Chapter 25: Sustainability

Graduate Macroeconomics Slides

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January 23, 2026

Outline

Motivation and Context

Key Issue: Climate Change as a Macroeconomic Challenge

- Climate change is global: *aggregate* CO_2 emissions matter.
- Fossil fuels remain central to energy use ($\sim$ 5% of global GDP devoted to energy).
- Sharp reductions in energy use may cause large macroeconomic fluctuations (e.g., the 1970s oil-price shocks).
- Policymaking challenge: evaluating long-run policies with limited direct evidence.

Objective: Develop simple *macroeconomic* tools to assess climate policy impacts on the climate and on welfare.

What is Sustainability?

- **Broad concern**: Do humans — now and in the future — have enough resources for survival and well-being?
- **Focus**: Natural resources, climate, and how they intersect with economic growth.
- **Policy questions**:
  - How to manage finite natural resources?
  - Should we aim for *de-growth* to protect the environment?
  - Key trade-offs between preserving nature vs. promoting economic activity.
- This chapter: begin to address these questions using macro models and insights from public/environmental economics.

The Economy in a Broader Natural Context

- **Environment** in micro theory: preferences, technology, etc.
- Here: environment = *nature*.
- Movements to preserve the environment (especially in advanced economies).

Conceptual framework :

- The economy (*households*, *firms*, *government*) interacts with *land mass*, *finite resources*, *climate*, *water*, *biodiversity*, *solar energy*.
- Different degrees of property rights:
  - Land typically has stronger property rights.
  - Atmosphere/climate is a global public good $\rightarrow$ very limited property rights.

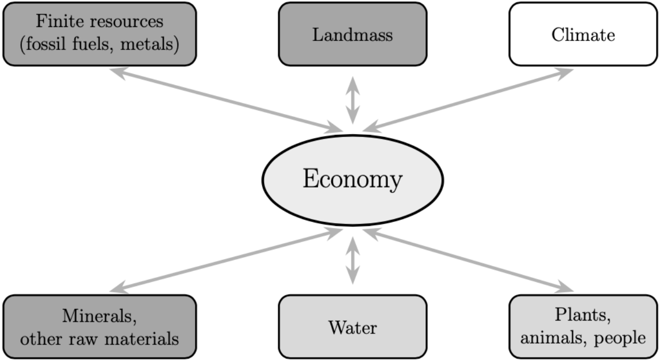

Figure 25.1: The economy and the environment. Darker shades of grey reflect a higher degree of property rights.

Integrated Assessment Models (IAMs)

- **IAM**: Integrates economy, carbon cycle, and climate module.
  1. *Economy*: Usually a growth model with fossil-fuel energy use $\rightarrow \mathrm{CO}_2$ emissions.
  2. *Carbon Cycle*: The pathway of CO_2 among atmosphere, land, and oceans.
  3. *Climate Module*: Models warming from CO_2 in the atmosphere, capturing greenhouse effects.
- **Damages**: Higher temperature $\rightarrow$ climate-related damages (storms, sea-level rise, etc.) $\rightarrow$ reduces economic output/utility.
- **Policy**: Negligible private cost to emit $\Rightarrow$ negative externality. Proper *carbon pricing* or other policy recommended.

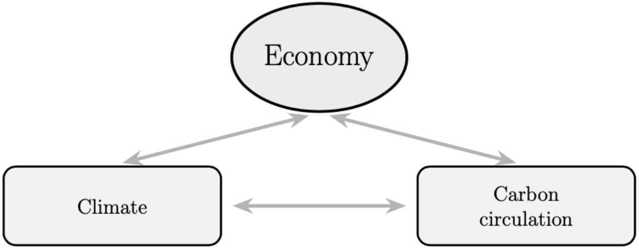

Figure 25.2: Integrated Assessment Models, IAMs, consist of three building blocks: an economy, a representation of the carbon cycle, and a climate module.

