Green fiscal consolidation and the optimal spending-tax mix

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Motivation

- Green transition demands major public/private investment, raising deficits.
  - Public green investment needs additional $\sim$ 0.5 - 1% GDP per year until 2030 (Bruegel - Darvas et al 2023).
  - EC: Public role critical for decarbonization, private sector support, and equity and ESG; 2031–2050 energy investment $>$ 3%GDP per year, around 1.5 pp above past average (Delbeke, 2024).
- In the EU currently:
  - Public debt to GDP quite high; new Fiscal Rules put in place to keep deficits on track
  - Green Deal and the Fit for 55 targets (GHG emission reduction by 55% relative to 2001 by 2030- ambitious?)
  - Public environmental investment quite low $\sim$ 1% of GDP
  - Public spending on defence on the rise (EC escape clause)
  - "Greenflation" from transition risks.

What this paper does

1. Evaluates the macroeconomic and environmental implications of public debt consolidation in the presence of climate externalities
2. Integrates carbon taxes and public green/dirty investment into a fiscal rule framework, using a climate New Keynesian DSGE model
3. Computes (constrained) optimized feedback coefficients of those fiscal rules
4. Compares and ranks various policy mixes to achieve both consolidation and "green transition" .

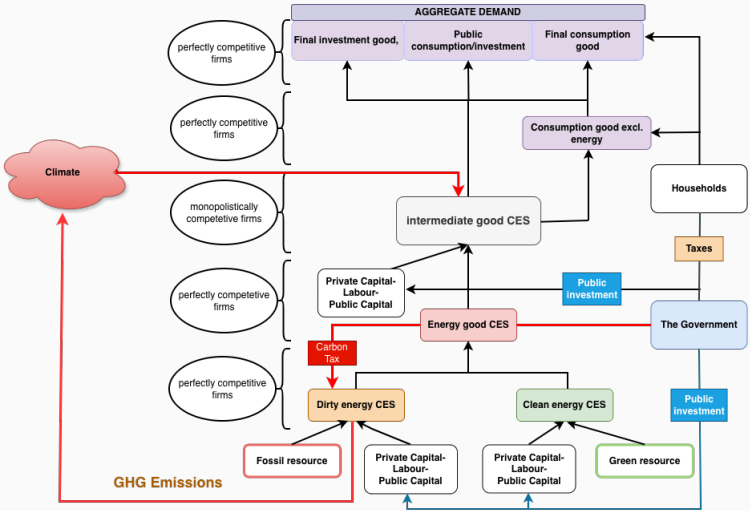
Preview of main results

1. Reducing public debt raises long-run output and welfare under every instrument pair — but the **spending–tax mix** and **climate externalities** shape the transition and the sectoral outcomes
2. **Without** climate externalities: raising the *capital income tax* alongside government-consumption cuts is welfare-dominant — both in the long run and along the transition (predetermined capital $\Rightarrow$ near lump-sum, Chamley–Judd)
3. **With** climate externalities: the *carbon tax* paired with government-consumption cuts dominates at longer horizons (**double dividend**: consolidation + cumulative TFP recovery)
4. The carbon tax pair is the *only* one that shifts the energy mix (dirty $\downarrow$, clean $\uparrow$)
5. **Robustness**: a Ramsey planner confirms carbon taxation as a consolidation tool — raising it even *without* externalities on purely fiscal grounds (taxing the fixed fossil rent), and to its upper bound once damages are internalized

Literature

- **DSGE-based studies on macro impacts of energy/carbon transition**: Economides and Xepapadeas (2025), Coenen et al. (2024), Bartocci et al. (2024), Airaudo et al. (2023), Ernst et al. (2022), Varga et al. (2021), Priftis et al. (2025) and earlier work Annicchiarico and Di Dio (2015).
- **Optimal carbon taxation and climate-economy or pollution models**: Golosov et al. (2014), Barrage (2020), Economides and Philippopoulos (2008) and Angelopoulos et al. (2010), Bovenberg and Goulder (1996).
- **Methodologically related to DSGE studies on fiscal consolidation and fiscal rules**: Leeper (1995, 2016), Bi and Kumhof (2011), Erceg and Linde (2013) (ad hoc policy), and Philippopoulos et al. (2015, 2017), , Cantore et al. (2019), and Sakkas and Varthalitis (2021).
- **Most closely related**: Seghini and Dees (2025),study fiscal limits of green transition — we instead pursue the green transition *and* debt consolidation jointly, in an implementable fashion.

Schematic representation of the model



▸ model equations ▸ households ▸ energy

Climate Damages and Output Elasticity

- Damage-adjusted productivity in intermediate goods production:

$$\hat{A}_t = [\exp(-\psi \Lambda \Omega_t)]\, A_t$$

  - A_t: baseline productivity
  - Exponential damage function wrt emissions multiplicative to the production function
  - For $\psi > 0$: damage elasticity—measures sensitivity to climate impacts
  - For $\psi = 0 \rightarrow \hat{A}_t = A_t$
  - Captures losses from weather disasters, infrastructure damage, and TFP declines
  - Each intermediate firm does not internalize, when making its decisions, the aforementioned detrimental effect, hence it takes the environmental externality as given.
  - As cumulative emissions grow, output is increasingly suppressed via climate-related productivity losses.

