Energy Transitions: Directed Technical Change Meets Directed Extraction

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In sharp contrast to the preindustrial era, the industrial era "has seen a series of remarkable energy transitions." – Smil (2010)

Marchetti (1977)

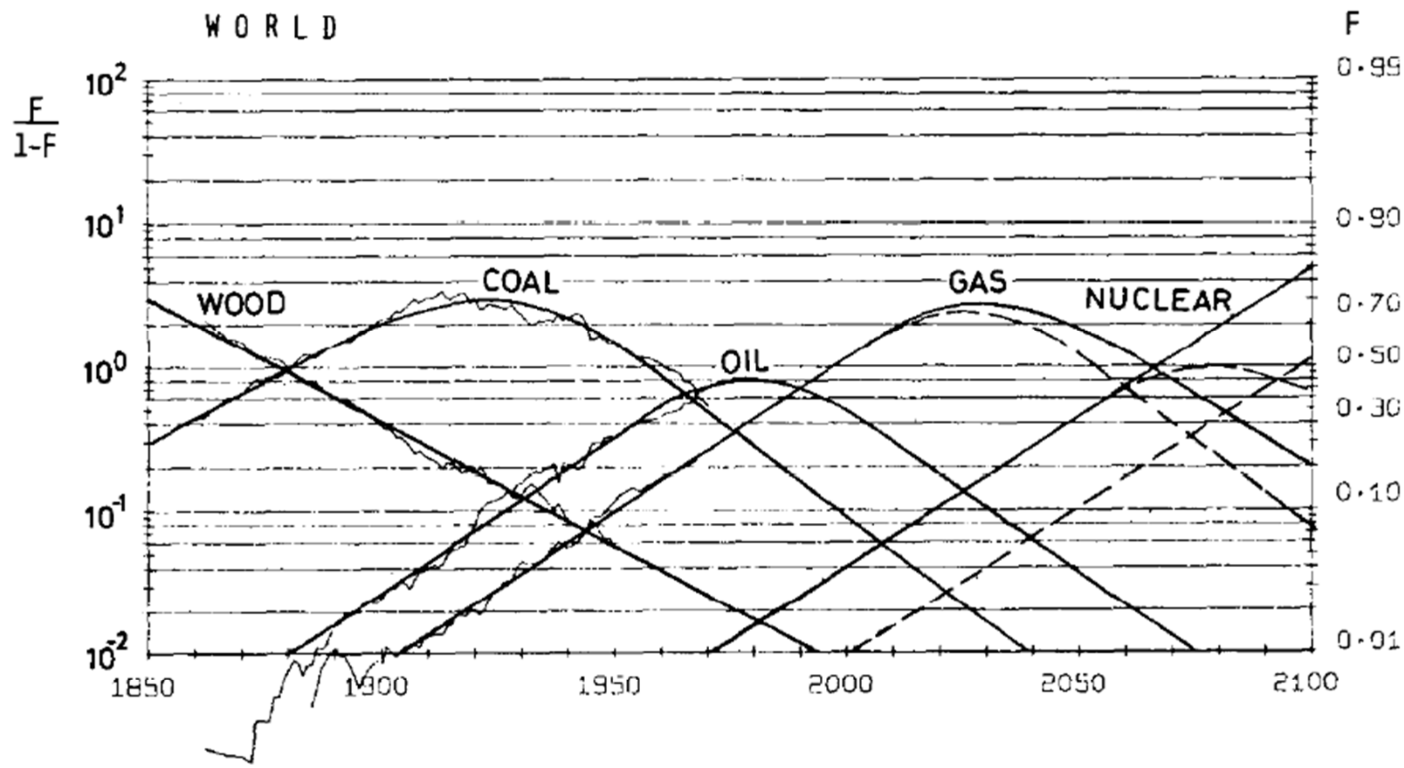
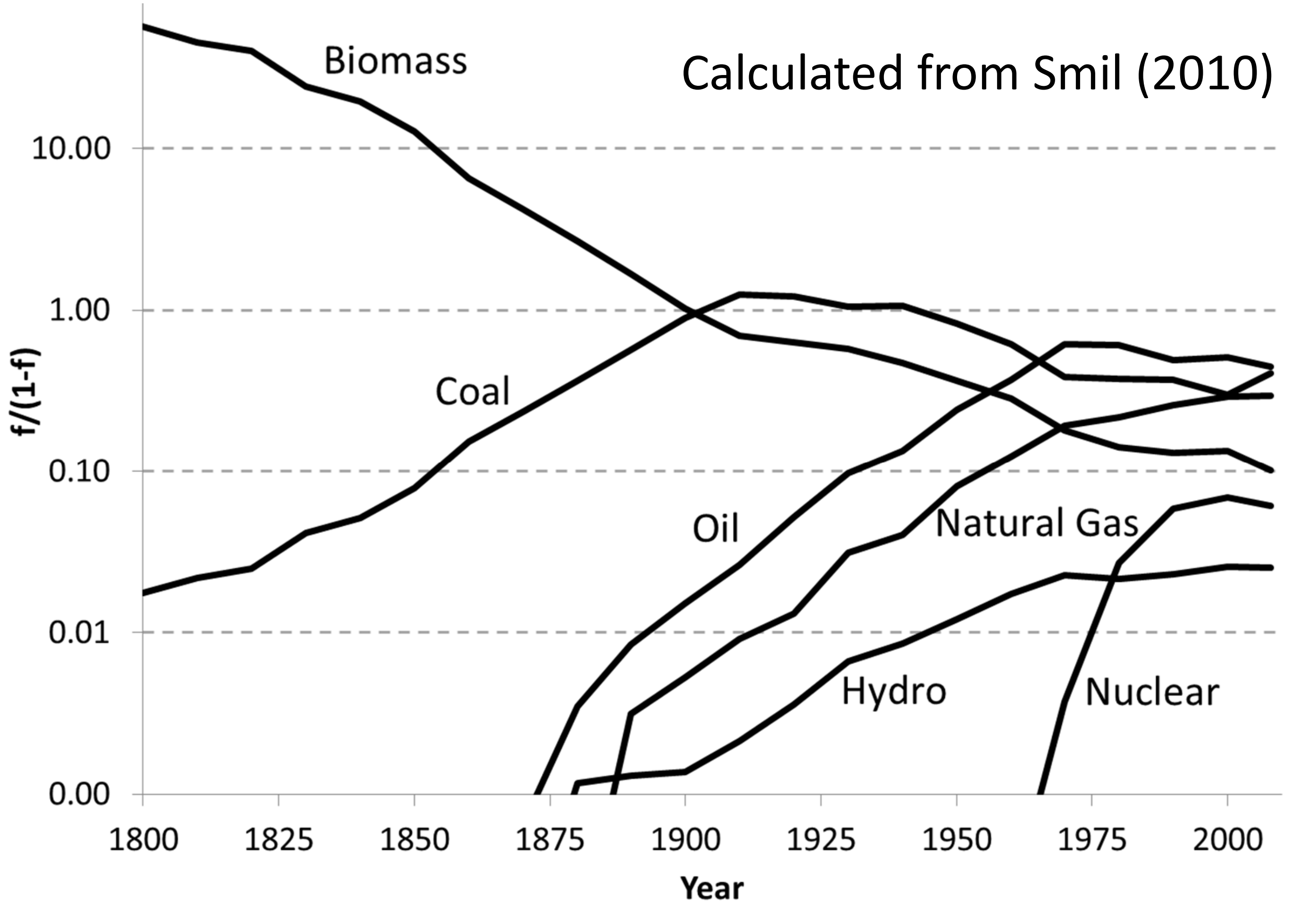


Fig. 7(a). Historical evolution of the primary energy mix for the *world*. Wriggling lines are statistical data, smooth lines computed. Some values for the actual market fractions are given on the right side of the figure. The effect of introducing a new source of primary energy (1% in year 2000), solar, fusion or else, is indicated by the dashed lines. This effect appears minimal on conventional sources, and dramatic only on nuclear, but in the second half of the next century.

