FONDAZIONE ENI ENRICO MATTEI

Directed technical change with capital-embodied technologies

James Lennox, FEEM &
Jan Witajewski, FEEM

Milan, 19 May 2014

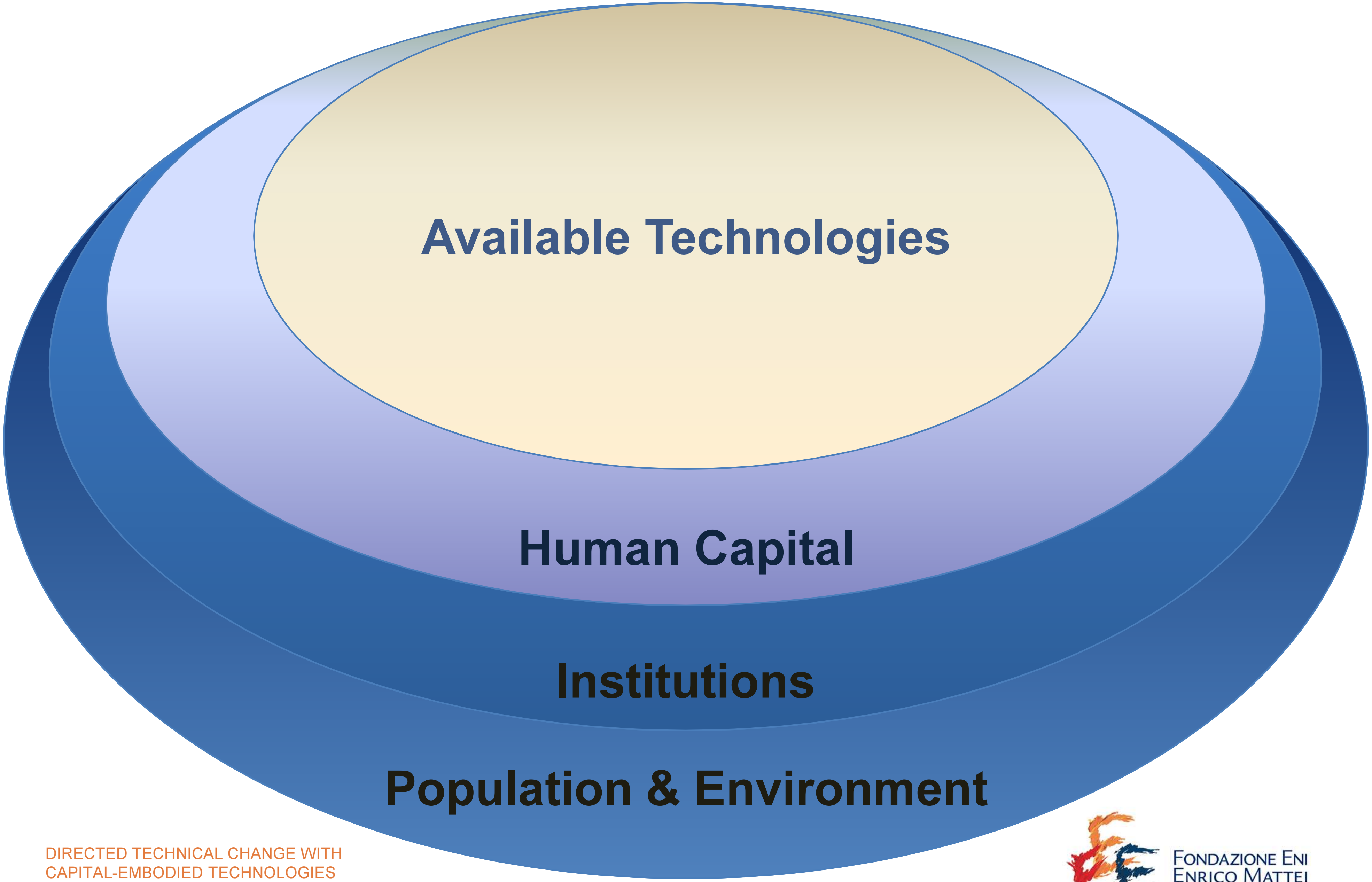
Overview

1. Capital-embodied technical change: what and why?
2. A model of directed technical change with embodiment
3. Optimal policies in the calibrated model
4. Conclusions and recommendations

1

Capital-embodied technical change: what and why?

