferences are

$$E_0 \sum_{t=0}^{\infty} \beta^t \log(c_t)$$

- production in region i, oil consumers:

$$y_{it} = A_{it} k_{it}^{\alpha} e_{it}^{\nu} \quad (l_t = 1)$$

- $A_{it} = exp(z_{it} - \gamma_{it} S_t)$, where
  - z_{it} grows exogenously at common rate
  - S_t is world atmospheric carbon concentration: endogenous
  - γ_{it} measures climate sensitivity AND damages: exogenous and region-specific.
  - e composite of oil, e^{oil}, coal, e^{coal}, and green, e^{green}

- energy production:

$$e_{it} = \left(\lambda_1 (e_{it}^{oil})^{\rho} + \lambda_2 (e_{it}^{coal})^{\rho} + \lambda_3 (e_{it}^{green})^{\rho}\right)^{\frac{1}{\rho}}$$

- oil spending in i: $p_t^{oil} e_{it}^{oil}$
- constant marginal production cost of coal in i: π_{it}^{coal}, in output units—a parameter
- same for green: π_{it}^{green}, also a parameter
- regional budget, thus:

$$c_{it} + k_{i,t+1} = y_{it} - p_t^{oil} e_{it}^{oil} - \pi_{it}^{coal} e_{it}^{coal} - \pi_{it}^{green} e_{it}^{green}$$

So the oil-consuming country saves and uses energy optimally given these constraints.

$\Rightarrow$ Closed-form solutions: constant saving rate (not exactly true with taxes, but good approximation), energy uses as simple functions of TFP, capital, oil price, marginal costs of coal and green.

Oil producers

- same preferences as for oil consumers
- oil is free to produce, a global stock R_t available at t
- world oil production: $E_t^{oil} = R_t - R_{t+1} \geq 0$
- perfect competition among producers
- regional budget, oil producers:

$$c_t + p_t R_{t+1} = p_t R_t$$

$\Rightarrow$ Closed-form solutions: $E_t^{oil} = (1 - \beta) R_t$ (and $R_t = \beta^t R_0$).
Thus: supply of oil independent of oil price. Reason: income and substitution effects cancel under logarithmic utility of oil producers.

World interaction

- Oil market: $E_t^{oil} = \sum_i e_{it}^{oil}$ for all t
  - supply-determined quantity: p_t^{oil} adjusts so that demand equals E_t^{oil}
  - distribution of oil use will depend on price
- climate feedback—carbon cycle—modeled linearly:

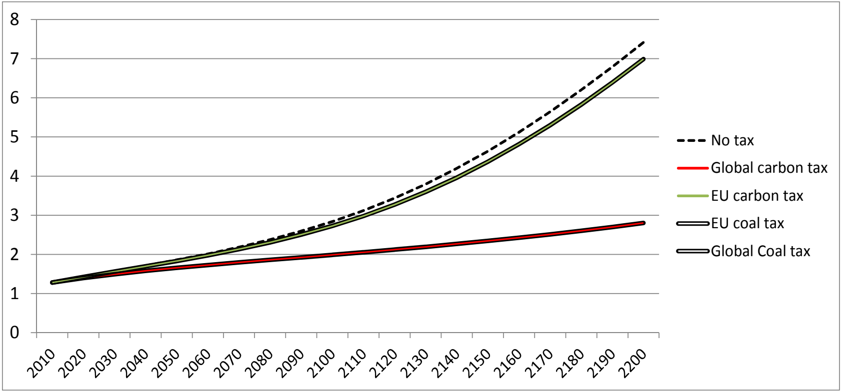
$$S_t = \sum_{j=0}^{t} (1 - d_{t-j}) \left[E_{t-j}^{oil} + \sum_i e_{i,t-j}^{coal} \right],$$

with $0 < 1 - d_s < 1$ represents how much carbon is left $s \geq 0$ periods after emitting one unit. 3-parameter structure on d_{t-j}s can match actual cycle rather well!