Emissions and Climate Dynamics

Climate module follows: van der Ploeg and Rezai (2021,JEEM); Economides and Xepapadeas (2025,RED)

- **Temperature anomaly**: $T_t - T_0 = \Lambda \Omega_t$
  - T_t: global average temperature at time t
  - T_0: pre-industrial baseline
  - Λ: transient climate response to cumulative emissions (TCRE); a constant number that implies a roughly linear relationship between a change in global average temperature and cumulative emissions. more details...
- **"Global" Cumulative CO_2 emissions at t:** $\Omega_t = (1 - \delta^e)\Omega_{t-1} + M_{f,t}^{domestic} + M_t^{ROW}$
  - δ^e: carbon depreciation rate (natural absorption)
  - $M_{f,t}^{domestic} = \varpi E_{f,t}$: by-product of dirty energy (carbon intensity ϖ)

Fiscal Policy Structure

Government budget constraint:

$$P_t^G G_t^c + P_t^G G_t^I + T_t + R_{t-1} B_{t-1} = B_t + \tau_t^D P_{f,t}^E E_t^f + \tau_t^C P_t^C C_t + \tau_t^N w_t L_t + \tau_t^K R_t^k K_t$$

Revenues:

- Taxes on capital ($\tau_t^K = 15\%$), labor ($\tau_t^N = 28\%$), consumption ($\tau_t^C = 18\%$)
- Carbon tax on dirty energy production ($\tau_t^D = 31\% \equiv 84.7$ euro$/tCO_2$)
- Bond issuance (one-period maturity)

Expenditures (output shares):

- Government consumption ($g_t^c = 15\%$)
- Public investment ($g_t^I = g_{m,t}^I + g_{f,t}^I + g_{g,t}^I = 5\%$) in intermediate, clean, and dirty sectors
- Interest payments on public debt

Fiscal Rules

- Debt-contingent rules: Fiscal instruments can react to deviations in public debt-to-GDP ratio:

$$\underbrace{\phi_t - \phi_0}_{\text{taxes/expenditures change}} = \underbrace{\gamma_\phi}_{\text{feedback coefficient}} \times \underbrace{(debt_{t-1} - debt^*)}_{\text{Public debt to gdp imbalances}}$$

- $\gamma_\phi > 0$ for taxes, $\gamma_\phi < 0$ for spending; $\phi = \{\tau^D, \tau^K, \tau^N, \tau^C, g^C, g^I_{gr}, g^I_f\}$

Quantitative analysis steps

1. **Calibration**: EU-15 data; 2021–2024 (IEA, Eurostat–COFOG, EUKLEMS) ▸ calibration

2. **Set the long-run targets.** Permanently cut public debt 90% → 75%; the freed fiscal space is absorbed by a *single* adjusting instrument ▸ SS impacts. We pick, *ad hoc*, the public green-investment ($\sim \uparrow 0.5\%$ of GDP) economy (robustness: ramsey planner chooses optimally long-run targets)

3. **Transition to that target**: debt is run down to 75% by cutting g^c and letting *one* tax react to the debt gap — **four pairwise mixes**:

#	Consolidation scenario	Instruments reacting to debt
1	Carbon tax pair	g^c & τ^D
2	Labor income tax pair	g^c & τ^N
3	Capital income tax pair	g^c & τ^K
4	Consumption tax pair	g^c & τ^C

4. Per pair, compute **constrained optimized** feedback coefficients maximizing conditional welfare (2nd order) - subject to a set of *implementability* restrictions (Schmitt-Grohé and Uribe, 2007) to mimic *realistic* plans.

5. Compare damage regimes: $\psi = 0$ vs $\psi = 0.066$

Further restrictions on the feedback coefficients space in the transition

- The resulting values of feedback will be "restricted" so that the **levels** of taxes and spending in the transition should be in accordance with the table below:

Instrument / horizon	**Restriction**
Income and consumption tax rates	$\in [0, 1]$
Spending ratios	($\sim$ 1pp of GDP; see Alesina, Favero, Giavazzi (2019))
Carbon tax	$\leq 3\times$ the current EU Net ECR (IEA near-term)
Non-energy / green public investment	feedback fixed at 0: restriction imposed by EU Medium Term Fiscal Plan
Consolidation horizon	28 quarters (7 years), as in the EU Medium Term Fiscal Plan

