1

Introduction

1.1 Capital-embodiment of technologies

Majority of technologies are capital-embodied

- Especially true of energy technologies
  - Gas turbines, distillation columns, solar panels, wind turbines, LED bulbs, batteries, …

Transition to low carbon requires

- R&D to develop new and improve existing low-C technologies
- Investments to adopt these technologies

1.2 Why model capital-embodiment?

Adoption of new technologies requires investments

- Increasing the pace of adoption is increasingly costly

User cost of capital increases with the innovation rate

- Return on real assets must cover:
  - Required return on equity
  - Physical depreciation
  - Expected change in asset price
- TC causes *declining* asset prices ⇔ obsolescence costs
  - => If rates of TC varies between sectors or over time, so should rates of economic depreciation

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Model

2.1 Original framework

Acemoglu, Aghion, Burzstyn & Hémous (AABH), 2012 in AER

- Two production sectors: clean & dirty

$$Y_{j,t} = L_{j,i,t}^{1-\alpha} \int_0^1 A_{j,i,t}^{1-\alpha} x_{j,i,t}^{\alpha} \, di, \quad j \in \{c,d\}$$

- Composite good used for final & intermediate consumption

$$Y_t = \left(Y_{c,t}^{(\varepsilon-1)/\varepsilon} + Y_{d,t}^{(\varepsilon-1)/\varepsilon} \right)^{\varepsilon/(\varepsilon-1)}, \quad \varepsilon > 1$$

- Dirty output -> emissions -> climate -> damages
- Representative household composed of workers and scientists
  - Maximises intertemporal utility function
  - Workers can work in clean or dirty production
  - Scientists can work on clean or dirty technologies
- Monopolistic production of intermediates
  - Successful scientists become one-period monopolists
  - Production uses only the final good

2.2 Capital-embodied technologies

Production uses capital services instead of intermediate inputs

- Clean and dirty production functions become:

$$Y_{j,t} = L_{j,i,t}^{1-\alpha} \int_0^1 k_{j,i,t}^{\alpha} di \quad j \in \{c,d\}$$

- Technical change becomes “investment specific” (Krusell, 1998):

$$k_{j,i,t} = (1-\delta) k_{j,i,t-1} + A_{j,i,t} z_{j,i,t}$$

- New capital produced by monopolists using only the final good

$$p_{j,i,t} = \left(p_{j,i,t}^{K} A_{j,i,t} - 1\right) z_{j,i,t}$$

- Monopolists rent capital to producers at constant mark-up over user costs

$$r_{j,i,t} = \frac{1}{\alpha} \left[\frac{1}{A_{j,i,t}} - \frac{(1-\delta)}{(1+i_t)} \frac{1}{A_{j,i,t+1}} \right]$$

2.3 Embodiment and obsolescence costs

Rental rate per unit of effective capital of type (*j,i*)

$$r_{j,i,t} \equiv \left(\delta + i_t + g_{j,i,t}\right) \big/ \left(\alpha A_{j,i,t}\right), \quad g_{j,i,t} \equiv A_{j,i,t+1} \big/ A_{j,i,t} - 1$$

- $1/A_{j,i,t}$ cost per unit of effective capital
- $1/\alpha$ monopolists' mark-up over investment costs
- $g_{j,i,t}$ growth rate of technology

Response of clean to dirty output ratio to a step change in $g_{c,t}$

$$\frac{Y_{c,t}}{Y_{d,t}} \equiv \left(1 + \tau_t\right)^{\varepsilon} \left(\frac{i_t + \delta + g_{c,t}}{i_t + \delta + g_{d,t}}\right)^{-\alpha\varepsilon} \left(\frac{A_{c,t}}{A_{d,t}}\right)^{\alpha\varepsilon}$$

- *Decreases* with increase in $g_{c,t}$ — once-off short-run effect
- *Increases* with growth of $A_{c,t}$ — dominant long run effect

2.4 Research and development

Research and development firms

- One R&D firm per capital good. Hires scientists to improve technology building on previous sector-average technology
- Knowledge frontier as in AABH: $A_{j,i,t} = \left(1 + h_j s_{j,i,t}\right) A_{j,t-1}$

Symmetry

- Deterministic progress implies symmetry of firms within each sector:
- Complete spillovers and deterministic progress unrealistic, but convenient
  - Concerned with productivity differences between not within sectors.

