Online Supplementary Materials

Energy R&D Investments and Emissions Abatement Policy

Appendix 1 Endogenous Variables

U_t	utility in period t
c_t	per capita consumption of goods and services (constant 2005 USD per person)
Q_t	total net output (trillions of constant 2005 USD)
$Q_{i,t}$	net output in capital sector *i* (trillions of constant 2005 USD)
Ω_t	damage function (climate damages as a fraction of world output)
Λ_t	abatement cost function (abatement costs as a fraction of world output)
μ_t	emissions-control rate (fraction of uncontrolled emissions)
K_t	total physical capital stock (trillions of constant 2005 USD)
$K_{i,t}$	physical capital stock in sector *i* (trillions of constant 2005 USD)
I_t	investments in physical capital (trillions of constant 2005 USD)
$ES_{i,t}$	energy service used in sector *i*
$ER_{i,t}$	raw energy used in sector *i*
$P_{i,t}$	oil products used in sector *i*
$W_{i,t}$	coal products used in sector *i*
$G_{i,t}$	natural gas used in sector *i*
$B_{i,t}$	backstop energy used in sector *i*
$CE_{i,t}$	energy cost in sector *i*
$z_{i,B,t}$	energy cost of backstop energy in sector *i*
b	the scale factor of the energy cost of backstop energy
$R_{E,t}$	R&D investments in energy efficiency
$R_{B,t}$	R&D investments in backstop technology
$H_{E,t}$	knowledge stock on energy efficiency
$H_{B,t}$	knowledge stock on backstop technology
EM_t	total carbon emissions
E_t	energy-related carbon emissions

$M_{A,t}$	atmospheric CO2 concentration
$M_{U,t}$	upper oceans/biosphere CO2 concentration
$M_{L,t}$	lower oceans CO2 concentration
F_t	radioactive forcing, increase over the preindustrial level
T_t	atmospheric temperature, increase over 1900 level
TL_t	lower ocean temperature, increase over 1900 level

Appendix 2 Exogenous Variables and Parameters

t	time period	30
i	1=capital-goods production sector, 2=consumption-goods production sector	1,2
r	pure rate of social time preference (per year)	0.015
α	the elasticity of marginal utility of consumption (pure number)	1.45
L_0	the initial population level	7403
$L_{1.0}$	2015 initial labor percentage in the capital-goods sector	0.126
$L_{2.0}$	2015 initial labor percentage in the consumption-goods sector	0.874
$g_{L,t}$	growth rate to calibrate to 2050 pop projection	0.13449
L_{max}	asymptotic population	11500
Y_0	initial world gross output	105.5
$Y_{1,0}$	initial world gross output in the capital-goods sector	21.1
$Y_{2,0}$	initial world gross output in the consumption-goods sector	84.4
K_0	initial capital value 2015	223
$K_{1,0}$	initial capital value in capital-goods sector 2015	50
$K_{2,0}$	initial capital value in consumption-goods sector 2015	173
$A_{1,0}$	initial level of TFP in the capital-goods sector	
$A_{2,0}$	initial level of TFP in the consumption-goods sector	
$g_{A,0}$	initial growth rate of total factor productivity per five years	0.076
d_A	the rate of decline of the growth rate of total factor productivity	0.005
β_i	Capital elasticity in output function of sector i	0.2828/0.3258
γ_i	Energy elasticity in output function of sector i	0.0784/0.0806
$a_1 a_2$	parameters of damage function	0/0.00266

$H_{m,0}$	initial knowledge stock in energy efficiency/ backstop technology	0.001/1
$R_{m,0}$	initial R&D investments in energy efficiency/ backstop technology	0.00453/0.00429
$\varphi_{E,n}$	parameters of energy stock in energy efficiency, n=1,2,3	0.00213/0.20/0.55
$\varphi_{B,n}$	parameters of energy stock in backstop technology, n=1,2,3	0.00429/0.005/0.1
α_H	scale parameter	0.336
ρ	substitution parameter for raw energy and knowledge	0.38
δ_K	the rate of depreciation of physical capital (per period)	0.1
δ_H	the rate of depreciation of knowledge stock (per period)	0
$S_{J,0}$	proved reserve of fossil fuel J in 2005 (J=P, W, G, namely, oil, coal, and gas)	9496.2/28750.8/7039.8
$z_{1,J,t}$	energy cost of fossil fuel j used in the capital-goods sector (J=P, W, G, namely, oil, coal, and gas)	0.004647/0.013985/0.004375
$z_{2,J,t}$	energy cost of fossil fuel j used in the consumption-goods sector (J=P, W, G, namely, oil, coal, and gas)	0.020225/0.029204/0.011776
$z_{i,B,0}$	the initial cost of backstop energy in sector i, i=1,2	0.125808/0.138488
η_J	CO2-energy coefficient of fossil fuel j (J=P, W, G, namely, oil, coal, and gas)	0.0211/0.0289/0.0153
LU_0	initial land-use carbon emissions	2.6
δ_{LU}	the rate of decline of land-use carbon emissions	0.115
$M_{n,0}$	initial concentration in atmosphere/upper strata/lower strata 2015 (GtC), n=A, U, L	851/1540/10010
$M_{n,eq}$	equilibrium concentration in atmosphere/upper strata/lower strata 2015 (GtC), n=A, U, L	588/1350/10000
$\phi_{33}\phi_2$	Carbon cycle transition matrix	0.08800/0.00250
σ_n	temperature dynamics parameters, n=1.2,3,4	0.104/1.564/0.088/0.025