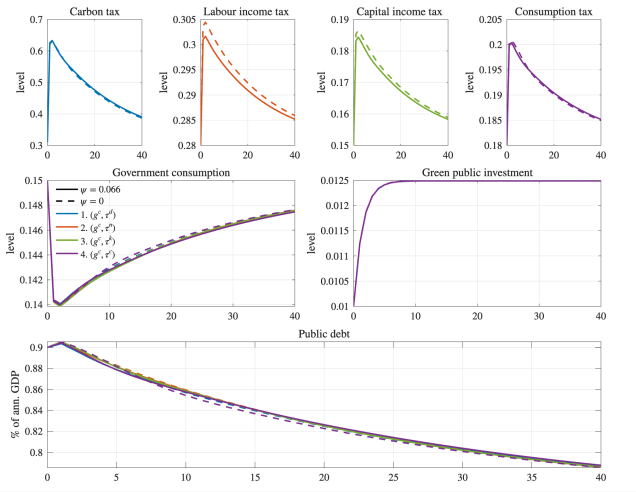
- Bounds reflect observed consolidation magnitudes; growth-enhancing (non-energy and green) spending is protected under the revised EU framework

Quantitative analysis: Optimized fiscal policy in the transition, γ_q

Consolidation pair	γ_{g^c} $[\psi = 0/\psi > 0]$	γ_τ $[\psi = 0/\psi > 0]$
1. (g^c, τ^D) – carbon tax	$-0.016/-0.016$	0.526 / 0.543
2. (g^c, τ^C) – consumption tax	$-0.016/-0.016$	0.035 / 0.034
3. (g^c, τ^N) – labor tax	$-0.016/-0.016$	0.039 / 0.035
4. (g^c, τ^K) – capital tax	$-0.016/-0.016$	0.059 / 0.056

▸ quant/steps

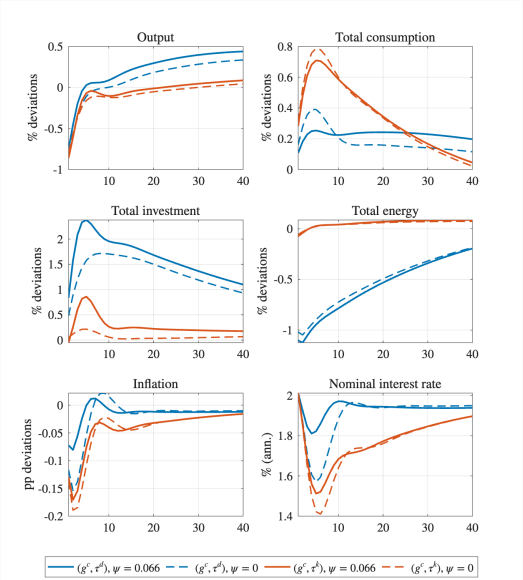
Fiscal instruments under optimized policy



- All pairs use the **maximum allowed public consumption cuts** ($\gamma_{g^c} = -0.016$), complemented by one tax
- The carbon tax pair $1.(g^c, \tau^D)$ more than doubles the carbon tax (0.31 to 0.65) on impact: **85** $\rightarrow$ **173 €/tCO$_2$** (within the IEA 2050 range of 230)

▸ quant/steps

Aggregate dynamics and transmission mechanism



- **Direct effect:** government consumption cuts lower aggregate demand and inflation; the Taylor rule cuts the nominal rate, crowding in investment.
- **Investment channel:**
  - (g^c, τ^D): carbon tax leaves the after-tax return to capital unchanged, so rate relief is capitalised into investment.
  - (g^c, τ^K): capital tax raises the cost of capital, attenuating crowding-in.
- **TFP-recovery channel** only if $\psi > 0$: carbon tax suppresses dirty energy, slows carbon-stock accumulation, and attenuates productivity losses over time.

Welfare ranking across consolidation pairs

CEV (%)	1.(g^c, τ^D)	2, (g^c, τ^N)	3.(g^c, τ^K)	4.(g^c, τ^C)
Panel A: $\psi = 0$				
$T = 8$	0.844	0.819	**1.283**	0.223
$T = 20$	0.561	0.590	**0.913**	0.064
$T = 80$	0.221	0.143	**0.261**	0.144
Panel B: $\psi = 0.066$				
$T = 8$	0.743	0.858	**1.247**	−0.105
$T = 20$	0.603	0.646	**0.916**	−0.047
$T = 80$	**0.303**	0.187	0.272	0.130

Consumption-equivalent welfare; T in quarters.

- **Without damages** ($\psi = 0$): the capital tax pair, 3.(g^c, τ^K), wins at every horizon (predetermined capital $\Rightarrow$ partly lump-sum, Chamley–Judd)
- **With damages** ($\psi = 0.066$): ranking **reverses** long-run — by 80q the carbon tax pair, 1.(g^c, τ^D), leads (0.303 vs 0.272), via TFP recovery
- The consumption tax pair 4.(g^c, τ^C) turns to short-run welfare *losses* under $\psi > 0$ — no environmental channel to offset the damage drag

Macroeconomic and sectoral transition

	quarter	1.(g^c, τ^D)	2.(g^c, τ^N)	3.(g^c, τ^K)	4.(g^c, τ^C)
Output Y	8	$-0.01/0.06$	$-0.64/-0.53$	$-0.11/-0.08$	$0.04/0.14$
	40	$0.34/0.44$	$-0.05/0.02$	$0.04/0.09$	$0.63/0.68$
Dirty E_f	8	$-1.22/-1.31$	$-0.11/-0.10$	$0.02/0.02$	$-0.03/-0.03$
	40	$-0.40/-0.44$	$-0.02/-0.01$	$0.02/0.02$	$0.10/0.12$
Clean E_{gr}	8	$0.23/0.26$	$-0.07/-0.06$	$0.08/0.09$	$0.03/0.03$
	40	$0.31/0.36$	$0.15/0.18$	$0.20/0.23$	$0.30/0.34$

Each cell: ψ=0 / ψ=0.066; % dev. from the initial high-debt steady state.