Spillovers

- Knowledge spillovers *between* sectors empirically significant *but not* primarily between clean and dirty energy technologies
- => Assume spillovers from an exogenously growing technology frontier

$$A_{j,t} = \left(1 + h_j f\left(\frac{A_{t-1}^{exogenous} - A_{j,t-1}}{A_{t-1}^{exogenous}}\right)^{j} s_{j,t}\right) A_{j,t-1}$$

2.6

Decentralised R&D decisions

Scientists are the sole input to R&D

- Fixed supply of scientists, equally capable of working on any technology

Profit-maximising allocation of scientists

- R&D firms seek to maximise their profits
  - Capture PV of investment in their technology in the current period
  - Do *not* capture future value because of inter-temporal spillovers
- Profits depend only on level of raw investment not on the level of output as in AABH: $p_{j,t} = z_{j,t}\left(s_{j,t}\right)\left(1 - a\right)/a$

Hiring more scientists in sector *j* improves *j* technologies

- Increases demand for *effective* capital $k_{j,t}$ and hence $A_{j,t}z_{j,t}$
- Decreases *raw* capital $z_{j,t}$ per unit of effective capital

2.5 Climate

Analytical model

- 25% of emissions permanent, 75% slowly degrading (Archer 2005)
- Damage proportional to CO_2 concentration

Numerical implementation

- Climate sub-model from DICE (Nordhaus & Sztorc 2013)
- Environmental quality from Weitzman (2010) damage function

$$F_t = 1 - \frac{1}{1 + aT^2 + bT^{6.754}}$$

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Optimal policies in the calibrated model

3.1 Structure of optimal policies

Capital rental subsidy corrects monopoly distortion

- Optimal subsidy rate = α (inverse of the mark-up factor)
  - Could use (time-varying) investment subsidies with equivalent economic effect

Dirty tax corrects emissions externality

- Marginal cost of a unit increase in CO_2 concentration
- *Less* present value of future CO_2 removals (by biogeophysical sinks)

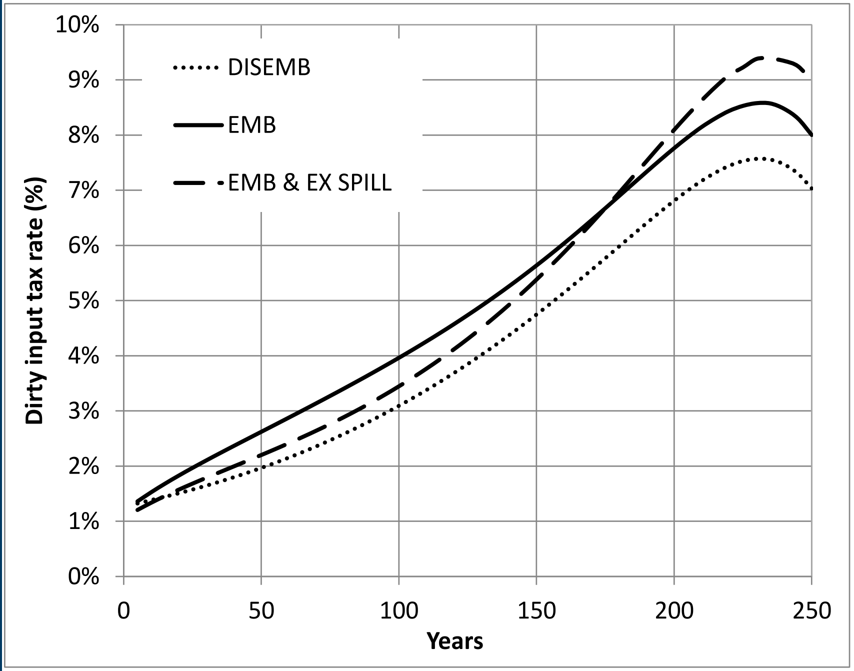
R&D subsidy internalises intertemporal tech spillovers