Greenhouse Effect: A Primer

Energy balance approach:

- Earth receives *solar radiation*, reflects some energy, emits heat.
- $\mathrm{CO_2}$ *does not* affect incoming solar radiation but *does* impede outgoing heat radiation.
- $\mathrm{CO_2}$ in atmosphere acts like a greenhouse: traps heat.
- Without the natural greenhouse effect, Earth would be $-20^\circ\mathrm{C}$; currently $\sim 15^\circ\mathrm{C}$.

Basic model:

$$\frac{dT(t)}{dt} = \sigma_1\Big(f(t) \; - \; \kappa \, T(t)\Big),$$

where T is temperature deviation, f is *forcing*, and κ includes feedback effects (e.g., ice albedo).

Logarithmic Forcing of CO_2

- **Arrhenius greenhouse law**: forcing from CO_2 is proportional to $\ln(S/S_0)$.

$$f_{\mathrm{CO}_2} = \eta \ln\left(\frac{S}{S_0}\right) / \ln(2),$$

  where S_0 is pre-industrial CO_2 concentration.
- η/κ is the *equilibrium climate sensitivity* (ECS): expected long-run ΔT from doubling CO_2.
  - IPCC likely range: 2.5$^\circ\mathrm{C}$–4$^\circ\mathrm{C}$, with best estimate $\sim 3^\circ\mathrm{C}$.
- Ocean heat absorption slows warming: multi-box energy-balance models often used (two-layer system for atmosphere/oceans).

Carbon Cycle

- **Three main reservoirs**:
  1. Atmosphere
  2. Surface ocean & biosphere
  3. Deep oceans
- $\mathrm{CO_2}$ is emitted into atmosphere (E_t) and circulates among these reservoirs.
- Example (Nordhaus RICE model):

$$
\begin{aligned}
S_t - S_{t-1} &= \phi_{12} S_{t-1} + \phi_{21} S^U_{t-1} + E_{t-1}, \\
S^U_t - S^U_{t-1} &= \phi_{12} S_{t-1} - (\phi_{21} + \phi_{23}) S^U_{t-1} + \phi_{32} S^L_{t-1}, \\
S^L_t - S^L_{t-1} &= \phi_{23} S^U_{t-1} + \phi_{32} S^L_{t-1}.
\end{aligned}
$$

- **Key property**: A portion of $\mathrm{CO_2}$ stays in atmosphere *for centuries* or longer.

Constant Carbon-Climate Response

- **Empirical finding**: ΔT is approximately **linear** in **cumulative** emissions.

$$T_t \approx \sigma_{\mathrm{CCR}} \sum_{s=0}^{t} E_s, \qquad \text{(carbon-climate response CCR)}$$

- **Implications**:
  - *Irreversibility* in warming: temperature remains elevated even if emissions go to zero.
  - *Carbon budget*: a desired temperature target implies a maximum total CO_2 that can be emitted.
  - Many emission paths can yield the same cumulative total, but differ in economic welfare outcomes.
- IPCC 6th report: TCRE range $1.0^\circ\mathrm{C}$–$2.3^\circ\mathrm{C}$ per 1000 GtC (roughly 0.27–0.63 $^\circ\mathrm{C}$ per $TtCO_2$).

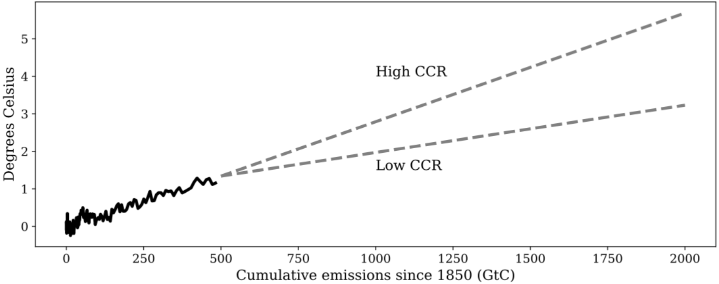

Figure 25.3: Cumulative carbon emissions and the global mean temperature. Solid line: historical data 1850-2022. Dashed lines: forecasts based on constant CCR.

