Energy Efficiency and Direct Technical Change: Implications for Climate Change Mitigation

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Env Climate discussion group S9

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Research goals

How will aggregate energy efficiency respond to policies designed to mitigate climate change?

- A directed technical change model of economic growth and energy efficiency to theoretically and quantitatively study the impact of environmental policy interventions
- focus on final-use energy efficiency (energy use reductions, instead of substitution between sources of primary energy)

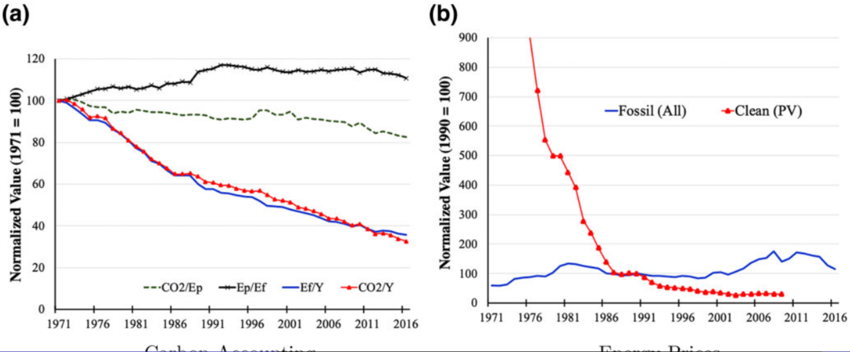
Preview of results:

- The standard Cobb-Douglas production function ignores transition dynamics & overstates the reduction in cumulative energy use that can be achieved with energy taxes.
- In the model, the government **combines energy taxes with R&D policy that favors output-increasing technology** — rather than energy efficiency technology — to maximize welfare subject to a constraint on cumulative energy use.
- Study energy use dynamics following sudden improvements in energy efficiency
  - Exogenous shocks also decrease the incentive for subsequent energy efficiency R&D and increase long-run energy use relative to a world without the original shock

Empirical Motivation: final-use energy

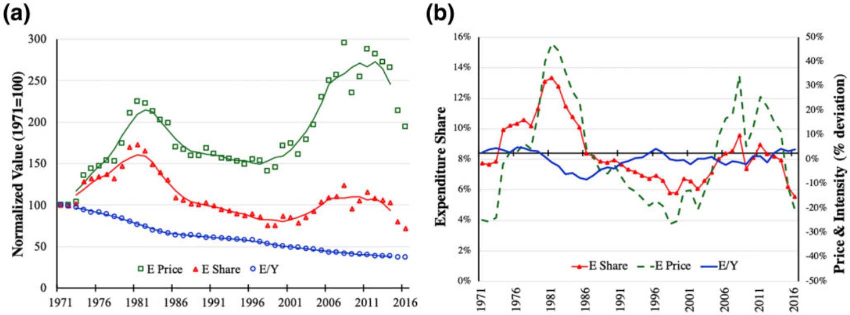
Observation 1: Final-use energy efficiency ($\frac{E_f}{Y}$) has played a crucial role in reducing the carbon intensity of output ($\frac{CO_2}{Y}$). Decompose using

$$\frac{CO_2}{Y} = \underbrace{\frac{CO_2}{E_p}}_{\text{[carbon intensity of primary energy]}} \underbrace{\frac{E_p}{E_f}}_{\text{[efficiency of the energy sector]}} \underbrace{\frac{E_f}{Y}}_{\text{[final-use energy intensity of output]}}$$



Empirical Motivation: energy demand

Observation 2: The expenditure share of energy (E_{share}), but not the energy intensity of output ($\frac{E}{Y}$), reacts to the short-run price fluctuations ($E_{share} = p_E \frac{E}{Y}$) $\longrightarrow$ difficult to substitute between energy and non-energy inputs in the short run

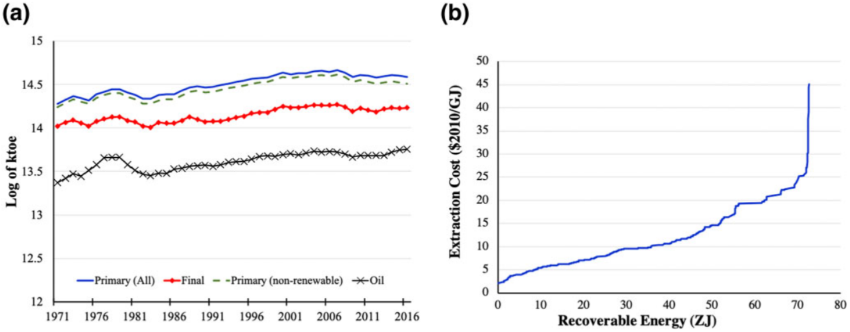


Normalized Values Detrended

(E_{share}: deviate from LR average & no LR trend)