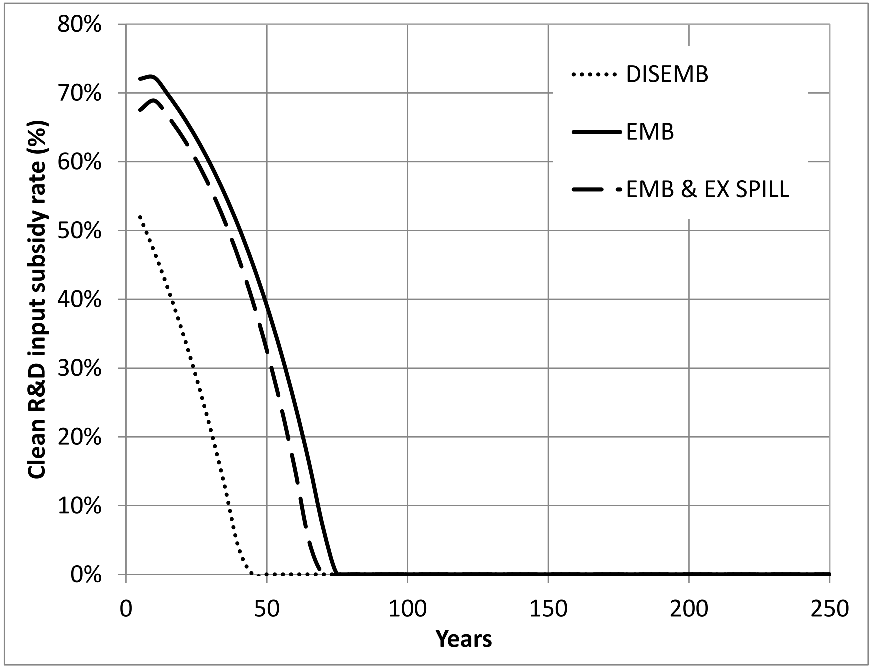
- Fixed R&D supply implies subsidy can be phased out once clean technology is sufficiently advanced that clean profits exceed dirty
- Intersectoral spillovers make R&D in backward sector relatively more productive => subsidy rate need to induce clean R&D is lower

3.2

Optimal policies: effects of embodiment & spillovers

Policies induce immediate switch to clean R&D in all models





Dirty tax rates

- Similar initial rates but rising faster

Including spillovers

- Lower initial rates but rising faster because faster clean progress lowers aggregate costs