Fossil Energy Supply

- **Proven reserves** vs. **resources**:
  - *Reserves*: can be extracted profitably with current technology/prices.
  - *Resources*: total amount in discovered+undiscovered deposits, not necessarily profitable now.
- Example (Oil):
  - OPEC holds $\sim 80\%$ of world crude reserves.
  - Unconventional vs. conventional oil: unconventional has much higher extraction cost.
- **Reserve sizes** (in GtC or $GtCO_2$):
  - Coal reserves: $\sim$ 2,759 $GtCO_2$ (BP, 2021).
  - Oil reserves (OPEC): $\sim$ 500 $GtCO_2$.

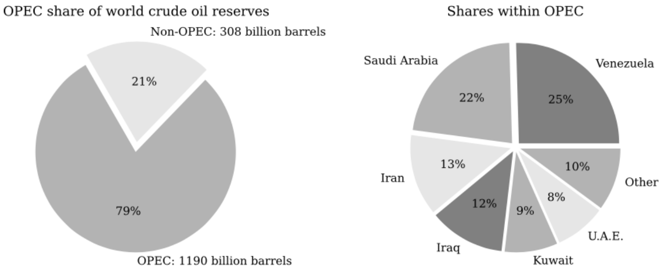

Figure 25.4: Oil Supply.

Source: OPEC (2019).

Table 25.1: Reserves and resources in GtC

	Reserves	Resources (Rogner)	Resources (BGR)
Oil (conv+unconv)	173	$\approx 400 - 2,200$	≈500
Coal	1,074	≈6,200	≈11,500
Gas	100	≈350	≈365

Sources: Rogner (1997), BGR (2020). BGR is the Federal Institute for Geosciences.

Figure: (Rogner, 1997), (BGR, 2020)

Damages

- **Economic perspective**: climate damages are negative externalities from emissions.
- **Valuation approaches**:
  1. Bottom-up: sum costs (agricultural losses, health impacts, sea-level rise, extreme events, etc.).
  2. Top-down: relate changes in output (GDP) or mortality to temperature changes (cross-section or panel).
- **Examples**:
  - **Stern Review** (2007): large estimated damage costs, motivating aggressive policy.
  - **Nordhaus DICE**: more modest damage estimates, $\sim$ 2.4% of GDP lost at +3°C.
- **Adaptation** offsets some damages (e.g., building sea walls, adopting new crop varieties).
- **Discounting debate**: market discount rates vs. ethical considerations for future generations.

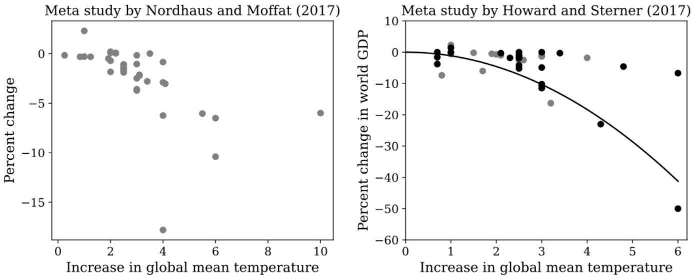

Figure 25.5: Meta studies of damages. Left: study by Nordhaus and Moffat (2017). Right: study by Howard and Sterner (2017) with black dots showing non-duplicate studies and the regression line preferred by those authors.