"It is as though the system had a schedule, a will, a clock." – Marchetti and Nakicenovic (1979)

More recent data suggests that this clock has broken.

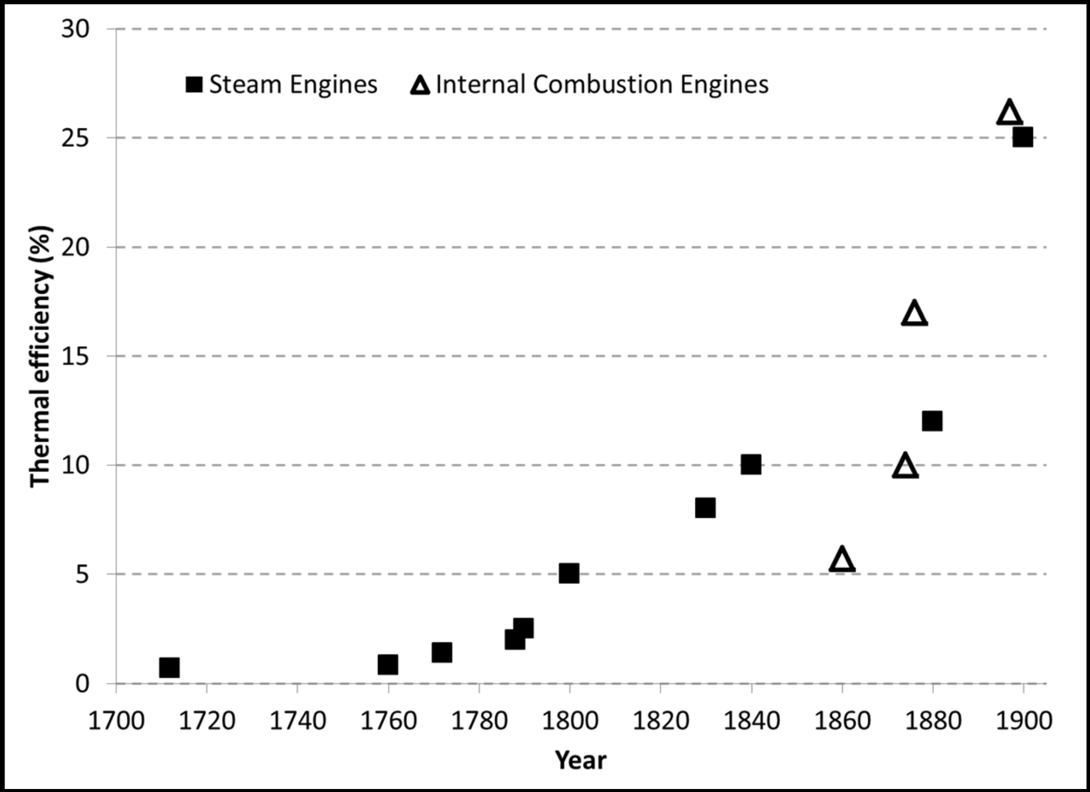


We want to understand the economic drivers of these transitions because energy use is tightly linked to both the First (via coal) and Second (via electricity and oil) Industrial Revolutions.

Further, policymakers are currently attempting to induce a new transition, to low-carbon (renewable) energy.

Yet growth theory has largely abstracted from energy.

There has been a mismatch between economic theories of resource use and the experience of the past centuries.



Data from Smil (1994) and Smil (2005)

Economists have focused on how depletion or exhaustion can induce transitions between resources (e.g., Herfindahl 1967; Nordhaus 1973; Chakravorty and Krulce 1994; Chakravorty et al. 1997).

But many energy historians have noted that technological change, not depletion, has been crucial to past transitions (e.g., Marchetti 1977; Rosenberg 1983; Grübler 2004).

I integrate innovation and depletion in a dynamic model of resource use in order to understand the drivers of past and future energy transitions.

I show that both innovation and depletion are necessary to explain the regularity of past transitions.

An initially dominant resource attracts most research effort. Eventually, the returns to further research decline and some effort begins shifting to the other resource, which is also less depleted. As that resource's technology improves, it begins attracting more extraction effort, which generates even stronger incentives for research.

This positive feedback loop can make the second resource eventually displace the first one as the dominant resource.

My setting can generate the types of transitions in extraction and technology that marked 1800-1970. It also generates the stability that has marked the years since 1970.

The key modeling innovation is to recognize <u>complementarities</u> between resources and the machines for using them.

These complementarities generate positive feedbacks between research and extraction.

In the most similar paper (Acemoglu et al. 2012), equilibrium research incentives are independent of extraction.

- They use a Cobb-Douglas production function to combine resources and machines.
- Increasing extraction raises the relative reward to researching machines via a market size effect and decreases it via a price effect. These two effects exactly cancel due to their Cobb-Douglas assumption.

However, this knife-edge case appears to have been counterfactual. By recognizing complementarities between resources and the machines for using them, the present setting allows market size effects to direct research effort.

The new role for market size effects has important policy implications.

Most economists recommend reducing greenhouse gas emissions by combining emission pricing with R&D support. However, mandates and subsidies for renewable energy are far more common in practice.

I describe a novel *market transformation motive* for renewable mandates.

I show that, consistent with recent evidence (Johnstone et al. 2010 and evidence shown later), even a seemingly small renewable energy mandate can redirect research towards renewable energy technologies.

Over time, the improvement in technology increases the incentive to employ capital and labor in developing renewable resources rather than fossil resources, so that the mandate eventually makes itself nonbinding.

A small mandate can even end up inducing a transition that makes renewable energy supplant fossil energy as the dominant resource.

This paper differs in objective and formalism from other work that combines directed technical change and energy.

Most analyses have divided technologies between those that augment resources and those that augment other factors such as labor (Smulders and de Nooij 2003; Di Maria and Valente 2008; Grimaud and Rouge 2008; Pittel and Bretschger 2010; André and Smulders 2012).

– They have focused on the potential for tech change to enable long-run growth when an essential resource is exhaustible. In contrast, I allow research to be directed between multiple types of resources in order to explore questions about energy transitions.

Acemoglu et al. (2012) consider the use of research subsidies and emission taxes to avoid dangerous climate change

Valente (2011) considers the dynamics between an exhaustible resource and a perfectly substitutable backstop, with technology driven by a form of learning-by-doing.

I aim to explain stylized facts from historical transitions. Formally, I introduce complementarities, depletion, and more general innovation functions into a model of directed technical change.