1.1. Modern growth theory



Available Technologies

Human Capital

Institutions

Population & Environment

1.2. Technical change and economic growth

Neo-classical aggregate production function $Y = F\left(L, K\right)$

- Positive but decreasing marginal returns to each factor input
- If constant returns to scale: $\lambda F\left(L, K\right) = F\left(\lambda L, \lambda K\right)$

Neo-classical growth model $Y_t = A_t F\left(L_t, K_t\right)$

Considering A_t only as technology (ignore institutions, etc.):

- A_t is a *non-rival* input
- A_t may be *non-excludable*
  - Typically *partially* excludable with use of patents, secrecy, etc.

1.3 Capital-embodiment of technologies

R&D mostly directed at new or improved *products* esp. capital *equipment*

- Good evidence for declining real equipment prices
- US productivity growth >60% capital-embodied (Greenwood *et al.*)
- Macro literature focuses on IT revolution
- But clear relevance to new and old energy technologies
  - Gas turbines, solar panels, wind turbines, LED bulbs, batteries, …

Why is capital-embodiment important?

Diffusion of new technologies requires investments

- Models with disembodied TC ignore this dependence

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

Directed technical change

Models with *directed* technical change (DTC)

- Single sector with factor-augmenting TC

$$Y = F\left(A_L L, A_K K\right)$$

  - where *F*(.) is *not* Cobb-Douglas and A_L and A_K are *disembodied* technologies

- TFP growth in heterogeneous sectors

$$Y_t = \prod_i Y_{i,t}^{\alpha_i} = \prod_i \left[A_{i,t} F_i \left(L_{i,t}, K_{i,t}\right)\right]^{\alpha_i}$$

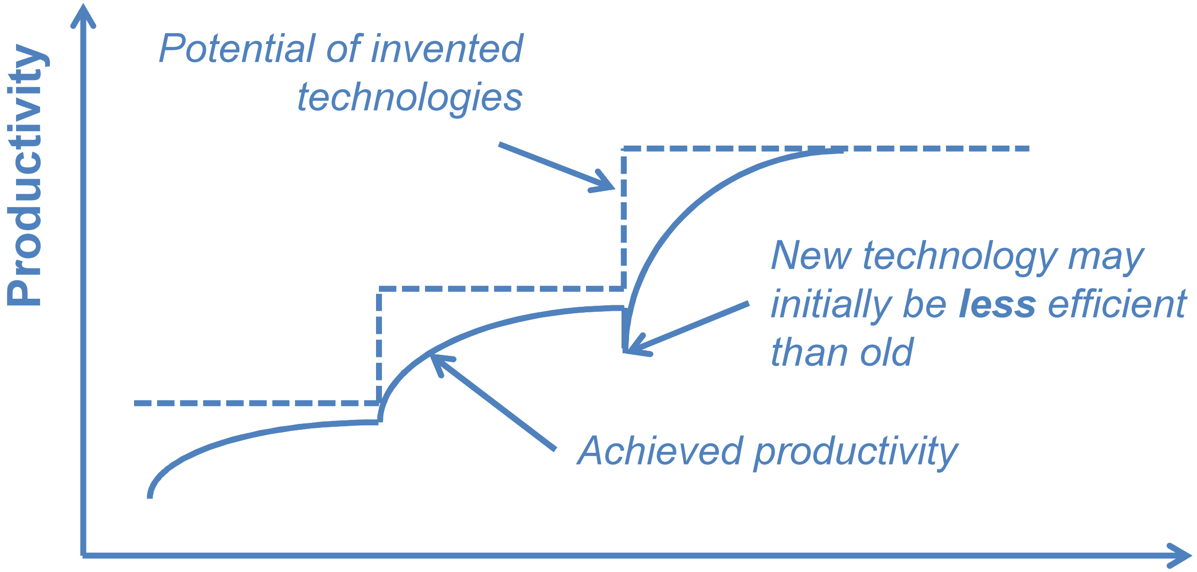
  - Technical change can be partially embodied, depending on the nature of *K*. We will return to this at the end.