Figure: (Nordhaus and Moffat, 2017)

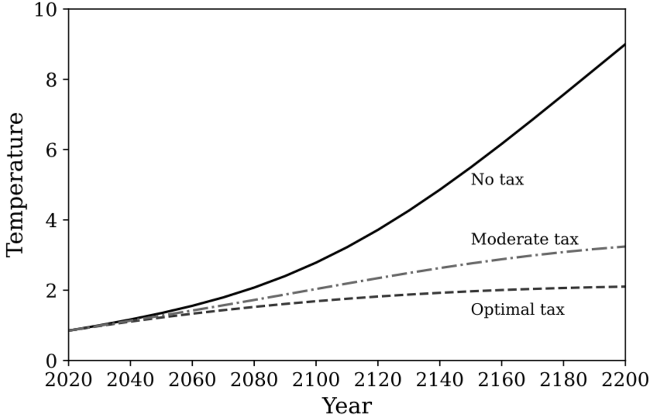

Figure 25.6: The effect on the global temperature of different carbon taxes.

Notes: The optimal tax is set to U.S. \$25 per ton CO_2 and the moderate tax is U.S. \$8 per ton CO_2.

Figure: (Howard and Sterner, 2017)

A Simple Static IAM

- **Sectors**:
    1. Final goods: uses capital, labor, and *energy services* in production.
    2. Energy services: produced from coal with cost p per unit.
- **Production:** $Y = A\,K^{\alpha} L^{1-\alpha-\nu} E^{\nu}$. In a simplified form, set $K = L = 1$, so $Y = AE^{\nu}$.
- **Damages:** $D(E) = \gamma E^2$.
- $\Rightarrow$ *Consumption*: $C = AE^{\nu} - pE - \gamma E^2$.

Social Planner vs. Market Outcome

Market economy (private firm) solves:

$$\max_{E} \; AE^{\nu} - (p + \tau)\, E.$$

First-order condition: $\nu A E^{\nu-1} = p + \tau$.
Social planner internalizes damages:

$$\max_{E} \; AE^{\nu} - pE - \gamma E^{2}.$$

First-order condition: $\nu A E^{\nu-1} = p + 2\gamma E$.

- **Pigouvian Tax**: $\tau^{\star} = 2\gamma E^{\star}$.
- **Interpretation**: tax each unit of emissions by the *marginal damage* it imposes on society.

Prices vs. Quantities (Regulation)

- **Cap-and-trade (quantity restriction)**:
  - Government issues emissions permits up to $\overline{E}$.
  - Market price of a permit: λ.
  - If $\overline{E} = E^*$ (socially optimal), then $\lambda = 2\gamma E^*$.
  - Price-based vs. quantity-based policy $\Rightarrow$ *equivalent* in deterministic framework (Weitzman, 1974, with caveats).
- **Firm heterogeneity**:
  - A single aggregate emissions limit $\overline{E}$ still leads to cost-effective allocation if permits are tradable.

A Two-Region Model Setup

- **Regions**:
  1. *Oil producer*: has finite stock R_t.
  2. *Oil consumer*: invests in capital, uses labor, can import oil or use alternative energy.
- **Preferences**:

$$\sum_{t=0}^{\infty} \beta^t \ln(C_t).$$

- **Production function** (oil-consuming region):

$$Y_t = e^{z_t - \gamma S_t} K_t^{\alpha} L_t^{1-\alpha-\nu} E_t^{\nu}.$$

  - Damages: factor productivity is $\exp(-\gamma S_t)$.
  - S_t evolves with the **carbon cycle** plus emissions from oil/coal use.

Energy Aggregation and Resource Constraint

Three energy sources: oil (o), coal (c), green (g).

$$E_t = \left[\lambda_o \, e_{o,t}^{\rho} + \lambda_c \, e_{c,t}^{\rho} + \lambda_g \, e_{g,t}^{\rho}\right]^{1/\rho}.$$