Outline

- Setting
- Extraction and research incentives
- Transitions
- Renewable energy mandate

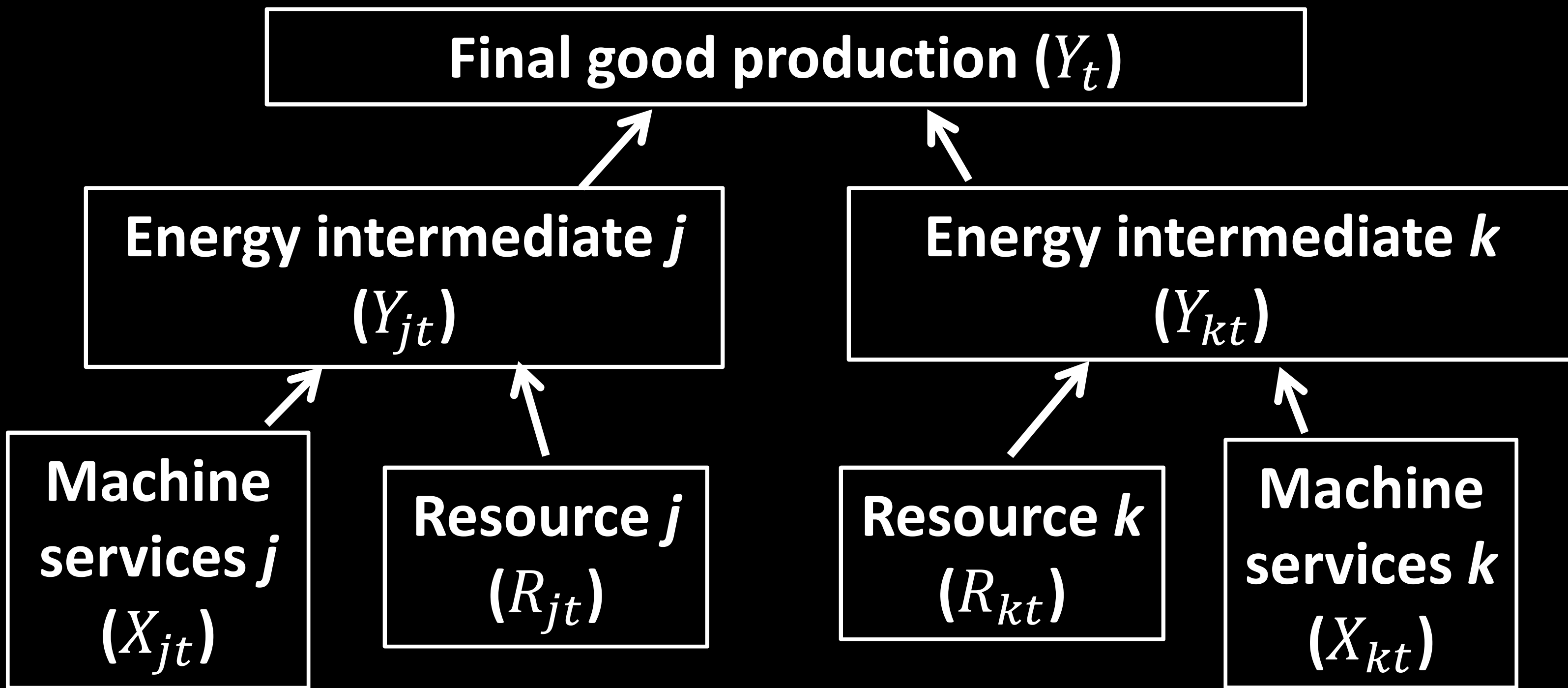
Final good production (Y_t)

Energy intermediate *j* (Y_{jt})

Energy intermediate *k* (Y_{kt})

$$Y_t = \left(\nu \, Y_{jt}^{\frac{\epsilon-1}{\epsilon}} + (1-\nu) Y_{kt}^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}}$$

Two energy intermediates are gross substitutes ($\epsilon > 1$) in final-good production.



$$Y_{jt} = \left(\kappa \left[R_{jt} / C(Q_{j(t-1)}) \right]^{\frac{\sigma-1}{\sigma}} + (1-\kappa) X_{jt}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}$$

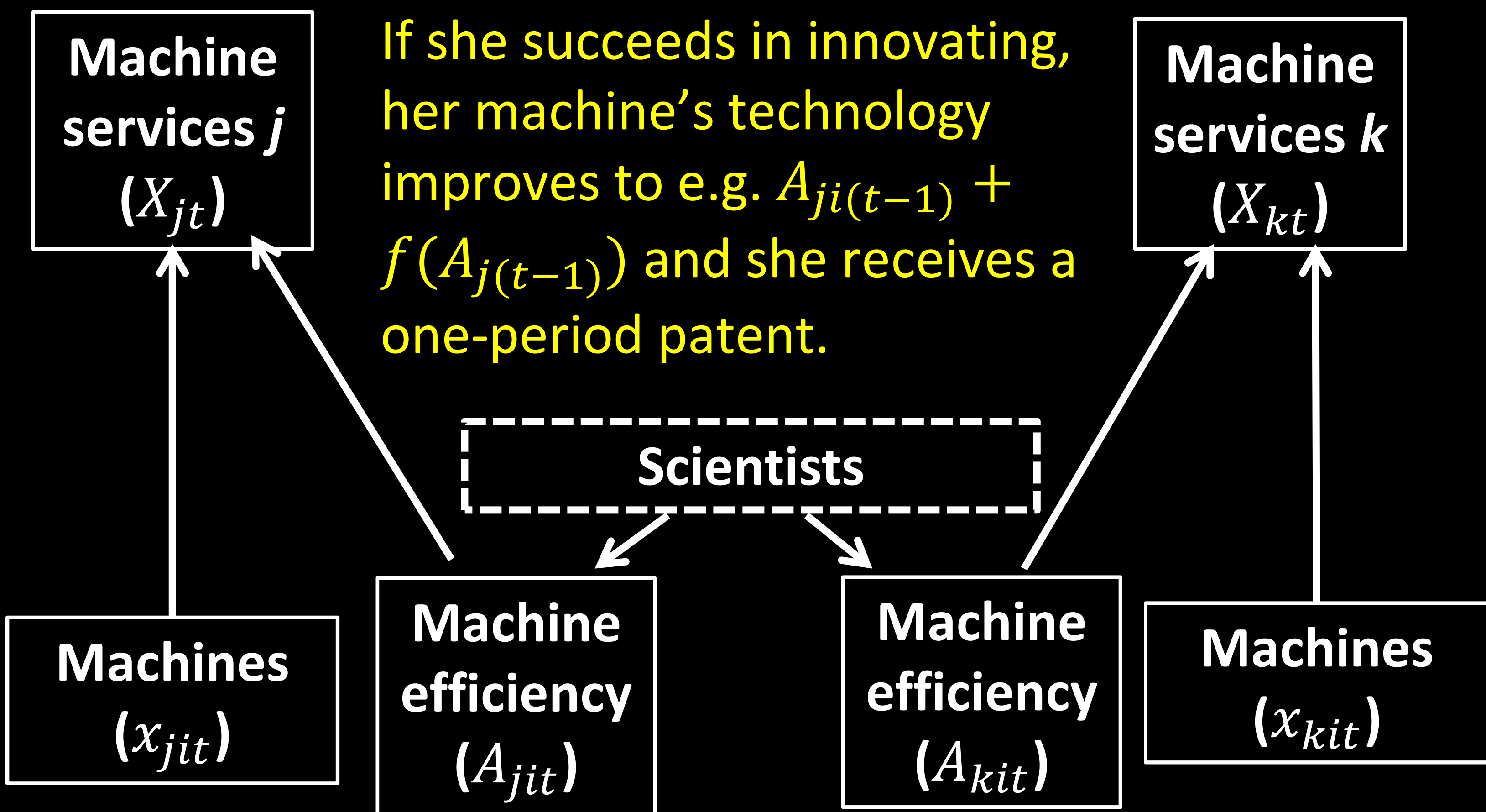
$$Y_{kt} = \left(\kappa \left[R_{kt} / C(Q_{k(t-1)}) \right]^{\frac{\sigma-1}{\sigma}} + (1-\kappa) X_{kt}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}$$

Each energy intermediate is produced competitively by combining resource inputs and machine services, which are gross complements ($\sigma < 1$).