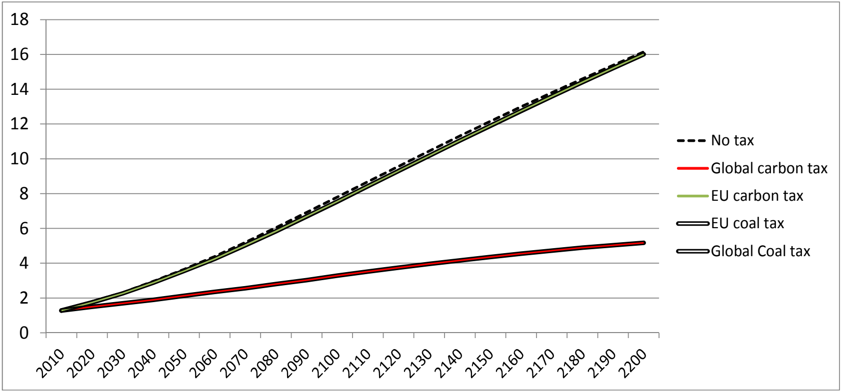
Calibration, 4 regions: US, China/Asia, EU, Africa

- sizes of regions calibrated to relative output sizes in data
- 1 period: 10 years; annual discounting 1.5%, TFP growth 1.5%
- R_0 to match available amount of (cheap) oil: 300Gt.
- energy share 3%, capital share 30%, initial capital stocks on balanced growth paths
- energy input prices:
  - coal price about 45 dollars/ton
  - oil $\sim$ 6 times more expensive than coal per carbon unit
  - coal 20% cheaper in Africa, 100% more expensive in Europe
  - energy input price elasticity 0.95
- depreciation of S: 20% stays forever, 60% "disappears" within decade, rest depreciates at 2.2%.
- $e^{-\gamma(S_t-600)}$ matches Nordhaus's inverse-quadratic damage function of T; and $T = \frac{3}{ln2}(\ln S - \ln 600)$ well if $\gamma \sim 5 \cdot 10^{-5}$
- regional damage estimates from Nordhaus:
  - USA and China both γ_{lo}: 2x$S \Rightarrow T \uparrow 3^o$, $Y \downarrow 0.8\%$
  - Europe and Africa both γ_{hi}: 2x$S \Rightarrow T \uparrow 3^o$, $Y \downarrow 4.7\%$

Temperature, energy input elasticity 0.95



Temperature, energy input elasticity 2



Lessons so far (without technical progress in energy)

- When oil and coal are closer substitutes, coal production will be higher as oil runs out, and temperatures will increase more (both in optimum and laissez faire).
- Optimal global taxes make a huge difference for temperatures.
- EU taxes help very little.
- Coal taxes are key. Oil taxes seem quantitatively irrelevant.
- Welfare gains for EU, quantitatively (relative to laissez faire):
  - from global carbon tax: 2.4% in flow consumption equivalent (Europe: 5.4, China 0.3, US 0.8, Africa 7.2)
  - from global coal tax: 2.2%
  - from EU carbon tax: 0.35% (Europe: 0.6, China 0.1, US 0.2, Africa 1.1)
  - from EU coal tax: 0.25%
  - if high energy input elasticity: 24%, 24%, 1.2%, 0.9%, respectively

Endogenous Technical Progress in Energy Use

Aim: tractability.

- Technical progress is energy-augmenting:

$$e_{it} = \left(\lambda_1(A^o_{it}e^{oil}_{it})^\rho + \lambda_2(A^c_{it}e^{coal}_{it})^\rho + \lambda_3(A^g_{it}e^{green}_{it})^\rho\right)^{\frac{1}{\rho}} \quad (1)$$

  A^j_{it} depends on research effort n^j_{it}:

$$A^j_{it} = \bar{A}^j_{it-1}g(n^j_{it}), \qquad j \in o, c, g \quad (2)$$

- Research is done efficiently from the point of view of small countries (not centrally in big regions like Europe).
- In each country, an exogenous amount of research effort is split between research on the efficiency of oil, coal and green:

$$n^o_{it} + n^c_{it} + n^g_{it} = \bar{n} \quad (3)$$

- At the end of the period (which is 10 years), the new technology level becomes common to all countries in the region: $\bar{A}^j_{it} = A^j_{it}$.
  Externalities (energy efficiency, climate) not internalized!