Oil producer: stock R_t, evolves via

$$R_{t+1} = R_t - e_{o,t}, \quad R_0 = \overline{R}.$$

Market clearing in energy: price of oil $p_{o,t}$ determined by *equalizing supply/demand* each period, with no storage.
Household invests in capital and consumes:

$$C_t + K_{t+1} = Y_t - (p_{o,t} e_{o,t} + p_c e_{c,t} + p_g e_{g,t}).$$

Government, Emissions, and Policy

- **Carbon tax** τ_t on fossil use:

$$\tau_t(e_{o,t} + e_{c,t}) \quad \text{with proceeds rebated to consumers.}$$

- **Emissions**:

$$M_t = e_{o,t} + e_{c,t} \quad \text{(in carbon units).}$$

- **Carbon cycle**:

$$S_{t+1} = S_t + (1 - \delta)M_t + \dots \quad \text{(e.g., see linear approximation or multi-box models).}$$

- **Dynamic** problem typically solved *numerically*, but with special functional forms (Cobb-Douglas in production, log utility), an almost closed-form solution emerges.

Marginal Damage and the Pigou Principle

- With $\ln(C)$ utility and exponential damage $\exp(-\gamma S)$:

$$\tau_t = \Big(\text{Marginal Damage}\Big) = Y_t \left[\gamma \sum_{j=0}^{\infty} \beta^j (1 - d_j)\right].$$

- $\tau_t \uparrow$ with:
  - higher γ (damage),
  - slower carbon decay $(1 - d_j)$,
  - lower discount rate β.
- **Key takeaway:** The optimal carbon tax depends on:
  1. The magnitude of damages (γ),
  2. The longevity of CO_2 in atmosphere,
  3. The social discount factor.

Simulation Example

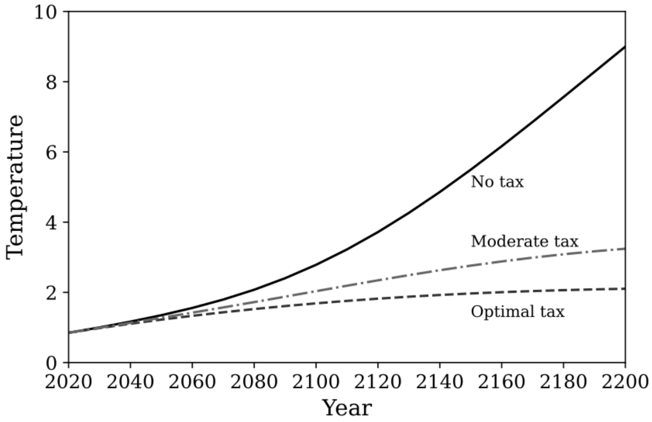

Figure 25.6: The effect on the global temperature of different carbon taxes.

Notes: The optimal tax is set to U.S. \$25 per ton CO_2 and the moderate tax is U.S. \$8 per ton CO_2

Simulation Example cont'd

- **Calibration** (following (Golosov et al., 2014)):
  - Period = 10 years, $\alpha = 0.3$, $\nu = 0.05$, $\beta = (0.985)^{10}$, damage parameter γ from Nordhaus.
  - Initial oil stock, initial atmospheric carbon S_0, etc.
- **Policy scenarios**:
  1. $\tau = 0$ (laissez-faire).
  2. $\tau = \tau^\star$ (optimal).
  3. $\tau = \frac{1}{3}\tau^\star$ (moderate).
- **Result**:
  - No policy: temperature could rise by 9°C by 2200.
  - Optimal $\tau \approx \$25$/ton CO_2: limit warming to $\approx 2^\circ$C.
  - Even moderate tax significantly reduces warming from the no-policy path.

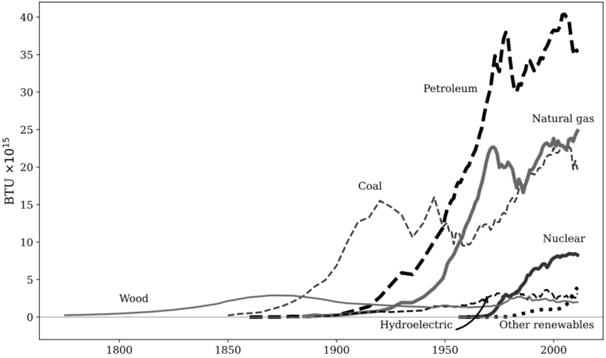

Figure 25.7: U.S. energy consumption.