- **Output:** the consumption tax pair delivers the strongest short-run output gains, the labor tax pair the largest cost; climate damages ($\psi > 0$) lift output slightly via TFP recovery
- **Energy mix:** only the carbon tax pair (g^c, τ^D) meaningfully contracts dirty and expands clean energy — more so under $\psi > 0$

Consolidation by a Ramsey planner

Long-run tax levels & macro outcomes

	Pre-consol. (90%)	Post-consol. (75%)	
tax levels		$\psi = 0$	$\psi = 0.066$
τ^D	0.31	0.41	2.99
τ^K	0.15	0.144	0.092
τ^C	0.18	0.171	0.137
vars.			
Y	—	0.55	**3.72**
E_f	—	−0.49	−11.94
E_{gr}	—	0.20	2.57
CEV	—	0.22	**2.37**

(% deviations)

- Ramsey benchmark: planner chooses optimally τ^D, τ^K, τ^C for the public debt to GDP of 75%.
- Ramsey planner confirms the transition rankings are not driven by the ad-hoc steady-state target, and shows how far an unconstrained planner pushes each instrument.
- Even at $\psi = 0$, the carbon tax rises ($0.31 \rightarrow 0.41$) on *purely fiscal* grounds — it taxes the fixed fossil rent, lowering the **Marginal Cost of Public Funds** vs capital/consumption taxes.

Consolidation by a Ramsey planner (transition)

Feedback coefficients γ

	$\psi = 0$	$\psi = 0.066$
γ_{g^c}	-0.016	-0.016
$\gamma_{g_f^I}$	-0.015	-0.015
γ_{τ^D}	0	0.801
γ_{τ^C}	0.006	0
γ_{τ^N}	0	0
γ_{τ^K}	0	0

- Debt reduction is carried by **spending cuts** (g^c, g_f^I);
- Under $\psi > 0$, the **carbon tax feedback turns on** ($\gamma_{\tau^D} = 0.801$) and its level reaches the bound ($\sim$ 820 €/tCO$_2$) — main results reconfirmed.

Variable	Quarter	$\psi = 0$	$\psi = 0.066$
Y	$T = 8$	0.21	3.13
	$T = 20$	0.61	4.45
	$T = 80$	0.88	6.86
E_f	$T = 8$	-0.55	-10.88
	$T = 20$	-0.55	-11.29
	$T = 80$	-0.47	-11.09
E_{gr}	$T = 8$	0.13	2.23
	$T = 20$	0.24	2.56
	$T = 80$	0.31	3.14
CEV	$T = 8$	1.469	0.661
	$T = 20$	1.276	0.698
	$T = 80$	0.596	1.700

Further sensitivity

- **Climate damages:** a lower elasticity $\psi = 0.026$ (4% vs 9% productivity loss) gives milder magnitudes but the same qualitative ranking; robust to Λ, δ_e
- **CES elasticities** (ϵ_c, ϵ_m): higher substitutability strengthens the dirty-to-clean shift under the carbon tax; main result unchanged
- **Consolidation horizon:** tighter/looser time constraints leave the welfare ranking and energy-mix implications unchanged

To explore:

- Fiscal rules reacting to climate anomalies ("fiscal damage functions" - Barrage, 2024)
- Household heterogeneity (HANK) or firm heterogeneity — distributional incidence of carbon taxation

Concluding remarks

- Public debt reduction delivers long-run output and welfare gains regardless of the instrument pair — but the **policy mix and climate externalities** shape short-run and sectoral outcomes
- **Without damages**, the capital income tax pair is welfare-dominant; **with damages**, the carbon tax pair dominates at long horizons through cumulative TFP recovery
- The carbon tax is the only instrument that jointly consolidates debt and drives the dirty-to-clean energy shift; paired with green public investment it is welfare-improving and supports the green transition
- A Ramsey planner confirms these results — and raises the carbon tax even absent externalities, on purely fiscal grounds

APPENDIX A: MODEL BLOCKS AND EQUATIONS

model overview

The model: Households

Households consume a basket of energy and non-energy goods, work in each of the three sectors, and can save in short-term government bonds (We assume perfect labor mobility across sectors)

$$V_t = E_0 \sum_{i=0}^{\infty} \beta^t \left[\frac{\left(C_{t+i} - hC_{t+i-1} + \theta G^C_{t+i} \right)^{1-\sigma} - 1}{1-\sigma} - \frac{\chi}{1+\varphi} L^{1+\varphi}_{t+i} + \frac{\left(1 + \alpha_d (\Lambda \Omega_t)^2)\right)^{-(1-\sigma)} - 1}{1-\sigma} \right] \tag{1}$$

where

$$C_t = \left[\omega_e^{\frac{1}{\varepsilon_e}} \left(E^C_t \right)^{\frac{\varepsilon_e - 1}{\varepsilon_e}} + (1-\omega_e)^{\frac{1}{\varepsilon_e}} \left(C^X_t \right)^{\frac{\varepsilon_e - 1}{\varepsilon_e}} \right]^{\frac{\varepsilon_e}{\varepsilon_e - 1}}$$