Optimal research in each country, each t

Problem boils down to sequence of static problems.
Intermediate problem in energy sector:

$$\min_{E_j, A_j} \sum_i (p_i + \tau_i) E_i \tag{4}$$

subject to

$$\mathcal{E}(A_1 E_1, \ldots, A_n E_n) = e \tag{5}$$

$$A_i = \bar{A}_i g(n_i), \qquad i = 1, \ldots, n \tag{6}$$

$$\sum_i n_i = \bar{n} \tag{7}$$

Endogenous Technical Progress: CES case

Assume CES energy production function:

$$\mathcal{E}(\hat{E}) = \left[\sum_{j=1}^{n} a_j^{\frac{1}{\sigma}} (A_j E_j)^{\frac{(\sigma-1)}{\sigma}} \right]^{\frac{\sigma}{(\sigma-1)}} \tag{8}$$

Optimal energy demands are

$$\frac{E_i}{E_j} = \frac{a_i}{a_j} \left(\frac{A_i}{A_j} \right)^{\sigma-1} \left(\frac{p_i + \tau_i}{p_j + \tau_j} \right)^{-\sigma} \tag{9}$$

Assume the dynamic equation

$$A_{j,t} = \bar{A}_{j,t-1} n_{j,t}^{\zeta} \tag{10}$$

Then

$$\frac{n_{i,t}}{n_{j,t}} = \left[\left(\frac{a_i}{a_j} \right)^{\frac{1}{\sigma-1}} \frac{\bar{A}_{i,t-1}}{\bar{A}_{j,t-1}} \left(\frac{p_{i,t} + \tau_{i,t}}{p_{j,t} + \tau_{j,t}} \right)^{-1} \right]^{\frac{\sigma-1}{1-\zeta(\sigma-1)}} \tag{11}$$

Interpretation

- What matters is effective price of energy: $\frac{p_{i,t}+\tau_{i,t}}{a_i^{\frac{1}{\sigma-1}}\bar{A}_{i,t-1}}$
- If demand elasticity σ greater (smaller) than 1, more resources go into the type of energy where the effective price is lower (higher).
- Taxing a type of energy increases research into this energy if $\sigma < 1$.

Parameter values

- Technical progress: we choose
  1. $\bar{n} = 12$
  2. $\zeta = 0.1$

  Examples:
  1. setting
     - $n^o_{it} = n^c_{it} = 1$
     - $n^g_{it} = 10$

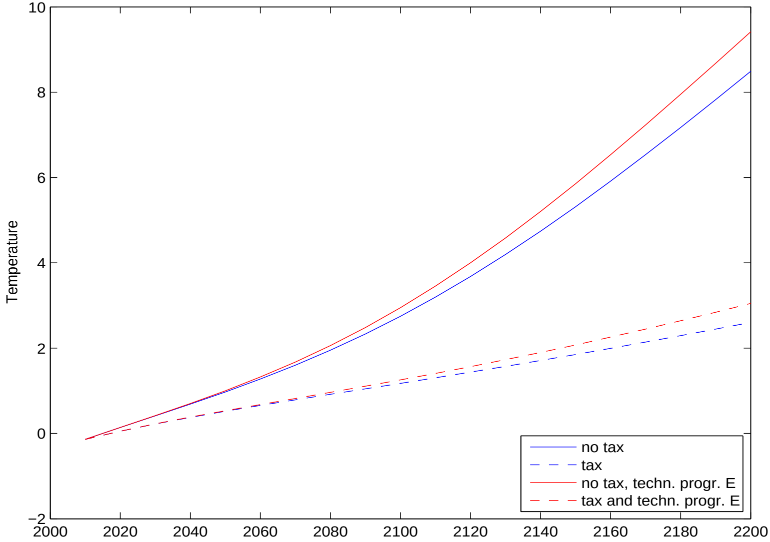
     keeps technology in oil and coal constant, improves efficiency in green energy by factor 10 in 10 periods (100 years).
  2. setting
     - $n^o_{it} = n^c_{it} = 4$

     improves by factor 4 per 100 years in all energies.
- Green energy (not yet available in benchmark): initially,
  - green energy as productive as coal
  - 10 times more expensive than coal