Other forms of embodiment

Embodiment in workers or firms

- Learning to use new equipment
- *Incremental* (‘engineering’) improvements or adaptations of existing technologies

Arguably, *bounded* by invented technologies (Young, 1993)



2

Modelling capital-embodied environmentally directed technical change

2.1 Directed technical change with embodiment

Framework of Acemoglu *et al.*, 2012 (AABH)

- Clean, dirty and final production

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

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

- Profit-driven R&D to improve clean or dirty intermediates $x_{j,i,t}$
- Emissions from dirty sector -> climate -> damage costs

Embodying technical change:

- Clean and dirty *capital* goods: $Y_{j,t} = L_{j,i,t}^{1-\alpha} \int_0^1 k_{j,i,t}^{\alpha} di \quad j \in \{c, d\}$
- Technical change
  "investment specific" (Krusell, 1998): $k_{j,i,t} = (1-\delta) k_{j,i,t-1} + A_{j,i,t} z_{j,i,t}$

2.2 Embodiment and obsolescence costs

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

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

- $1/A_{j,i,t}$ 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 $g_{c,t}$

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

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

2.3 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: $A_{j,i,t} = \left(1 + \eta_j s_{j,i,t}\right) A_{j,t-1}$

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

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

2.4 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: $\pi_{j,t} = z_{j,t}\left(s_{j,t}\right)\left(1-\alpha\right)/\alpha$

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

3

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

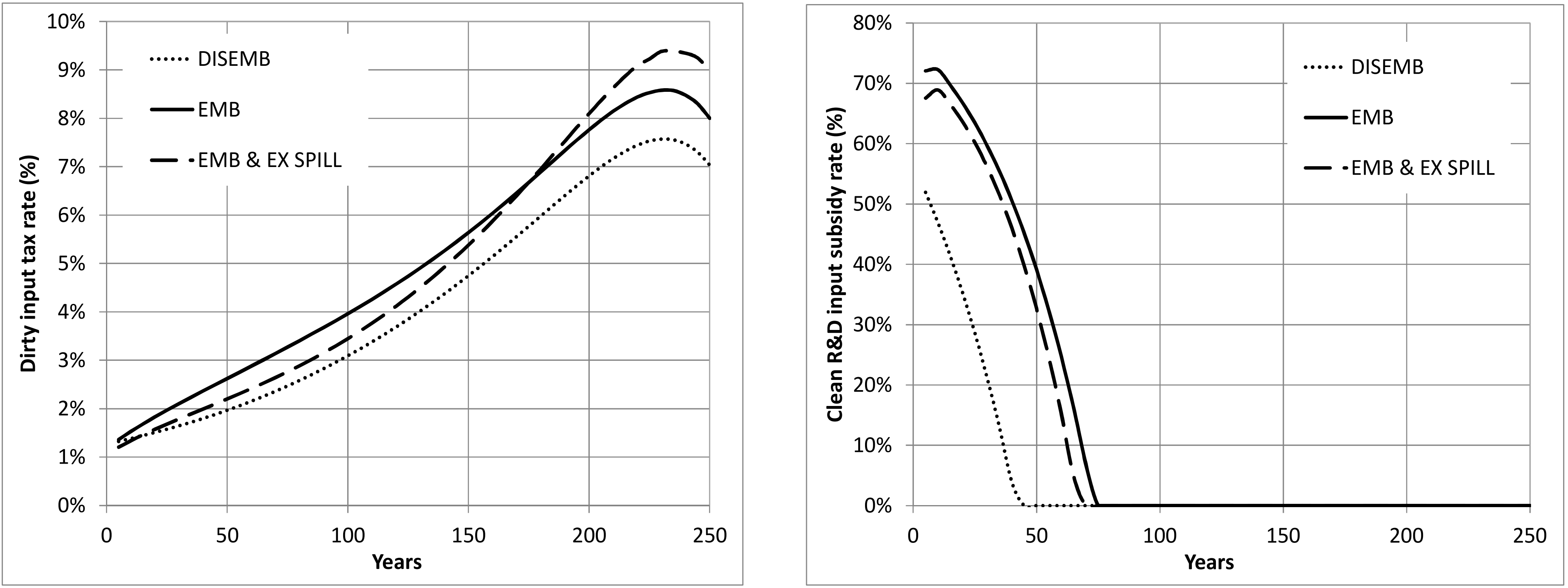
- Marginal cost of a unit increase in CO_2 concentration
- *Less* present value of future CO_2 removals (by biogeophysical sinks)