HBC:

$$(1+\tau^c_t) P^C_t C_t + B_t = (1-\tau^n_t)\, w_t L_t + D_t + R_{t-1} B^b_{t-1} + T_t \tag{2}$$

▸ model overview

The model: Production

Intermediate Goods Producers use a CES of value added and energy:

$$Y_{m,t} = \hat{A}_t \left[(\omega_m)^{\frac{1}{\epsilon_m}} (KL_{m,t})^{\frac{\epsilon_m - 1}{\epsilon_m}} + (1 - \omega_m)^{\frac{1}{\epsilon_m}} \left(E_t^Y\right)^{\frac{\epsilon_m - 1}{\epsilon_m}} \right]^{\frac{\epsilon_m}{\epsilon_m - 1}} \tag{3}$$

Value added: Cobb douglas in 3 inputs:

$$KL_{m,t} = (K_{m,t})^{\alpha_{1,m}} (L_{m,t})^{1-\alpha_{1,m}} \left(K_{m,t}^{pub}\right)^{\alpha_{2,m}} \tag{4}$$

▸ model overview

Profits and pricing

- Intermediate good producers operate within a monopolistically competitive market and maximize profits,
- prices are in a staggered manner with backward-looking indexation.

$$\mathbb{E}_t \sum_{j=0}^{\infty} \psi_m^j \Lambda_{t,t+j} \left[p_{m,t}^* - \xi_m P_{m,t+j} \right] Y_{m,t+j} = 0 \tag{5}$$

where $\xi_m = \frac{\epsilon_m}{\epsilon_m - 1}$ is the markup and $\Lambda_{t,t+j}$ represents the stochastic discount factor. The relation for the evolution of the core price level excluding energy is

$$P_{m,t} = \left[(1 - \psi_m) \left(p_{m,t}^* \right)^{1-\xi_m} + \psi_m (P_{m,t-1})^{1-\xi_m} \right]^{\frac{1}{1-\xi_m}} \tag{6}$$

Energy sector

- Energy in the production process uses natural resources with fixed endowments of fossils-based and clean energy
- Fossil-based energy with dual impact:
  - employs capital, labour and public inputs
  - Positively contributes to output (productive input)
  - Produces emissions and negatively contributes to output
- Clean energy:
  - employs capital, labour and public inputs
  - substitutes fossil based energy and implicitly redudes emissions

▸ model blocks

Energy Aggregation and Pricing

Energy production: CES aggregation of clean ($E_{gr,t}$) and dirty ($E_{f,t}$) energy (imperfect substitutes):

$$E_t = \left[\omega_c^{\frac{1}{\epsilon_c}} E_{gr,t}^{\frac{\epsilon_c - 1}{\epsilon_c}} + (1 - \omega_c)^{\frac{1}{\epsilon_c}} E_{f,t}^{\frac{\epsilon_c - 1}{\epsilon_c}} \right]^{\frac{\epsilon_c}{\epsilon_c - 1}}$$

Letting $P_{gr,t}$ and $P_{f,t}$ be the price of clean and dirty energy, respectively, the price of energy is given by

$$P_t^E = \left[\omega_c \left(P_{gr,t}^E \right)^{1-\epsilon_c} + (1 - \omega_c) \left((1 + \tau_t^D) P_{f,t}^E \right)^{1-\epsilon_c} \right]^{\frac{1}{1-\epsilon_c}}$$

price of dirty energy used in production is also subject to a surcharge, $\tau_t^D > 0$ (subsidy, if negative). model overview

Clean vs. Dirty Energy Production

CES production:

$$E_{f,t} = \left[\omega_f^{\frac{1}{\epsilon_f}} KL_{f,t}^{\frac{\epsilon_f - 1}{\epsilon_f}} + (1-\omega_f)^{\frac{1}{\epsilon_f}} \mathcal{F}_t^{\frac{\epsilon_f - 1}{\epsilon_f}} \right]^{\frac{\epsilon_f}{\epsilon_f - 1}}, \quad E_{gr,t} = \left[\omega_g^{\frac{1}{\epsilon_g}} KL_{gr,t}^{\frac{\epsilon_g - 1}{\epsilon_g}} + (1-\omega_g)^{\frac{1}{\epsilon_g}} \mathcal{GR}_t^{\frac{\epsilon_g - 1}{\epsilon_g}} \right]^{\frac{\epsilon_g}{\epsilon_g - 1}}$$

Value-added structure:

$$KL_{f,t} = K_{f,t}^{\alpha_{1,f}} L_{f,t}^{1-\alpha_{1,f}} (K_{f,t}^{pub})^{\alpha_{2,f}}, \quad KL_{gr,t} = K_{gr,t}^{\alpha_{1,g}} L_{g,t}^{1-\alpha_{1,g}} (K_{gr,t}^{pub})^{\alpha_{2,g}}$$