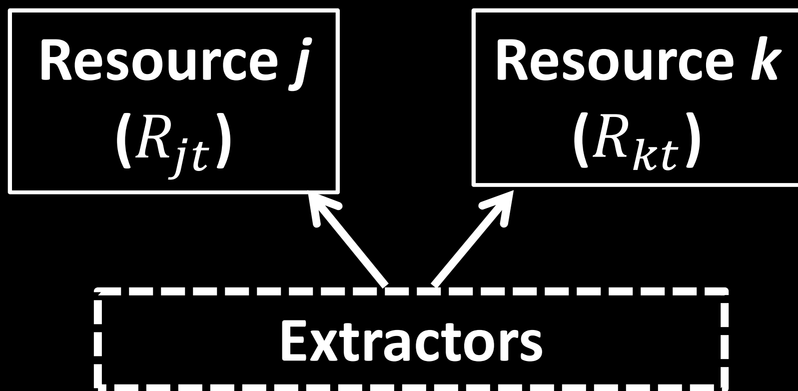
Machine services are produced in a Dixit-Stiglitz environment of monopolistic competition. Each scientist chooses which type of resource she wants to study and is then randomly allocated to a machine.

$$X_{jt} = \int_0^1 A_{jit}^{1-\alpha} x_{jit}^{\alpha} \, \mathrm{d}i \qquad\qquad X_{kt} = \int_0^1 A_{kit}^{1-\alpha} x_{kit}^{\alpha} \, \mathrm{d}i$$

If she succeeds in innovating, her machine's technology improves to e.g. $A_{ji(t-1)} + f(A_{j(t-1)})$ and she receives a one-period patent.



Each extractor supplies a scarce factor (such as labor or capital) to either resource's extraction sector.



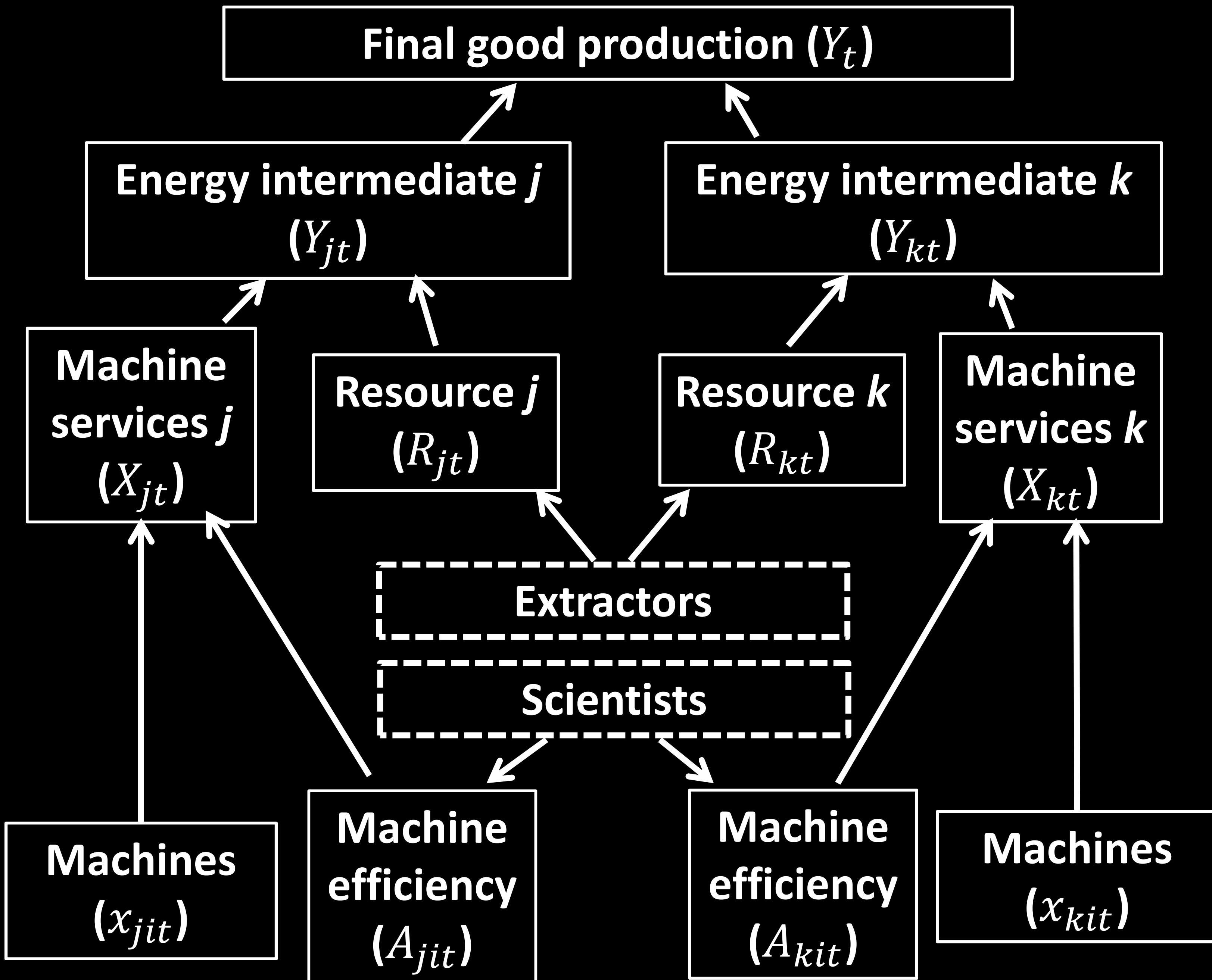
Extraction in e.g. sector *j* is $R_{jt}/C(Q_{j(t-1)})$, where R_{jt} is the factor supplied to sector *j* and $Q_{j(t-1)}$ is the cumulative quantity previously extracted. The positive, increasing function $C(\cdot)$ reflects the cost of depletion.

In equilibrium, all factor markets clear, all firms maximize profits, and all households (extractors and scientists) maximize earnings.

We restrict attention to equilibria that are stable in a natural tâtonnement sense.

Many studies with complementarities focus on the potential for multiple equilibria (e.g., Matsuyama 1995), but we have sufficient decreasing returns to obtain unique equilibria in many cases.

Proposition 1. *There exists* $\hat{\epsilon}_t \in (2\sigma, \infty)$ *such that the equilibrium at time* t *is unique and asymptotically stable if* $\epsilon < \hat{\epsilon}_t$ *and such that* $\hat{\epsilon}_t \to \infty$ *as* $\left|A_{j(t-1)} - A_{k(t-1)}\right| \to 0$.