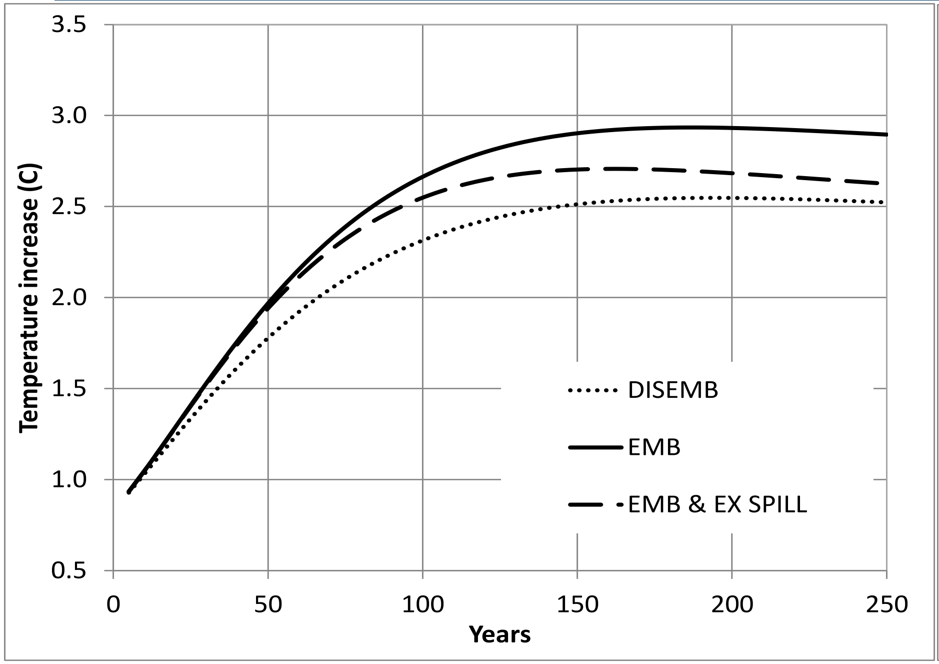
R&D subsidy rates

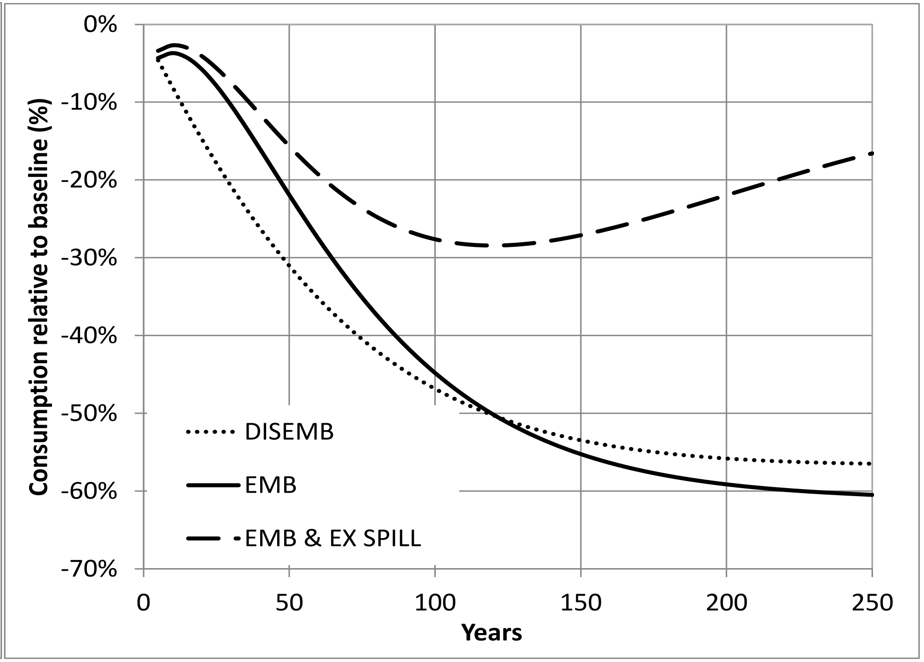
- Higher rates & slower phase-out

Including spillovers

- Reduces required subsidies

Embodiment & spillovers: temperature & consumption





Atmospheric temperature

- Mitigation more costly
  => Significantly higher peak temperature

Including spillovers

- Aggregate mitigation costs decline faster
  => Temperature peaks earlier & lower