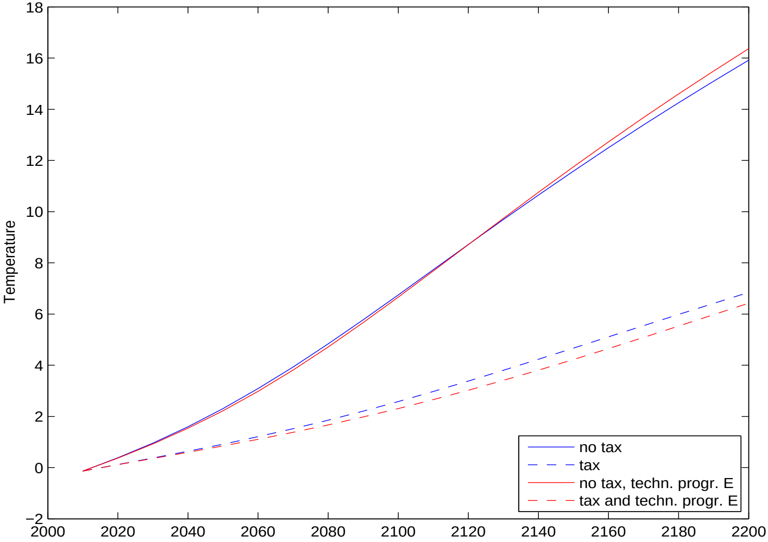
Numerical results

- With $\sigma < 1$:
  - most research goes into oil, since oil is very expensive
  - oil becomes relatively more abundant
  - relative demand for oil decreases, for given price ratio
  - relative price of oil also increases slightly
  - since absolute oil is constant, absolute demand for coal increases
- With $\sigma = 1.5$: sign of effect differs across regions
- Allowing for green energy:
  - again, most research goes into oil
  - effect of research on temperature still positive
- All technical progress in green energy ($n_{it}^{o} = n_{it}^{c} = 1$, $n_{it}^{g} = 10$): effect on temperature small and positive (it all depends on coal vs. oil, not fossile vs. green)