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

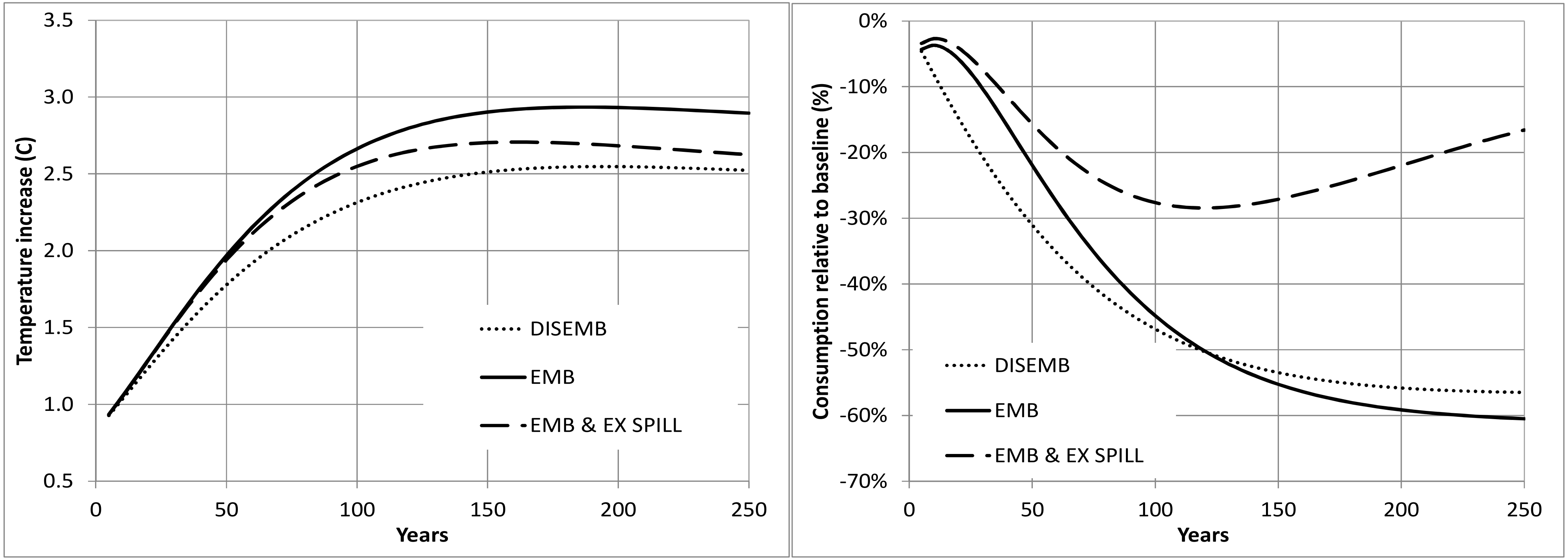
- Higher rates & slower phase-out

Including spillovers

- Reduces required subsidies

3.3

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

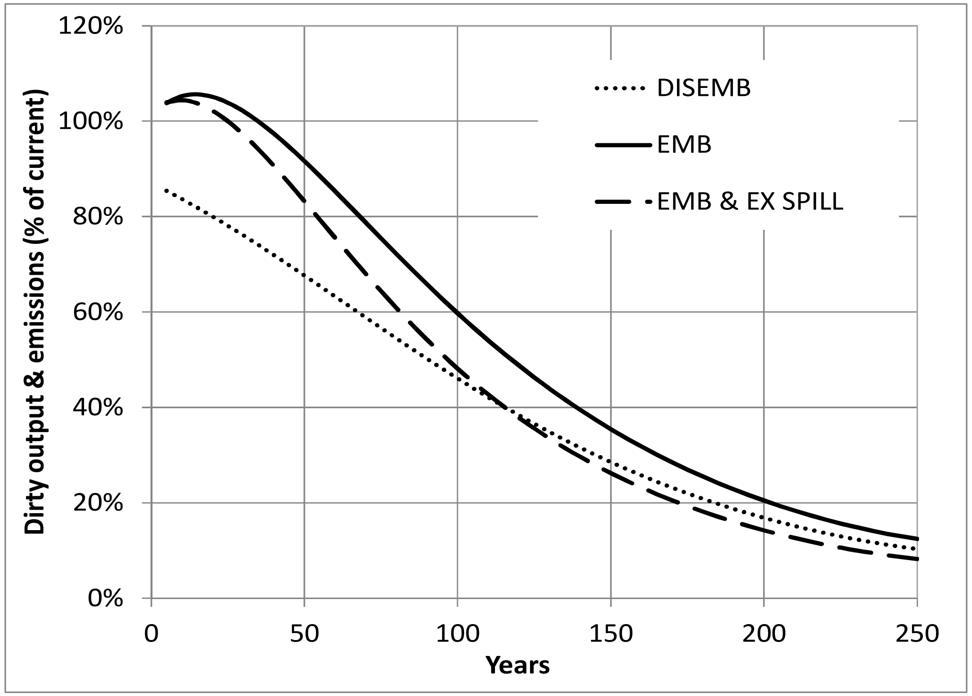
- Consumption losses reduced in first century but increased in second

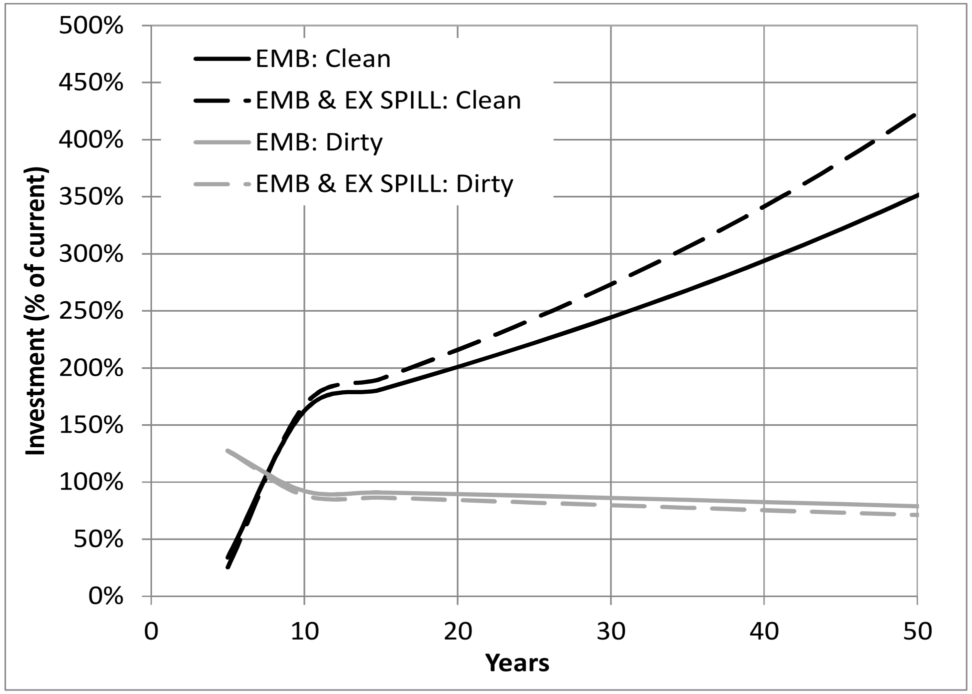
Including spillovers

- Consumption losses smaller and decline in second century

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

4

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 Potential theoretical extensions

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 model

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

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)

4.4 Future work: embodying technologies in ICES

Region- and *sector*-specific rates of TFP growth

- Exogenous rates (for now)
  - Based mainly on EU KLEMS database

Introduce heterogeneous capital

- Structures
- Several classes of equipment
  - Based on EU KLEMS &/or US BEA capital flows
- Distinguish “green” (wind turbines, PV modules, etc.)

Obsolescence costs

- Dependence of regional demand for investment on rate of change in real investment prices

Acknowledgements

The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme (FP7/2007-2013) under REA grant agreement no. 328454.