Fossil and green resource demands:

$$\mathcal{F}_t = (1-\omega_f) E_{f,t} \left(\frac{P_{\mathcal{F},t}}{P_{f,t}^E} \right)^{-\epsilon_f}, \quad \mathcal{GR}_t = (1-\omega_g) E_{gr,t} \left(\frac{P_{\mathcal{GR},t}}{P_{g,t}^E} \right)^{-\epsilon_g}$$

Capital goods producers

- Capital production takes place under perfect competition
- New capital is being sold to firms in sector $s \in \{m, f, g\}$ at the price $Q_{s,t}$.
- Producers choose investment, $I_{s,t}$, to maximize profits.

$$\max E_t \sum_{\tau=t}^{\infty} \Lambda_{t,\tau} \left(1 - \tau_t^k\right) \left\{ Q_{s,\tau} - \left[1 + f\left(\frac{I_{s,\tau}}{I_{s,\tau-1}}\right)\right] I_{s,\tau} \right\}$$

- The price of capital goods is equal to the marginal cost of investment goods production:

$$Q_{s,t} = 1 + f\left(\frac{I_{s,t}}{I_{s,t-1}}\right) + \frac{I_{s,t}}{I_{s,t-1}} f'\left(\frac{I_{s,t}}{I_{s,t-1}}\right) - E_t \Lambda_{t,t+1} \left(\frac{I_{s,t+1}}{I_{s,t}}\right)^2 f'\left(\frac{I_{s,t+1}}{I_{s,t}}\right)$$

- At the end of period t, each firm is left with a capital stock $(1 - \delta_s)K_{s,t}$. It then buys $I_{s,t}$ units of new capital from capital producers, so its capital stock in period $t + 1$ is given by:

$$K_{s,t+1} = (1 - \delta_s)K_{s,t} + I_{s,t}$$

Public Capital and Investment Shares

Aggregate public capital:

$$K_t^{pub} = K_{m,t}^{pub} + K_{f,t}^{pub} + K_{gr,t}^{pub}$$

Accumulation equation:

$$K_t^{pub} = (1 - \delta_g)K_{t-1}^{pub} + G_t^I$$

Public spending and investment shares

$$G_t^c = g_t^c Y_t, \quad G_t^I = g_t^I Y_t$$

$$G_t^I = G_{m,t}^I + G_{f,t}^I + G_{gr,t}^I, \quad G_{s,t}^I = g_{s,t}^I Y_t$$

Monetary authority

Taylor-type rule targeting variations in core inflation (i.e., inflation excluding energy) and output relative to their steady state levels:

$$\frac{i_t}{i_{t-1}} = \left(\frac{i_t}{i_{t-1}}\right)^{\kappa_i} \left[\left(\frac{\pi_{m,t}}{\pi_m}\right)^{\kappa_\pi} \left(\frac{Y_t}{\bar{Y}}\right)^{\kappa_y}\right]^{1-\kappa_i}$$

where $\kappa_i > 0$, $\kappa_\pi > 1$, $\kappa_y > 0$

APPENDIX B: CALIBRATION

Calibration: Climate Module — Key Parameters

- **Damage function** (ψ=0.06)
  - Links temperature anomaly ($T_t - T_0$) to long-run GDP losses ($\sim$ 8%).
  - Literature (2100, no-policy): $\sim$ 2–3% (Nordhaus, 2014; Tol, 2014; Weitzman, 2012) vs. $\sim$ 22–44% (Burke; Dietz & Stern; Bilal & Känzig, 2024;).
  - Implied range: $\psi \in [0.0025, 0.13]$.
  - **Calibration used:** $\psi = 0.0662$ (mean; Economides & Xepapadeas, 2025).
- **Transient climate response to cumulative emissions** (Λ)
  - Temperature increase per TtC emitted.
  - Baseline: $\Lambda = 1.65^{\circ}\mathrm{C}/\mathrm{TtC}$ (Economides & Xepapadeas; IPCC 2021).
  - Range: 1 to $2.5^{\circ}\mathrm{C}/\mathrm{TtC}$.
- **Carbon cycle & emissions**
  - Carbon depreciation rate: $\delta_e = 0.07$.
- **Note**: ψ choice not the paper's focus; selected as a representative mid-range value capturing moderate to severe scenarios.