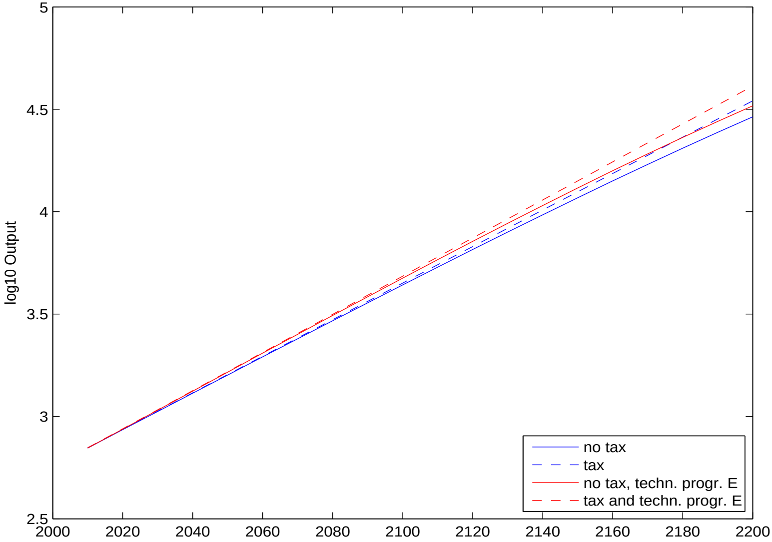
Benchmark calibr., temperature



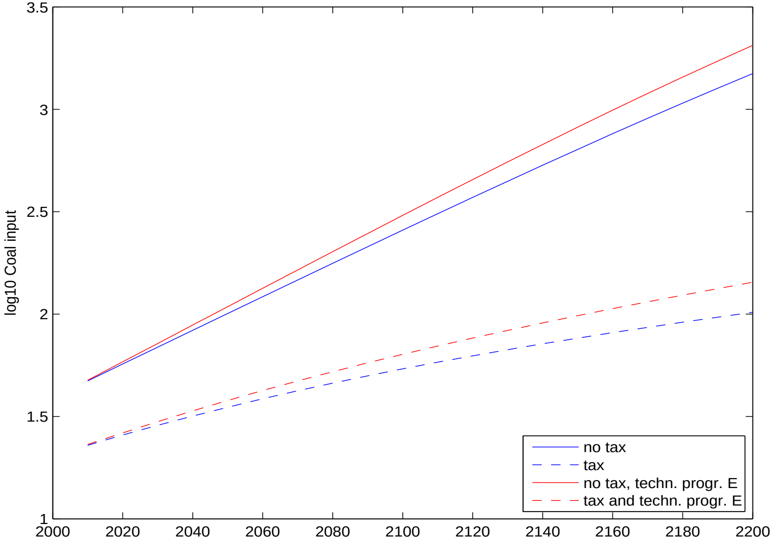
$\sigma = 1.5$, temperature



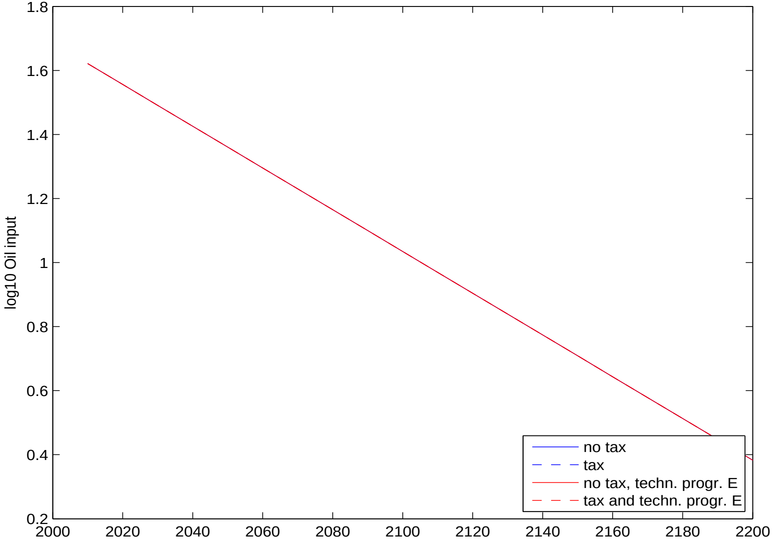
Benchmark, world output



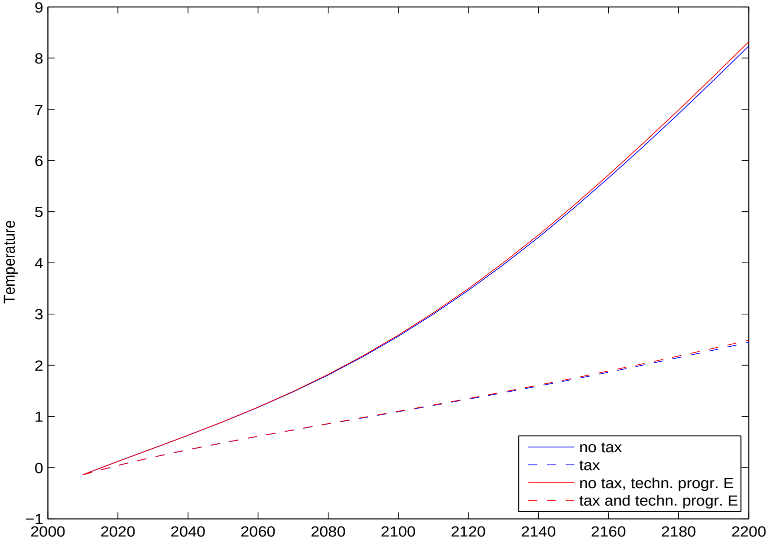
Benchmark, coal consumption



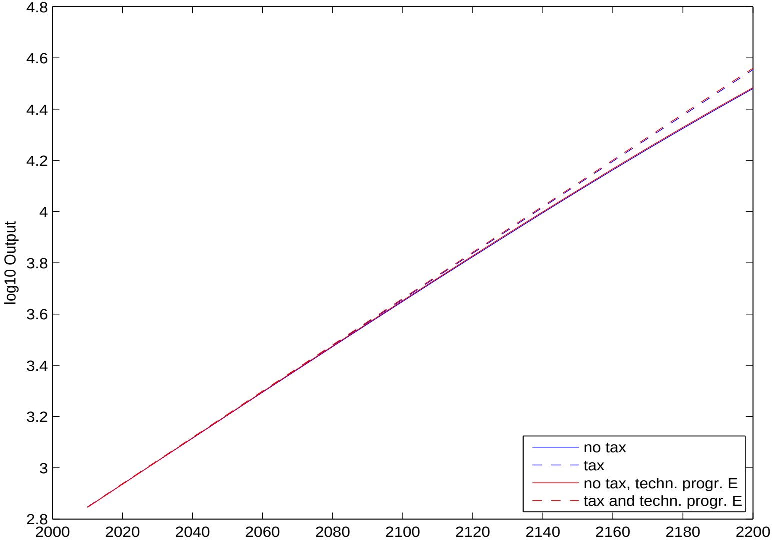
Benchmark, oil consumption