Empirical Motivation: energy supply

Observation 3: Energy use increases over the period of study, inconsistent with a model where increasing prices are driven by scarcity rents $\longrightarrow$ more in favor of the increasing extraction cost approach, which allows for increasing energy use on the BGP



Energy Use Extraction Costs

Model summary

- Directed technical change governs demand for energy
- Energy & non-energy inputs must be combined in fixed proportions for a given set of technologies
- Capital good producers respond to increases in the relative price of energy by lowering the energy input ratio through directed R&D activity
- The cost of supplying energy increases with cumulative extraction.

Model setup:

- Final good production (perfectly competitive, final good "numeraire")
  "Leontief" to match the low SR elasticity of substitution between energy and non-energy inputs

$$\underbrace{Q_t}_{\text{gross output}} = \int_0^1 \min[\underbrace{X_t(i)^a}_{\text{quantity (capital goods)}} (\underbrace{A_{N,t}(i)}_{\text{quality}} \underbrace{L_t}_{\text{labor supply}})^{1-a}, \underbrace{A_{E,t}(i)}_{\text{energy efficiency}} \underbrace{E_t(i)}_{\text{amount of energy}}]di$$

$$s.t. \quad \underbrace{A_{E,t}(i)E_t(i)}_{\text{energy-productivity of capital good i}} \leq X_t(i)^a(A_{N,t}(i)L_t)^{1-a} \quad \forall i$$

where i indexes different capital goods, $E_t \equiv \int_0^1 E_t(i)di$ denotes total energy use

Model Setup

- Energy Sector (cost increases in cumulative extraction; use final goods; "open access")
  Marginal cost of extraction = price:

  $$p_{E,t} = A_{V,t}^{-1} \underbrace{\bar{E}_{t-1}^{\psi}}_{\text{cumulative extraction}} \text{, where}$$

  - $A_{V,t}^{-1}$ captures the difference in the sate of technology between the energy extraction and final good sectors.
  - Exogenous process $A_{V,t}^{-1} = (1 - g_{Av})A_{V,t-1}^{-1}$ focuses on directed technical change in energy demand ($g_{Av} > 0$ means technological progress is faster in the energy extraction sector)
  - ψ: elasticity of energy extraction costs w.r.t. cumulative extraction
  - LoM for the energy extraction stock:
    $$\bar{E}_t = E_t + \bar{E}_{t-1}$$
  - Simplification: extraction costs are constant within each period

Model Setup

- Final output: = gross output - total energy extraction costs

$$Y_t = L_t^{1-a} \int_0^1 \underbrace{[1 - \frac{p_{E,t}}{A_{E,t}(i)}] A_{N,t}(i)^{1-a}}_{\text{productivity}} X_t(i)^a di$$

- Capital goods and research (each type produced by a monopolist; in-house R&D to improve $A_{N,t}(i)$ and $A_{E,t}(i)$)

  The R&D production function:

$$A_{J,t}(i) = A_{J,t-1}(i) + \eta_J R_{J,t}(i)^{1-\lambda} A_{J,t-1}, \quad J = N, E$$

  where
  - $R_{J,t}(i) =$ quantity of R&D inputs by firm i, $R_{J,t} \equiv \int_0^1 R_{J,t}(i) di$
  - $A_{J,t-1} \equiv \int_0^1 A_{J,t-1}(i) di$
  - $\lambda \in (0,1)$: decreasing returns to R&D
  - $\eta_J > 0$: exogenous component of research efficiency
  - all firms start from $A_{J,-1}(i) = A_{J,-1}\ \forall i \longrightarrow$ symmetry
  - single-period maximization, ignoring the intertemporal spillover in R&D productivity
  - free mobility + unit mass of R&D inputs: $R_{N,t} + R_{E,t} = 1 \longrightarrow$ interpret R_J as shares

Model Setup

- Capital goods depreciate fully when used in the production of the final good (every 10 years), and investment price =1:

$$\text{market clearing:} \quad \int_0^1 X_t idi \leq K_t \quad \text{where } K_t \text{ is aggregate capital, i.e. output saved in } t-1$$