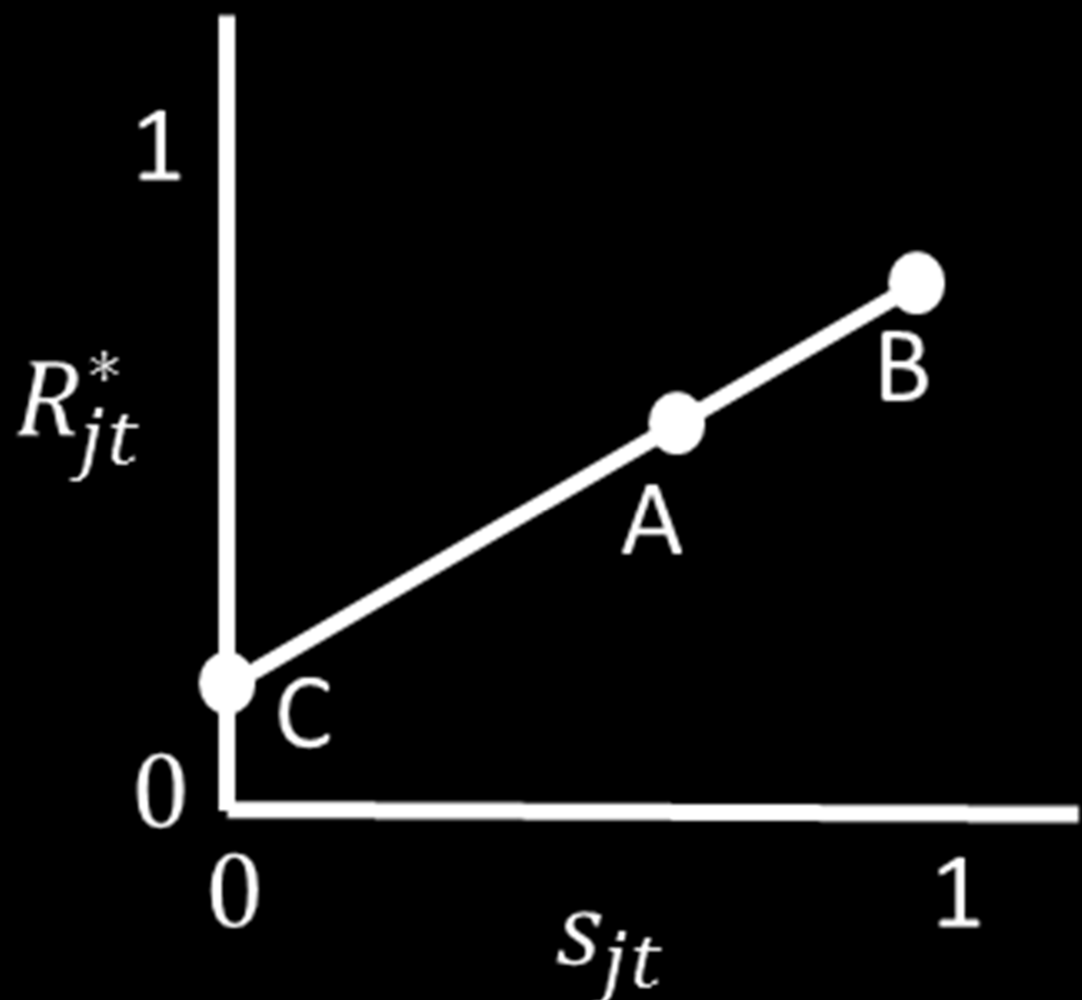

Final good production (Y_t)
Energy intermediate *j* (Y_{jt})
Energy intermediate *k* (Y_{kt})
Machine services *j* (X_{jt})
Resource *j* (R_{jt})
Resource *k* (R_{kt})
Machine services *k* (X_{kt})
Extractors
Scientists
Machines (x_{jit})
Machine efficiency (A_{jit})
Machine efficiency (A_{kit})
Machines (x_{kit})

Extraction and Research Incentives

$$\frac{w_{jt}}{w_{kt}} = \frac{\nu}{1-\nu} \underbrace{\left[\frac{R_{jt}/C(Q_{j(t-1)})}{R_{kt}/C(Q_{k(t-1)})}\right]^{-1/\sigma}}_{\text{resource price effect}} \underbrace{\left[\frac{C(Q_{j(t-1)})}{C(Q_{k(t-1)})}\right]^{-1}}_{\text{extraction cost effect}} \underbrace{\left[\frac{Y_{jt}}{Y_{kt}}\right]^{\frac{1}{\sigma}-\frac{1}{\epsilon}}}_{\text{market size effect}}$$

The relative incentive to extract resource *j* depends on four terms.

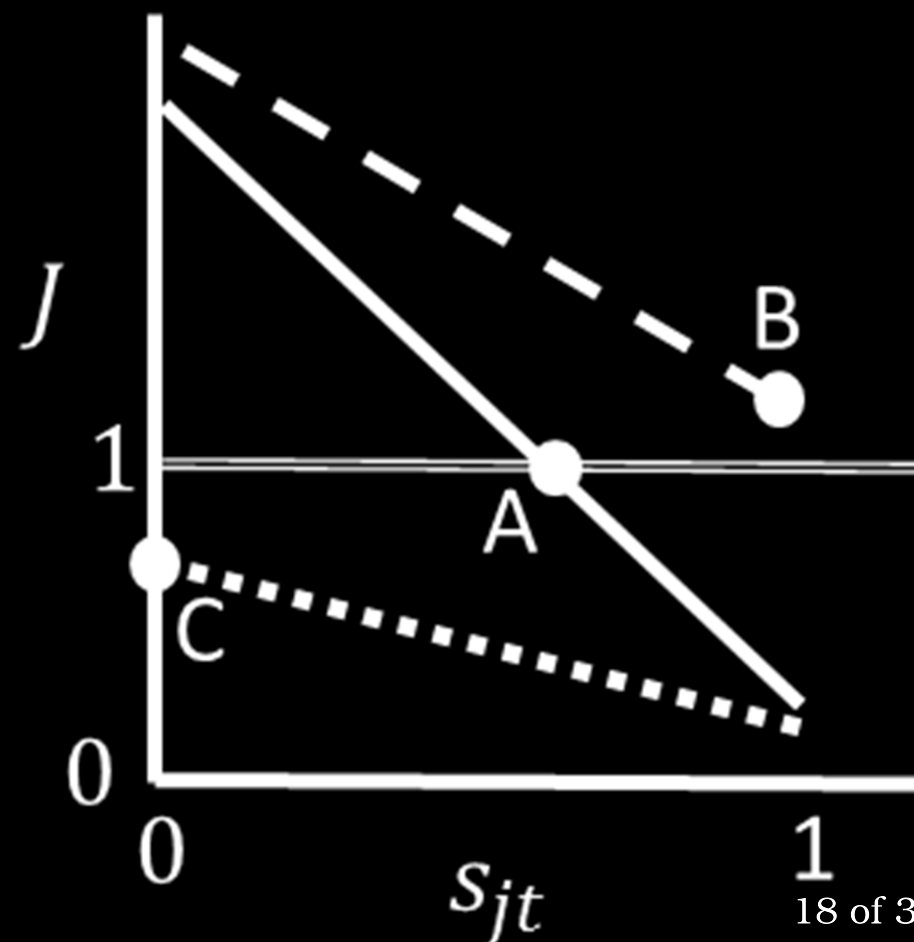
The market size effect directs extraction in line with research effort.