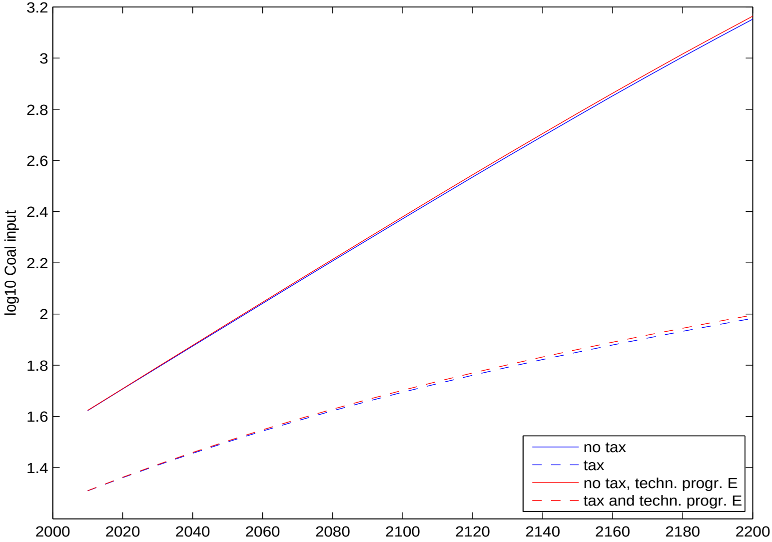
Only green research, temperature



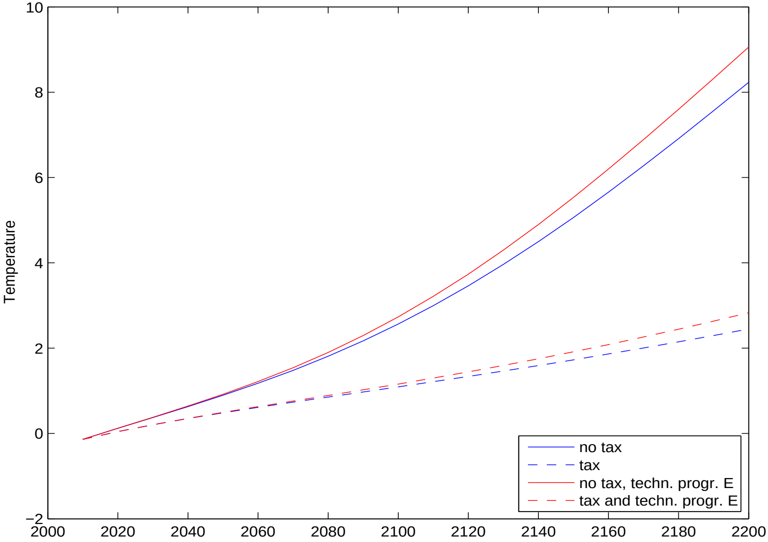
Only green research, world output



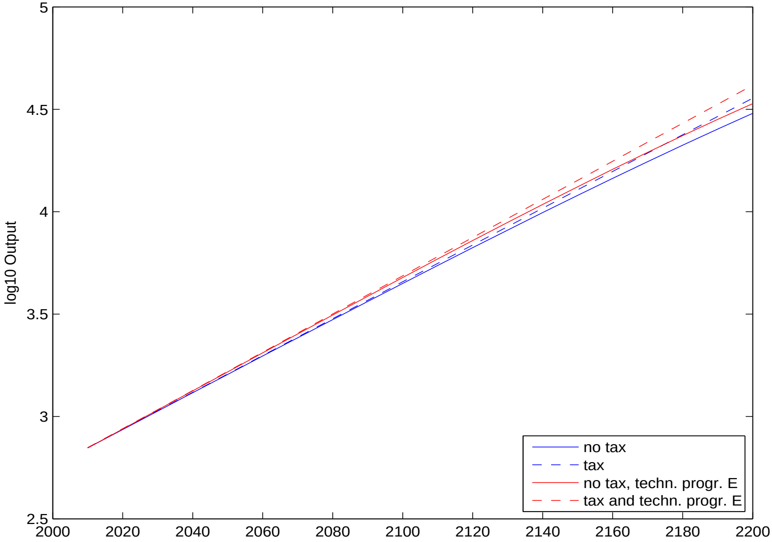
Only green research, coal consumption



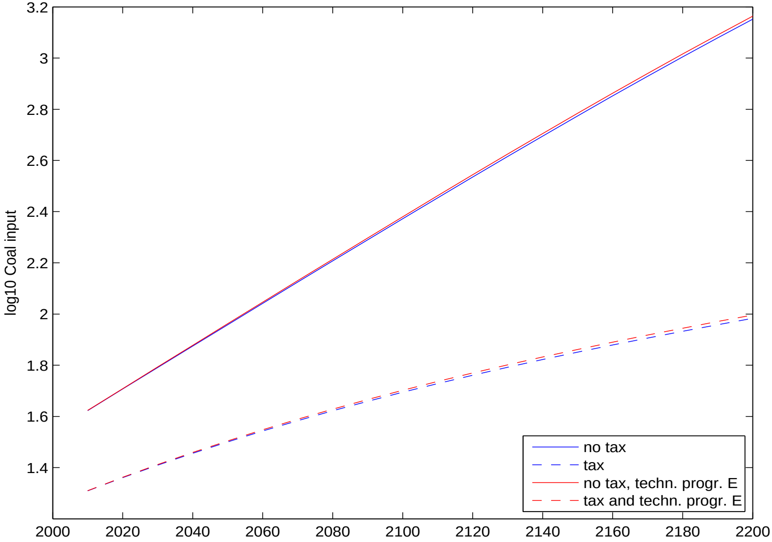
Green energy and opt.res. research, temperature



Green energy and opt.res. research, world output



Green energy and opt.res. research, coal consumption



General lessons

- To reduce warming, taxes are essential; effect of technical progress in energy is relatively small and ambiguous.
- Effect of technical progress in energy on output is small, since energy share in GDP is small.
- Elasticity of substitution important.