- Representative Household (standard consumer problem, path of consumption to maximize lifetime utility)

$$U \equiv \sum_{t=0}^{\infty} \beta^t L_t \frac{\tilde{c}_t^{1-\alpha} - 1}{1-\alpha} \quad \text{with} \quad \tilde{c}_t = \frac{C_t}{L_t}, \quad L_{t+1} = (1+n)L_t$$

HH owns both the capital stock and the R&D inputs, government ensures zero net revenue using lump-sum taxes or transfers.

$$BC: \quad C_t + K_{t+1} = L_t \omega_t + r_t K_t + \Pi_t + p_t^R + T_t \quad (= Y_t)$$

Analysis

Firms hire R&D inputs to maximize profits and take the result to aggregate level $\longrightarrow$ Research arbitrage condition: LHS=relative cost of using R&D inputs to improve the two types of technology, RHS = relative benefit of hiring R&D inputs

$$\frac{(1-\eta_t^S)p_{E,t}^R}{p_{N,t}^R} = (1-\alpha)^{-1}\left(\frac{\tau_t p_{E,t} A_{E,t}^{-1}}{\hat{\alpha}^{-1} w_t^{1-\alpha} r_t^{\alpha} A_{N,t}^{\alpha-1}}\right)\cdot\left(\frac{A_{N,t}}{A_{E,t}}\right)\cdot\left(\frac{\eta_E R_{E,t}^{-\lambda} A_{E,t-1}}{\eta_N R_{N,t}^{-\lambda} A_{N,t-1}}\right),$$

where

- $\tau_t - 1$: value-added tax on energy
- η^S: subsidy for energy efficiency R&D

Key forces:

1. **Input price effect:** numerator = cost of purchasing enough energy to produce 1 unit of output, denominator = cost of purchasing enough of the capital-labor composite per unit of output
2. **Role of low elasticity of substitution:** increase in $A_{N,t}$ raise the return to investing in $A_{E,t}$ and vise versa
3. **Research productivity effect:** return to investing in a particular type of R&D is increasing in the efficiency of the research process, which depends on inherent productivity η_J, accumulated knowledge $A_{J,t-1}$, impact of decreasing return $R_{J,t}^{-1}$

Equilibrium

Using energy expenditure share $\theta_{E,t} \equiv \frac{\tau_t p_{E,t} E_t}{Y_t}$, research arbitrage equation can be rewritten to show the equilibrium relationship between technology growth rates, factor shares, and R&D allocations:

$$\frac{1+g_{A_E,t}}{1+g_{A_n,t}} = \frac{\theta_{E,t}}{1-\alpha}\frac{\eta_E R_{E,t}^{-\lambda}}{\eta_N R_{N,t}^{-\lambda}},$$

and $\theta_{E,t}$ is the elasticity of final output w.r.t. energy efficiency, and $1-\alpha$ w.r.t non-energy technology.

There is an asymmetry in the way that technological progress affects these elasticities: changes in $A_{N,t}$ have no effect on the elasticity w.r.t. non-energy technology, but changes in $A_{E,t}$ have a negative effect on the elasticity w.r.t energy efficiency.

$p_{E,t}$ increases $\longrightarrow$ drive up the relative benefit of increasing $A_{E,t}$ $\longrightarrow$ energy expenditure share up $\longrightarrow$ capital good producers allocate R&D inputs to energy efficiency $\longrightarrow$ drive energy expenditure share back down.

On a BGP, increases in $A_{E,t}$ are just large enough to offset the increases in energy prices.

Balanced growth under laissez-faire: energy prices and energy efficiency grow at the same constant rate $\rightarrow$ constant energy expenditure share

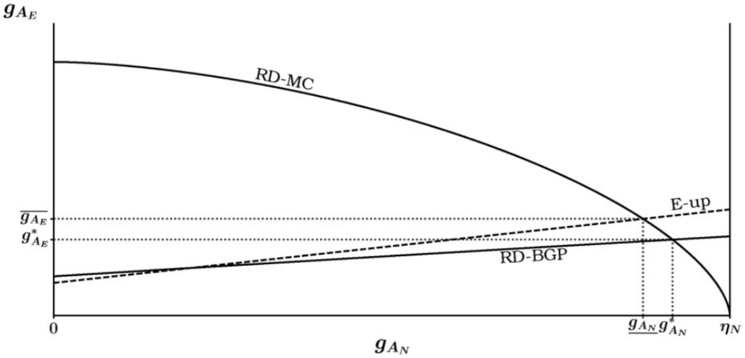


FIGURE 4

The intersection of (RD-BGP) and (RD-MC) gives the unique growth rates, $(g^*_{A_N}, g^*_{A_E})$, for a LFBGP with increasing energy use. The intersection of (RD-MC) and (E-up) defines the cutoff values $(\underline{g_{A_N}}, \overline{g_{A_E}})$ for increasing energy use. The LFBGP has increasing energy use if and only if $g^*_{A_N} > \underline{g_{A_N}}$.