▸ quant/steps

Climate block: CCR/TCRE (vs. DICE/Golosov)

- **DICE**: three-reservoir carbon cycle; radiative forcing from atmospheric concentration relative to pre-industrial, plus exogenous forcing.
- **Golosov et al. (2014)**: map (i) concentration $\rightarrow$ temperature, then (ii) temperature $\rightarrow$ damages; damages effectively exponential in Δ atmospheric concentration.
- **This approach: Carbon–Climate Response (CCR).**
  - Link *cumulative* CO_2 emissions $CE(t)$ directly to global mean temperature:

$$\Delta T(t) \sim \Lambda \cdot CE(t), \qquad \Lambda = \text{TCRE}.$$

  - TCRE Λ is approximately constant over a wide range; "each ton of CO_2 adds about the same warming."
  - Analytical + model results (e.g. MacDougall and Friedlingstein, 2015) explain constancy of Λ over large $CE(t)$ domains.
  - IPCC, multiple lines of evidence (observations, models) support a near-linear and robust relation between cumulative CO_2 and *peak* global mean temperature, robust up to $\sim$2000 PgC of total CO_2 emissions

▸ climate module

Calibration: Energy Structure and Elasticities

Energy targets:

- Energy share in consumption, $\frac{P^E E^C}{P^c C} = 5\%$
- Energy share in production of intermediates, $\frac{P^E E^Y}{Y_m} = 5\%$
- Fossil resource share in dirty energy $\frac{P_f FOS}{P_f^E E_f} = 71\%$
- Green resource share in dirty energy $\frac{P_{gr} GR}{P_{gr}^E E_g r} = 70\%$

Substitution elasticities:

- Between energy and non-energy goods: $\epsilon^c = 0.4$
- Between energy and value-added (all sectors): $\epsilon_m = \epsilon^f = \epsilon^g = 0.4$
- Between clean and dirty energy: $\epsilon^e = 1.8$
- $\epsilon^e > 1$ implies imperfect substitutes (Acemoglu et al. 2012)

Calibration: Taxation and public investment shares

Implicit tax rates (Eurostat average 2021–2024):

- Consumption tax, τ^C: 18%
- Labor income tax, τ^N: 30%
- Capital income tax, τ^K: 15%

Carbon taxation:

- Carbon rate, τ^D: €84.7 per tonne CO_2 (OECD, 2021)
- Fiscal revenue from carbon-related sources: 1.83% of GDP

Public investment shares (total: 3.5% of GDP):

- Green investment, g^I_{gr}: 1.0%
- Dirty investment, g^I_f: 1.0%
- Non-energy investment, g^I_m: 3%

▸ experiments

Other Calibration Elements

Green investment classification:

- Based on Eurostat COFOG, IEA, Batini et al. (2022)
- Broader scope includes emissions mitigation + nature-based solutions

Remaining parameters:

- Household preferences and non-energy sector values drawn from standard macro literature

Steady-State impacts (decrease from public debt $90\% \rightarrow 75\%$)

Panel A: $\psi = 0$				
Resid. instr.	Y	E_{gr}	E_f	CEV
1. τ^C:	0.12	0.03	0.02	0.05
2. τ^K:	0.65	0.13	0.10	0.24
3. τ^N:	0.23	0.06	0.05	0.10
4. g_m^I:	0.47	0.06	0.05	-0.02
5. g_{gr}^I:	0.18	0.27	0.00	-0.31
6. g^c:	0.17	0.01	0.01	-0.40

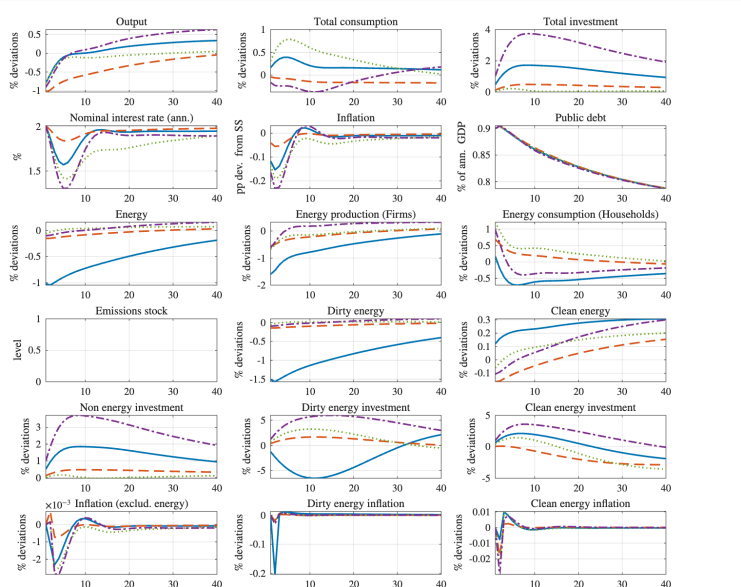
CEV: welfare gains/loss in consumption equivalents.