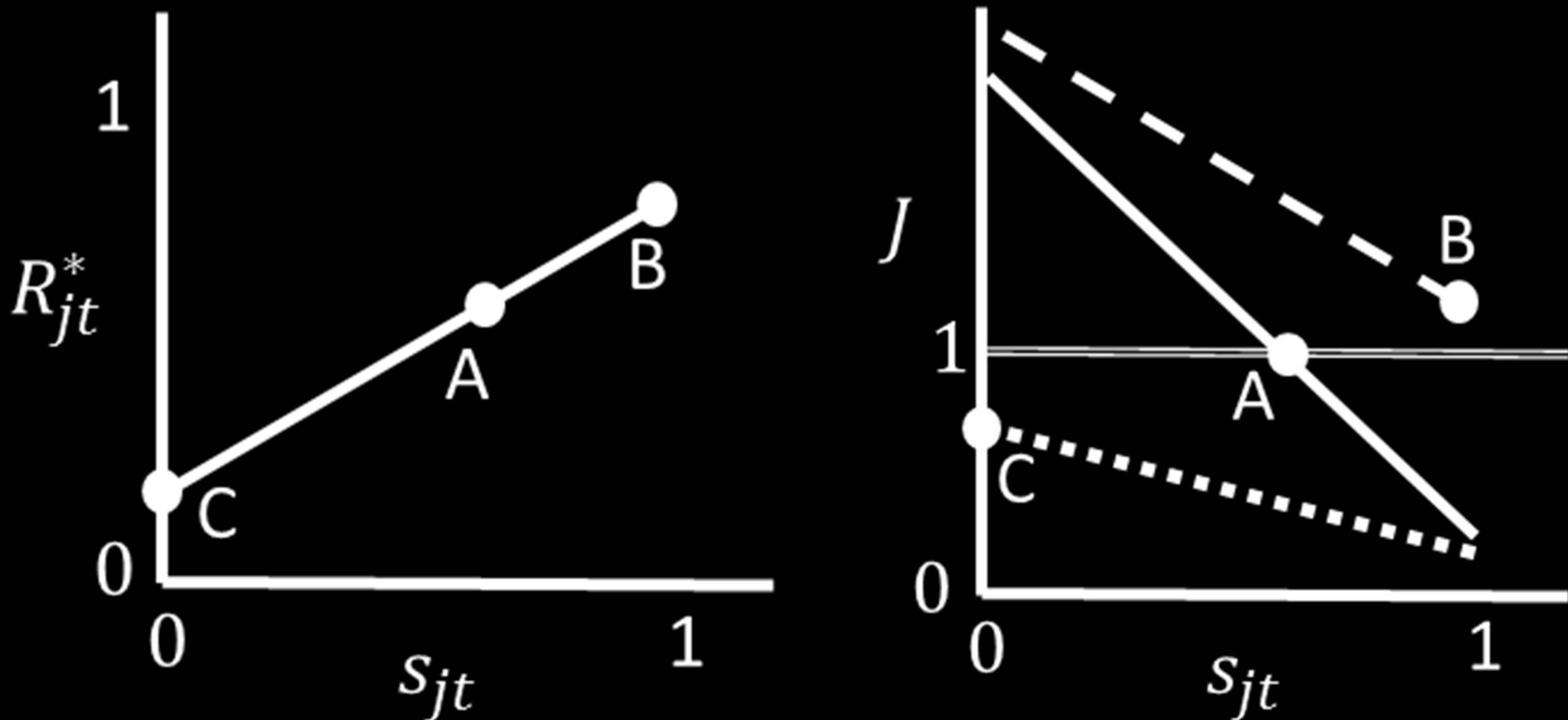
$$\frac{\Pi_{jt}}{\Pi_{kt}} = \overbrace{\frac{A_{j(t-1)} + f(A_{j(t-1)})}{A_{k(t-1)} + f(A_{k(t-1)})}}^{\text{technology transformation effect}} \underbrace{\left(\frac{A_{j(t-1)} + \eta s_{jt} f(A_{j(t-1)})}{A_{k(t-1)} + \eta s_{kt} f(A_{k(t-1)})}\right)^{\frac{-1}{\sigma+\alpha(1-\sigma)}}}_{\text{diminishing returns effect}} \underbrace{\left(\frac{R_{jt}/C(Q_{j(t-1)})}{R_{kt}/C(Q_{k(t-1)})}\right)^{\frac{1}{\sigma+\alpha(1-\sigma)}}}_{\text{market size effect}} \underbrace{\left[\frac{w_{jt}}{w_{kt}} \frac{C(Q_{j(t-1)})}{C(Q_{k(t-1)})}\right]^{\frac{\sigma}{\sigma+\alpha(1-\sigma)}}}_{\text{resource substitution effect}}.$$

The relative incentive to research machines for use with resource *j* in turn increases with extraction of resource *j*.

This equation, referred to as $J(s)$, implicitly defines the equilibrium research allocation.



These two plots jointly define the equilibrium.



Improving the quality of incoming technology in j shifts L^*_{jt} up. This change works to shift J up, but the improvement in tech can also shift *J* down directly. Extraction of *j* declines <u>only if</u> research in *j* declines.

Increasing resource *j*'s depletion shifts *J* down directly but can potentially shift L^*_{jt} up if ϵ is small. Research in *j* increases <u>only if</u> extraction effort (not necessarily net extraction) in *j* increases.

Transitions

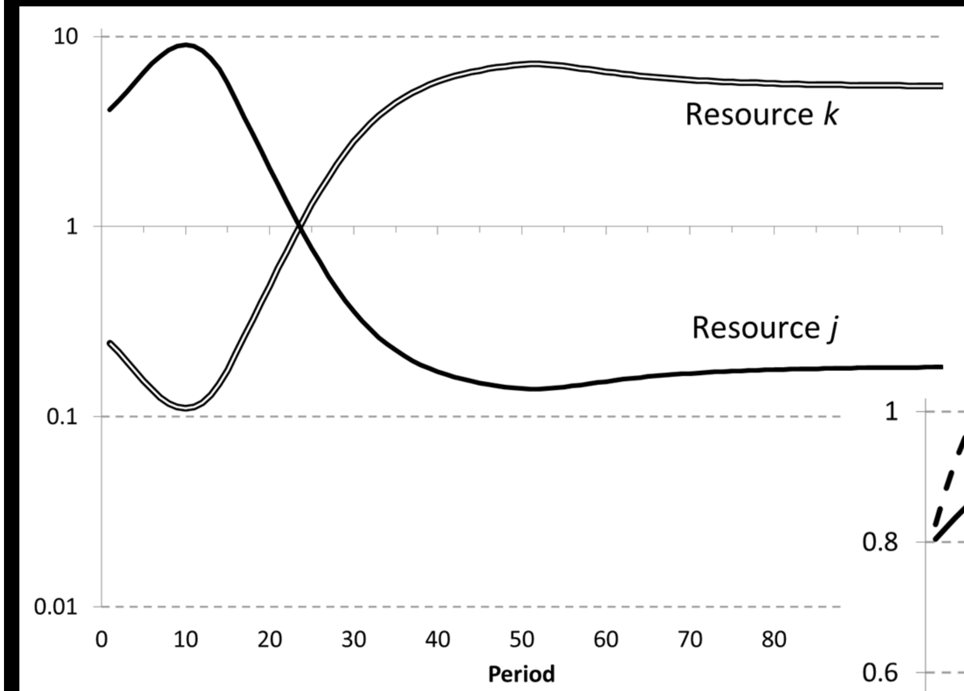
If either directed technical change or depletion is absent, then transitions can occur only if particular circumstances hold. Yet we have seen repeated transitions in the real world. This suggests that both innovation and depletion have been important.