Balanced growth with environmental policy: energy efficiency grows at the same rate as the tax-inclusive energy prices → two possibilities depnd on if long-run growth rate of energy use is positive (A4)

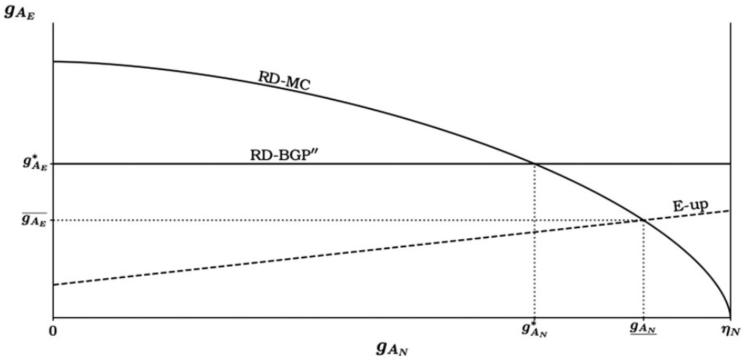


FIGURE 5

The intersection of (RD-BGP″) and (RD-MC) gives the unique growth rates, $g^*_{A_N}$ and $g^*_{A_E}$, for an EPBGP with decreasing flow energy use. The intersection of (RD-MC) and (E-up) defines the cutoff values, $\underline{g_{A_N}}$ and $\overline{g_{A_E}}$, that determine whether an EPBGP has a positive growth rate of flow energy use. The EPBGP has decreasing flow energy use if and only if $g^*_{A_N} < \underline{g_{A_N}}$

Implications

- neither the constant R&D subsidy, nor the level of energy taxes, has an impact on the BGP growth rates of energy use or any of the other macroeconomic aggregates (complements!)
- policy interventions must permanently reallocate R&D resources towards energy efficiency to decrease LR growth rate of energy use. (This will only occur if policy permanently increases the growth rate of tax-inclusive energy prices)
- When a constant subsidy for energy efficiency R&D is introduced, energy efficiency grows quickly, reducing energy use. The rapid growth in energy efficiency and reduced growth in energy extraction costs both push down the energy expenditure share, decreasing future incentives for energy efficiency R&D.

What else in the paper:

- Least-cost path to achieve an environmental target. To determine the policy mix that will implement the least-cost path: solve the social planner problem to find the least-cost path allocations and then compare the results to the competitive equilibrium

Proposition 3. *The government can implement the least-cost path using three policies: (1) a subsidy for capital good production $\tau_t^K = (1-\alpha)\ \forall t$, (2) a tax ($\tau_t^u > 0\ \forall t$) on energy use, and (3) a subsidy/tax (η_t^u) for energy efficiency R&D. In addition, η_t^u has the same sign as $(g_{A_E,t+1} - g_{A_E,t})$. In other words, the government subsidizes energy efficiency R&D in period t if energy efficiency grows faster in period $t+1$ than in period t, taxes energy efficiency R&D if the growth rate slows between t and $t+1$, and does neither if the growth rate is constant between periods.*

External parameters

Following Golosov et al. (2014) [optimal taxes on fossil fuel in general equilibrium, Econometrica]:

$\alpha = 0.35$, $\delta = 1$, $\sigma = 1$, $\beta = 0.86$

Limited data on energy expenditure: the period 1971-2016

- average growth rate of final output in the U.S.: $g_Y = 0.33$ (2.9%/year)
- population growth n=0.11 (1%/year)
- growth rate of income per capita $g^*_{A_N} = 0.2$ (1.9%/year)
- final-use energy consumption $g^*_E = 0.06$ (0.6%/year)
- growth rate of energy price $g^*_{p_E} = g^*_{A_E} = 0.25$ (2.3%/year)
- average energy expenditure share is 8.41%, the expenditure share of R&D is 2.65%