Source:Administration (2012).

Figure: (Administration, 2012)

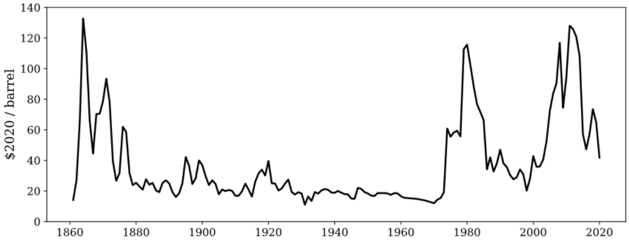

Figure 25.8: Crude oil price.

Source: BP (2021).

Figure: (BP, 2021)

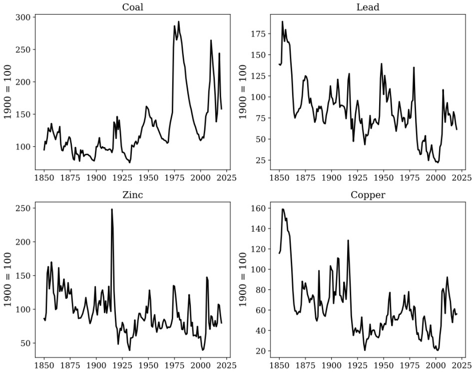

Figure 25.9: Inflation-adjusted prices for natural resources.

Source: Jacks (2019).

Figure: (Jacks, 2019)

Empirical Patterns

- **Energy use** (U.S., world):
  - Rapid increase in fossil fuel consumption historically.
  - Per capita oil use peaked in some regions (1970s).
- **Resource prices**: famously volatile (oil, metals, etc.), but no strong deterministic trend (some argue mild upward trend for oil post-WWII).
- **Challenge**: Basic Hotelling analysis would suggest a rising price path if the resource is scarce and extraction cost is constant, yet data show large volatility.

Hotelling's Rule

- **Cake-eating model** (no extraction cost):

$$\max \sum_{t=0}^{\infty} \beta^t \ln(c_t), \quad \text{s.t.} \quad \sum_{t=0}^{\infty} c_t = R_0.$$

  Solution: $c_t = (1 - \beta)\beta^t R_0$.

- **Market equilibrium**: The resource price in present-value terms must be constant over time if there is no cost of extraction.

$$p_{t+1} = (1 + r)\, p_t, \quad \text{with } r = \frac{\beta}{1 - \beta} \text{ or so, depending on the setup.}$$

- **Extraction cost or partial equilibrium**: if cost mc_t changes with time, it modifies the Hotelling relation: $p_t - \mathrm{mc}_t$ must grow at interest rate r.

Resource Use in a Growth Model

- **Dasgupta-Heal model**:

$$\max \sum_{t=0}^{\infty} \beta^t \ln(c_t), \quad c_t + k_{t+1} = A\, k_t^{\alpha} e_t^{\nu}, \quad \sum e_t = R_0.$$

- **Cobb-Douglas results**:
  - $e_t = (1-\beta)\beta^t R_0$: resource depletion path (similar to cake-eating).
  - If A grows over time, or if capital accumulates, net output grows even with finite resource.
  - Resource price grows at rate r.
- **Key policy insight**: with well-defined property rights, the competitive outcome can be *efficient* (no externality if no other side effects).