Appendix 3 Equation List

(A.1) $\max V = \sum_{t=1}^{T} U_t(c_t, L_t) R_t$

(A.2) $U_t(c_t, L_t) = L_t \frac{c_t^{1-\alpha}}{1-\alpha}$

(A.3) $Y_t = Y_{1,t} + Y_{2,t}$

(A.4) $Y_{i,t} = \Omega_t A_{i,t} K_{i,t}^{\beta_i} ES_{i,t}^{\gamma_i} L_{i,t}^{1-\beta_i-\gamma_i} - CE_{i,t}, i = 1,2$

(A.5) $\Omega_t = 1/(1 + a_1 T_t + a_2 T_t^2)$

(A.6) $L_t = L_0 \exp(g_{L,t})$

(A.7) $g_{L,t} = \left(\frac{g_{L,0}}{d_L}\right) * (1 - \exp(-d_L * t))$

(A.8) $L_t = L_{1,t} + L_{2,t}$

(A.9) $A_{i,t} = A_{i,0} \exp(g_{A,t})$

(A.10) $g_{A,t} = \left(\frac{g_{A,0}}{d_A}\right) * (1 - \exp(-d_A * t))$

(A.11) $K_t = I_t + (1 - \delta_K) K_{t-1}$

(A.12) $K_t = K_{1,t} + K_{2,t}$

(A.13) $ES_{i,t} = (\alpha_H H_{E,t}^{\rho} + ER_{i,t}^{\rho})^{1/\rho}, i = 1,2$

(A.14) $ES_{i,t} = P_{i,t} + W_{i,t} + G_{i,t} + B_{i,t}, i = 1,2$

(A.15) $S_{J,0} \geq \sum_{t=1}^{T} (J_{1,t} + J_{2,t}), J = P, W, G$

(A.16) $CE_{i,t} = z_{i,P,t} P_{i,t} + z_{i,W,t} W_{i,t} + z_{i,G,t} G_{i,t} + z_{i,B,t} B_{i,t}, i = 1,2$

(A.17) $z_{i,B,t} = z_{i,B,0} B_{i,t}^{zb1} H_{B,t}^{zb2}$

(A.18) $H_{m,t} = (1 - \delta_H) H_{m,t-1} + \varphi_{m,1} H_{m,t-1}^{\varphi_{m,2}} R_{m,t}^{\varphi_{m,3}}, m = E, B$

(A.19) $Y_{1,t} = I_t + R_{E,t} + R_{B,t}$

(A.20) $Y_{2,t} = C_t$

(A.21) $EM_t = E_t + LU_0 (1 - \delta_{LU})^t$

(A.22) $E_t = \sum_{J=P,W,G} \eta_J (J_{1,t} + J_{2,t})$

(A.23) $M_{A,t} = 5 * EM_t + \phi_{33} M_{A,t-1} + \phi_{23} M_{U,t-1}$

(A.24) $M_{U,t} = \phi_{32} M_{A,t-1} + \phi_{22} M_{U,t-1} + \phi_{12} M_{L,t-1}$

(A.25) $M_{L,t} = \phi_{11} M_{L,t-1} + \phi_{21} M_{U,t-1}$

(A.26) $F_t = 4.1[log_2(M_{A,t}/M_{A,1750})] + F_{EX,t}$

(A.27) $T_t = T_{t-1} + \sigma_1 [F_t - \sigma_2 T_{t-1} - \sigma_3 (T_{t-1} - TL_{t-1})]$

(A.28) $TL_t = TL_{t-1} + \sigma_4 (T_{t-1} - TL_{t-1})$