Define a transition from *j* to *k* as occurring at time *t* when extraction is greater in *j* at *t-1*, greater in *k* at *t+1*, and equal at *t*.

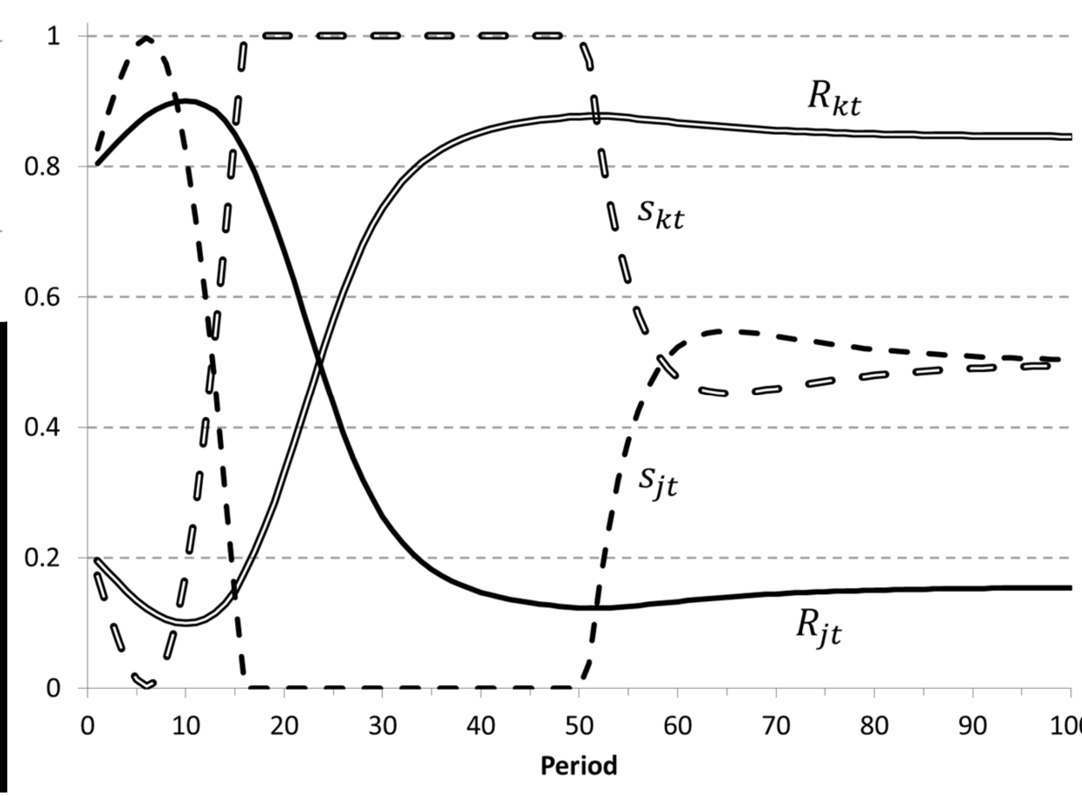
Proposition 5.

1. *A transition is not possible if* $\nu = 0.5$ *and either* $C'(\cdot) = 0$ *or* $\eta f(\cdot) = 0$.
2. *In a setting without innovation* ($\eta f(\cdot) = 0$) *and with equal technologies* ($A_{jt} = A_{kt}$), *a transition from resource j to resource k can occur only if* $\nu < 0.5$ *and* $Q_{j0} < Q_{k0}$.
3. *In a setting without depletion* ($C'(\cdot) = 0$), *a transition from resource j to resource k can occur only if* $\nu < 0.5$ *and* $A_{j0} > A_{k0}$. *And if the transition from resource j to resource k occurs at time t, then* $A_{jt} > A_{kt}$.

A possible transition without depletion: The tech for using resource *j* starts out more advanced but resource *k* receives more weight in final-good production.



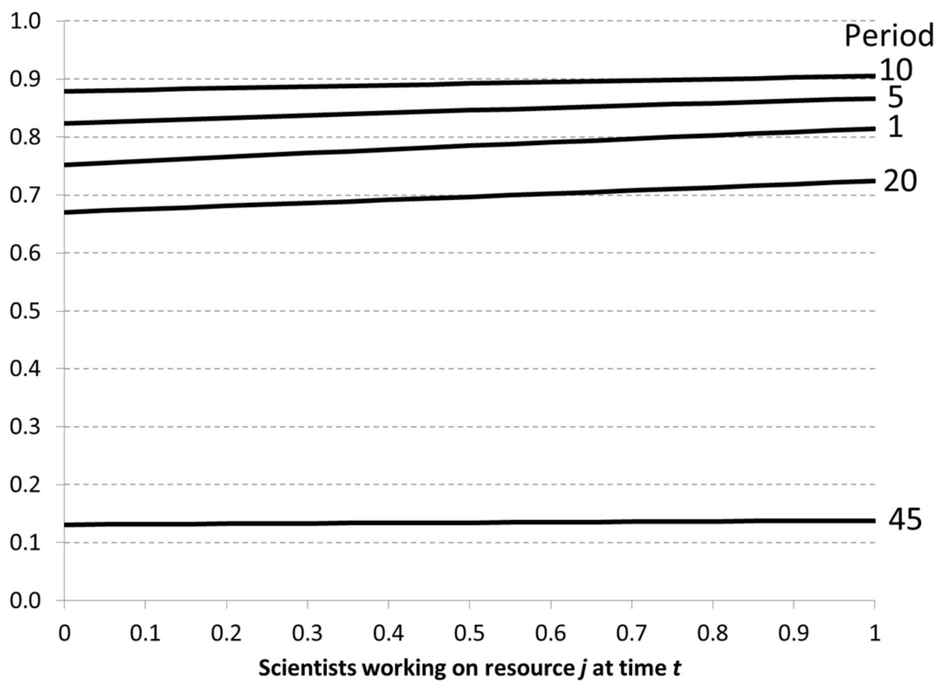
Extraction of each (Fisher-Pry)