Consumption

- Consumption losses reduced in first century but increased in second

Including spillovers

- Consumption losses smaller and decline in second century

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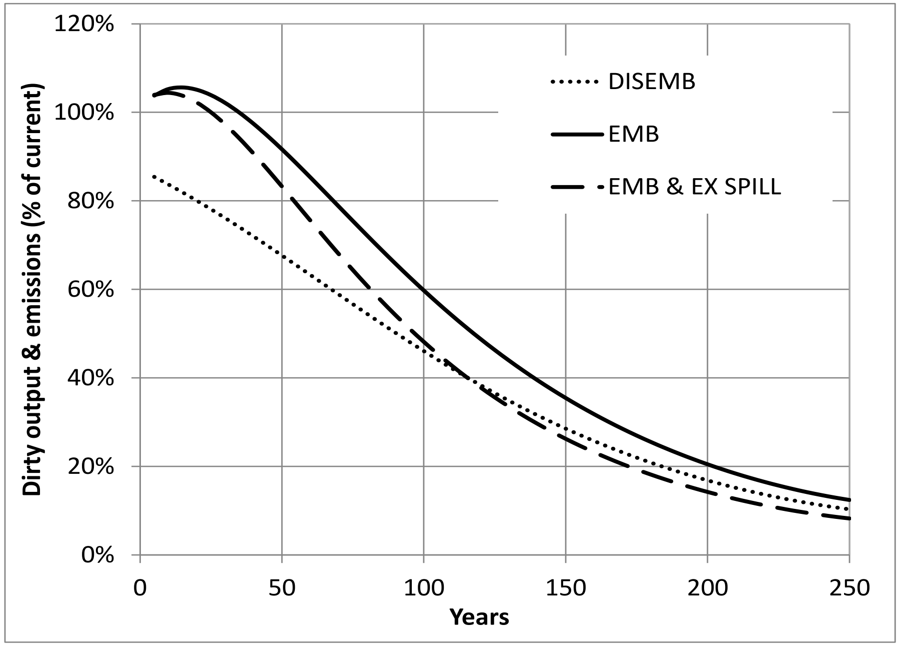
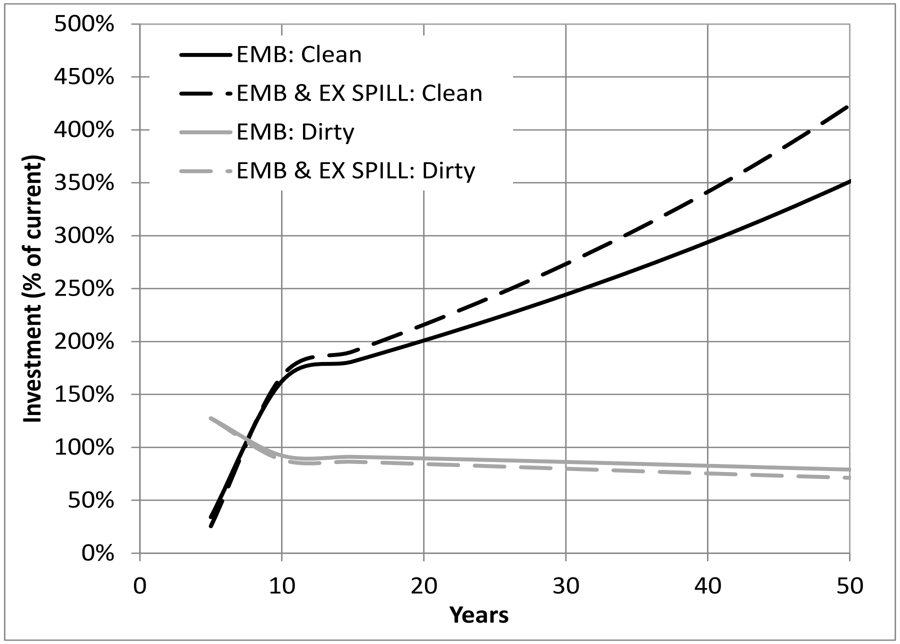
3.4 Embodiment & spillovers: output & investment





Dirty output

- Jump in clean capital rents vs. dirty
  => initial fall (rise) in clean (dirty) output
  => persistent lag in mitigation

Including spillovers

- Initial response unchanged
- Dirty output declines faster thereafter

Investment

- Jump in clean capital rents vs. dirty
  => initial fall (rise) in clean (dirty) investment

Including spillovers

- Faster growth of clean technology
  => accelerated demand for clean capital in long run

Conclusions and recommendations

4.1 Key findings

Capital-embodiment can substantially alter dynamic responses:

- Diffusion of new technologies requires investments
- Technical progress generates obsolescence costs
- Returns to R&D depend on investment not output

Increasing the rate of clean TC relative to dirty

- Naturally, beneficial in the long run
- Perverse level effect in the short(er) run

Optimal mitigation timing

- Investment & R&D decisions intimately linked

4.2 Extensions and implications

Adding a third, non-energy-intensive sector

- Additional margin of substitution
- Realistic composition effects => plausible macroeconomic costs
- Endogenous intersectoral spillovers

Two region or small open economy version

- New technologies embodied in imported equipment
- Disembodied international knowledge spillovers in R&D

Heterogeneous capital in large-scale CGE models

- Composition of capital differs by sector
- Different types of capital depreciate at different rates
- Some types are highly sector-specific

Implications for large-scale CGE or macro/energy models

Embodied technologies ⇔ heterogeneous capital

- Rarely considered in CGE models, although likely widely relevant
  - May be explained in significant part by data limitations
- Considered in some bottom-up energy (sub-)models
  - But linked to learning curves, not R&D-driven technical change

Embodiment distinct from irreversibility

- Irreversibility of investment binds only for "large" shocks to "narrowly defined" industries (or capital asset classes)

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