R&D calibration

- the R&D production functions have three unknown parameters: η_N, η_e, λ
- but LFBGP R&D allocations can be found without knowing any of the parameters:

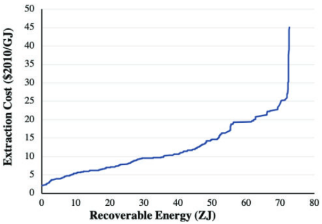
$$\frac{R_{E,t}}{1-R_{E,t}} = \frac{g_{A_E,t}}{1+g_{A_E,t}} \frac{1+g_{A_N,t}}{g_{A_N,t}} \frac{\theta_{E,t}}{1-\alpha}$$

- data: $R_E^* = 0.13$, $R_N^* = 0.87$
- and R&D share of income is $\theta_R^* = (1-\lambda)\alpha(1-\alpha)\frac{g_{A_N}^*/R_N^*}{1+g_{A_N}^*} \longrightarrow \lambda = 0.4$
- with $\lambda = 0.4$, solve for $\eta_E = 0.84$, $\eta_N = 0.22$ (improving energy efficiency technology is inherently easier than improving non-energy technology)

Energy sector calibration

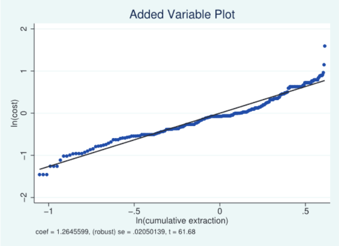
- LFBGP: flow and cumulative energy use grow at the same rate: observed flow rate $g_E^* = 0.06$
- calculate initial level of extracted energy using $E_0/\bar{E}_{-1} = g_E^* \longrightarrow \bar{E}_{-1}/E_0 = 15.7$
- Conditional on ψ (elasticity of energy extraction costs w.r.t. cumulative extraction), the ratio between the cumulative stock and per period flow of energy use determines the degree to which energy prices respond to policy-induced changes in energy use
- ψ: estimate of energy availability and extraction costs from McGlade and Ekins (2015b) (future global extreaction cost curves for coal, oil, and natural gas) using $\ln p_{E,t} = \ln A_{V,t}^{-1} + \psi \ln(\bar{E}_{-1} + \sum_{\hat{t}=0}^{\hat{t}-1} E_{\hat{t}}) \longrightarrow \ln cost_m = b_0 + b_1 \ln(16.5 + D_m)$, got $\hat{\psi} = 1.26$

(a)



Extraction Cost Curve

(b)



Estimating ψ

Energy sector calibration

- BGP relationship $\ln(1 - g_{A_V}) = \ln(1 + g_P^*) - \psi ln(1 + g_E^*)$. With an estimate of ψ $\longrightarrow g_{A_v} = -0.16$ over ten years. (technological progress in the energy extraction sector is significantly slower than technological progress in final good production)
- $A_{V,0}$ is a scale parameter and calibrated to the starting price $A_{V,0} = p_{E,0}/\bar{E}_{-1}^{\psi}$

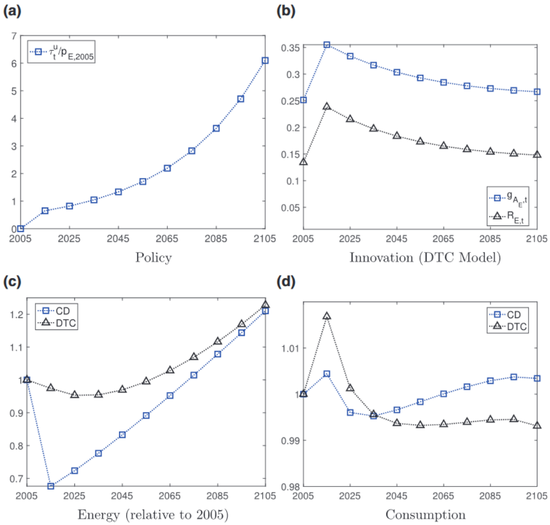
Background information

- investigate the impacts of environmental policy
- economy is on LFBGP in 2005 and policies or exogenous shocks begin to affect the economy in 2015
- environmental target based on Paris Agreement: U.S. aims to reduce carbon emissions to 80% below 1990 levles by 2050 $\longrightarrow$ final-use energy must fall over the next several decades (Williams et al. 2014), even if almost all electricity is generated from renewable sources by 2050
- construct a target for cumulative energy use between 2015 and 2114: cumulative energy use over the 10 periods from 2015 to 2105 $E_{target} = 9.3 * E_{2005}$; along the LFBGP: cumulative energy use: over 14 times greater than E_{2005}