Short-Run vs. Long-Run Substitution

- **Empirical observation**: in the short run, capital and energy may be near complements (low elasticity). Over the long run, technologies adapt (higher elasticity).
- **Leontief example**:

$$Y_t = \min\{A\, k_t^{\alpha},\ e_t\}.$$

  - If resource is abundant early, e_t can grow with capital.
  - Eventually resource constraints bind $\rightarrow$ e_t must fall.
- **CES approach**:

$$Y_t = \left[\theta(K_t^{\alpha} L_t^{1-\alpha})^{\frac{\epsilon-1}{\epsilon}} + (1-\theta)(A_e e_t)^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}.$$

  - ϵ¡1 for strong complementarity, ϵ=1 for Cobb-Douglas, etc.

Endogenous, Directed Technical Change

- **Evidence**:
  - Historically, high fossil fuel prices triggered *energy-saving* innovations.
  - Post-1970s: energy use per capita declined in some countries, but *energy efficiency* soared.
- **Modeling approach**:
  - Romer/Aghion-Howitt style R&D framework with multiple sectors: capital-labor augmenting vs. energy-augmenting technologies.
  - R&D resources shift toward the most profitable type of innovation.
- **Implication**: Over the long run, the effective substitutability is higher due to *directed* R&D: more energy-saving innovations if fossil fuels are scarce/expensive.

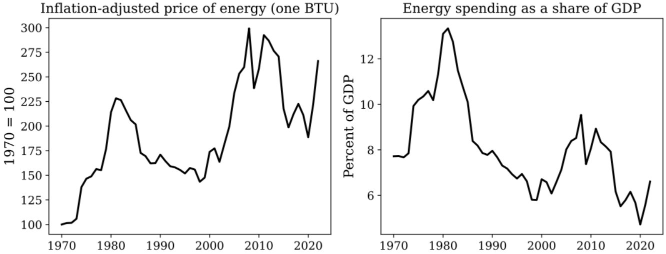

Figure 25.10: The price of fossil energy and its cost share.

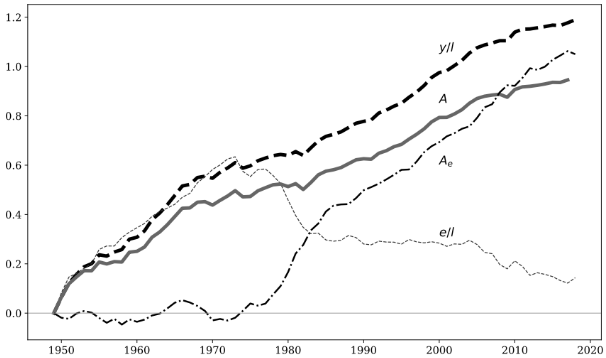

Figure 25.11: U.S. output, energy consumption and technological progress

Concluding Observations on Finite Resources

- **Market-based management**: With well-defined property rights, resource owners have incentive to optimize extraction over time (Hotelling logic).
- **No externality here means no direct policy needed** beyond typical market function.
- **Reality check**:
  - Costs of extraction vary, new discoveries occur, large price volatility is observed.
  - Directed technical change can ease scarcity constraints, enabling continued growth.
- **Bottom line**: Resource scarcity alone need not halt growth. But *environmental externalities* (like climate change) require policy.

Chapter Summary

- **Climate change and sustainability** are key macroeconomic issues.
- **IAMs** integrate a *growth model* with *carbon cycle* & *climate module* to study:
  - How emissions affect warming.
  - How warming impacts economic outcomes (damages).
  - Optimal policy design (e.g., carbon tax).
- **Key lessons**:
  1. A **Pigouvian carbon tax** can substantially reduce temperature rise with small short-run economic cost.
  2. Fossil fuels are large but finite: *Hotelling's rule* helps conceptualize resource depletion and price paths.
  3. **Energy-saving technical change** can mitigate scarcity and reduce damage from resource constraints.
- **Open questions**: discounting policy for future generations, uncertain climate feedbacks, catastrophic risks, distributional impacts, political economy of global agreements.

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Thank you!

Questions or comments?

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