Panel B: $\psi = 0.066$				
Resid. instr.	Y	E_{gr}	E_f	CEV
1. τ^C:	0.12	0.03	0.03	0.04
2. τ^K:	0.62	0.13	0.11	0.18
3. τ^N:	0.20	0.05	0.04	0.06
4. g_m^I:	0.47	0.07	0.05	-0.05
5. g_{gr}^I:	0.18	0.29	0.00	-0.33
6. g^c:	0.17	0.01	0.01	-0.43

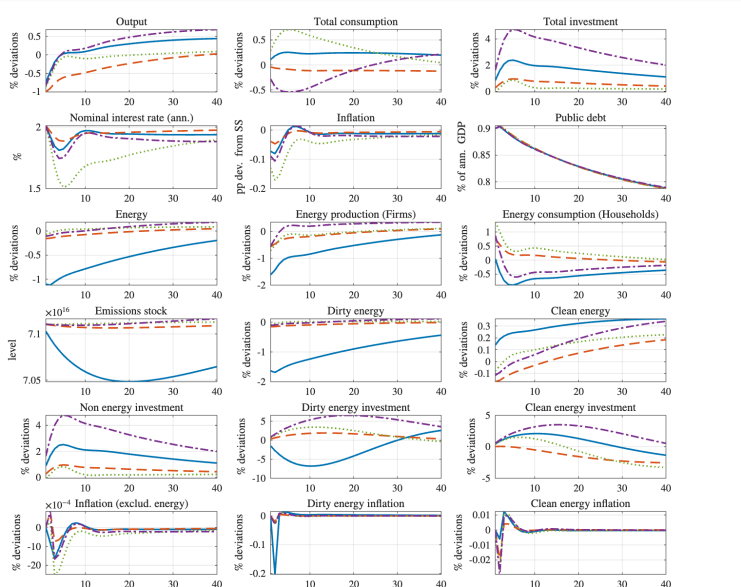
CEV: welfare gains/loss in consumption equivalents.

- When the residual fiscal space is used for increased long-run public green investment (5) we get modest output gains with the lowest environmental damage and stronger green transition. We choose this economy as the targeted steady-state so as to be in accordance with the EU Green Deal objectives.
- When the residual fiscal space is used capital taxes (2) (highest output gains and welfare but higher environmental damage) ▸ quant/steps

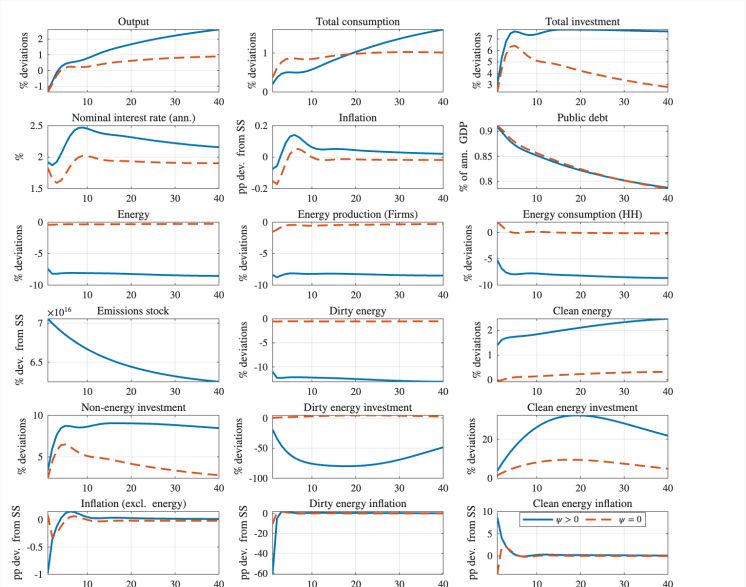
Impulse response functions ($\psi = 0$)



Impulse response functions ($\psi = 0.066$)



Impulse response functions (Ramsey)



Notes...

A note on EU fiscal governance...

Old rules:

- EU Fiscal Framework - a long story: Maastricht Treaty, Stability and Growth Pact, Treaty on Stability, Coordination and Governance in the Economic and Monetary Union - 3% ceiling for fiscal deficits and the 60% long-term target for the debt ratio

New rules:

- if $\frac{public\ \ debt}{gdp} < 60\%$: $\frac{g_t - g_{t-1}}{g_t} \leq \frac{gdp_t - gdg_{t-1}}{gdp_t}$
- if $\frac{public\ \ debt}{gdp} > 60\%$: $\frac{g_t - g_{t-1}}{g_t} \leq \frac{gdp_t - gdg_{t-1}}{gdp_t} - \omega_t$ where:

$$\omega_t \equiv \frac{policy\ \ target - \frac{primary\ \ def}{gdp_{t-1}}}{\frac{g_{t-1}}{gdp_{t-1}}}$$

policy target value for the structural primary balance, where the latter is supposed to be consistent with "debt ratios on a plausibly downward path based on DSA"+additional safeguards

▸ rules equations

A note on EU fiscal governance...

Old rules:

- Adjustment period to reach target: 20 years!
- Freedom on which fiscal items (spending-taxes) could be raised/cut.

New rules:

- Adjustment period: 4-7 years, pre-planned and pre-approved through Medium-Term-Fiscal Plans
- MS can extend their fiscal adjustment plans from 4 to up to 7 years if the EC approves an investment-and-reform package that: boosts growth, is consistent with debt sustainability, advances EU priorities (e.g., Green Deal, digitalisation, security), keeps national investment at least constant. The reformed rules do not grant a broad national-level exemption for public investment.
- Caveat: Spending that helps meet climate goals but doesn't always boost growth can't be used to justify extending the adjustment period. With no broad exemptions, any increase in green or digital outlays must be offset by cuts or savings elsewhere to stay within the rules.