Compare CD to DTC model: Summary

- build an alternative model that uses CD production function
- calibrate the CD model so that output, energy use ,energy prices and the energy intensity of output match the DTC model along the LFBGP (the two models have the same growth rates for all macroeconomic variables)
- find the path of per-unit energy taxes that implements the least-cost path to achieve the energy use target in the CD model
- examine the impact of the same taxes in the DTC model
- i.e. a thought experiment: "Suppose policy is designed with models that employ the usual Cobb-Douglas assumption, but reality actually follows the DTC model. How close will the economy come to meeting the policy goals?"

Result

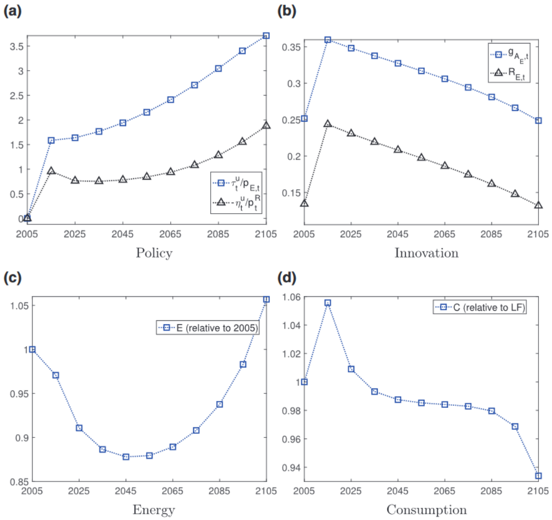


(a)
$\tau_t^u/p_{E,2005}$
Policy
(b)
$g_{A_E,t}$
$R_{E,t}$
Innovation (DTC Model)
(c)
CD
DTC
Energy (relative to 2005)
(d)
CD
DTC
Consumption

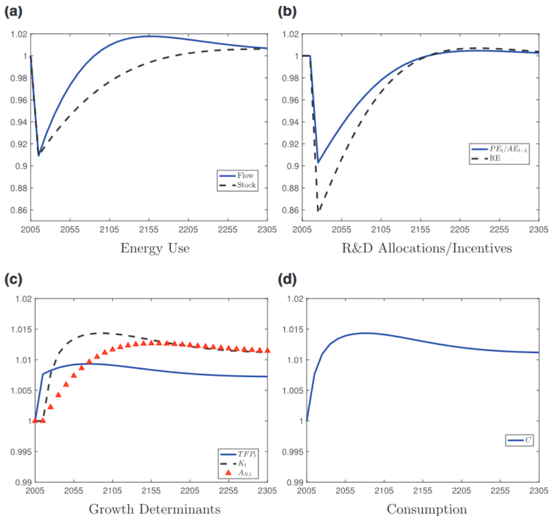
Implication

- take into account the low SR elasticity of substitution between energy and non-energy inputs; otherwise, overestimate the reduction in cumulative energy use generated by a given path of taxes
- ignoring slow transition dynamics: cause policymakers to underestimate both the initial spike and subsequent fall in the consumption
- (robust to alternative parameter values)

Least-cost path in the DTC model: different roles of energy taxes and R&D subsidies / taxes



Rebound:cost-less technology shock (one-time, unexpected shock causes $A_{E,2015}$ to be 10% higher



Round: a permanent 40% subsidy to energy efficiency R&D

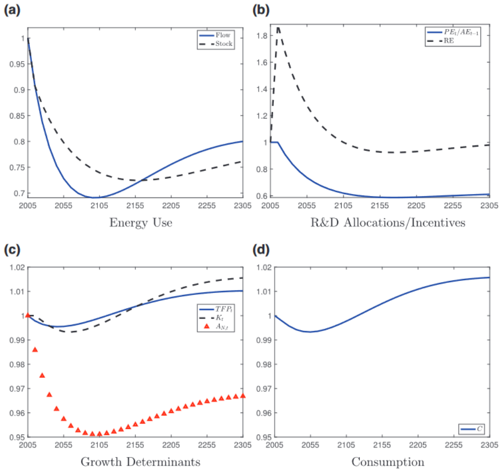


FIGURE 10

The end!