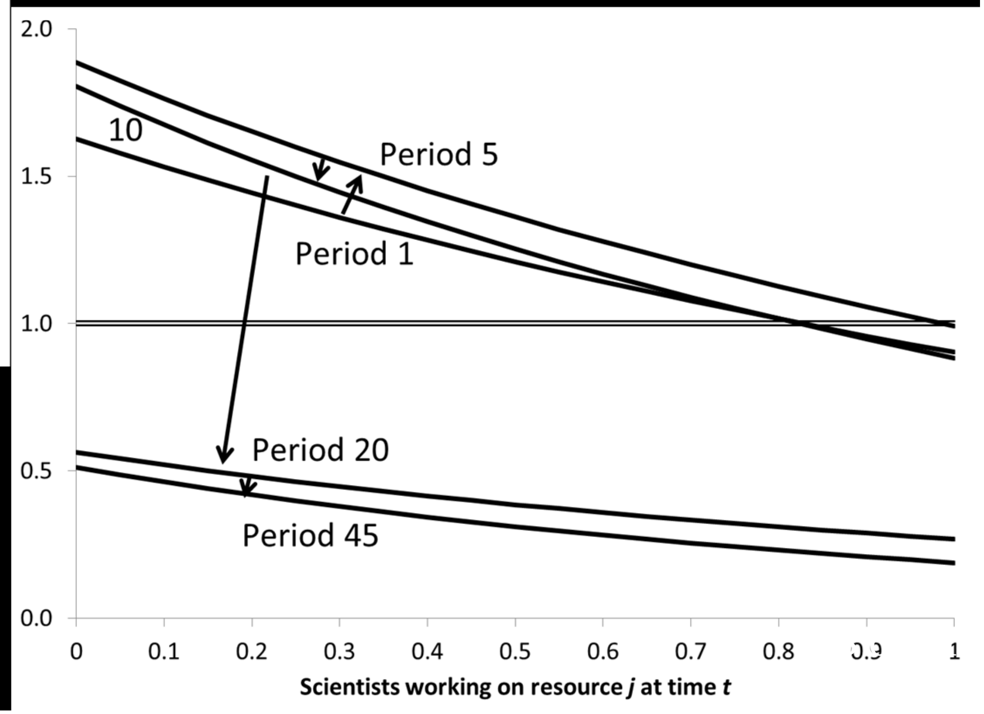
Extraction effort and research

At first, the improvement in tech for using *j* further increases the incentives to research *j*. However, as extraction approaches a corner solution, decreasing-returns effects kick in and research effort shifts towards *k*. By period 20, the improvement in technology for using *k* has begun shifting the extraction curve towards *k*.

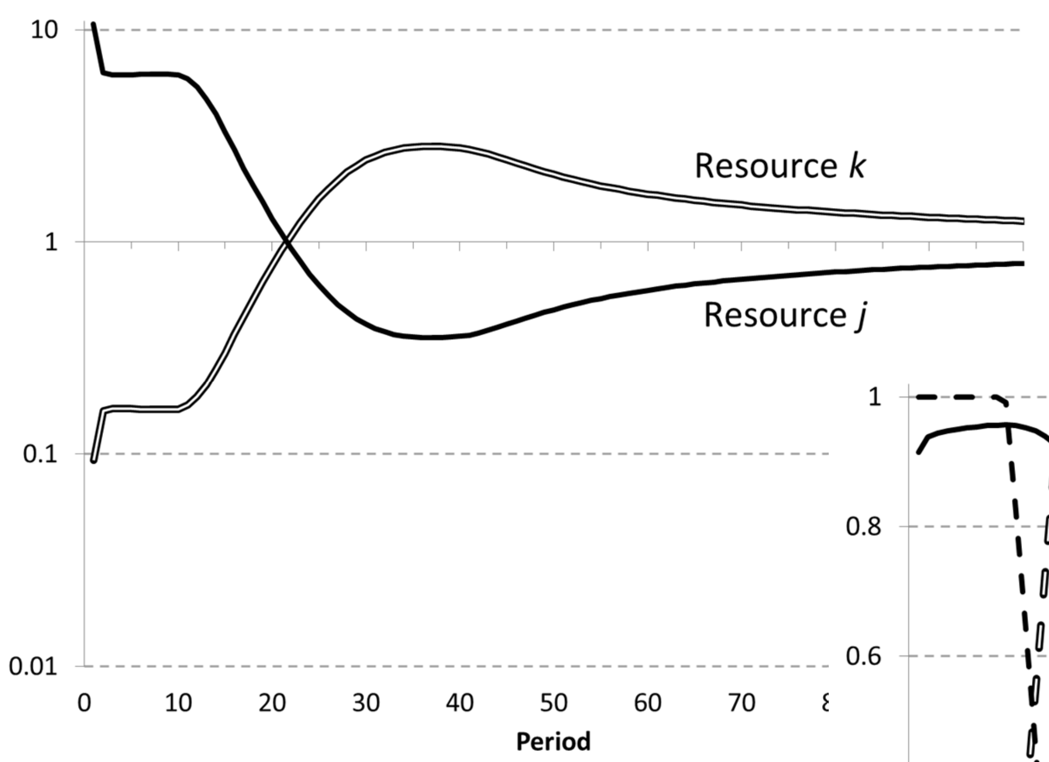
$R^{*}_{jt}(s_{jt})$



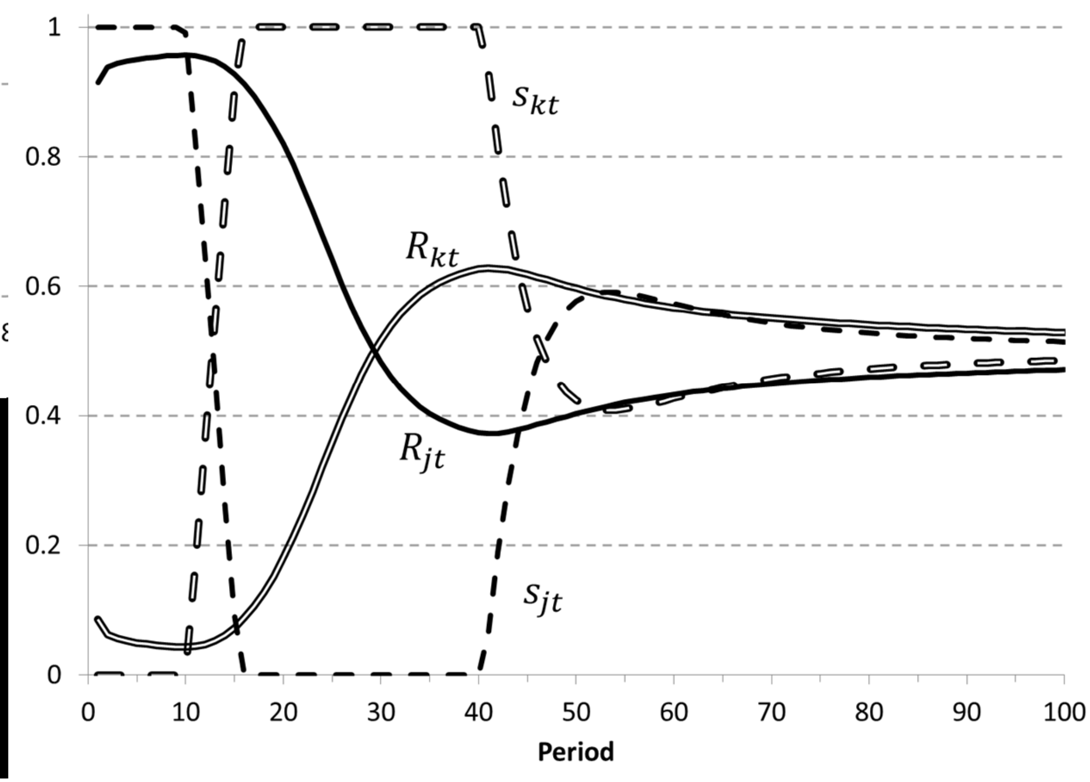
$J(s_{jt})$



Once we introduce depletion, we can get transitions even when treating both resources symmetrically in final-good production. In this example, *j* again starts out more advanced.



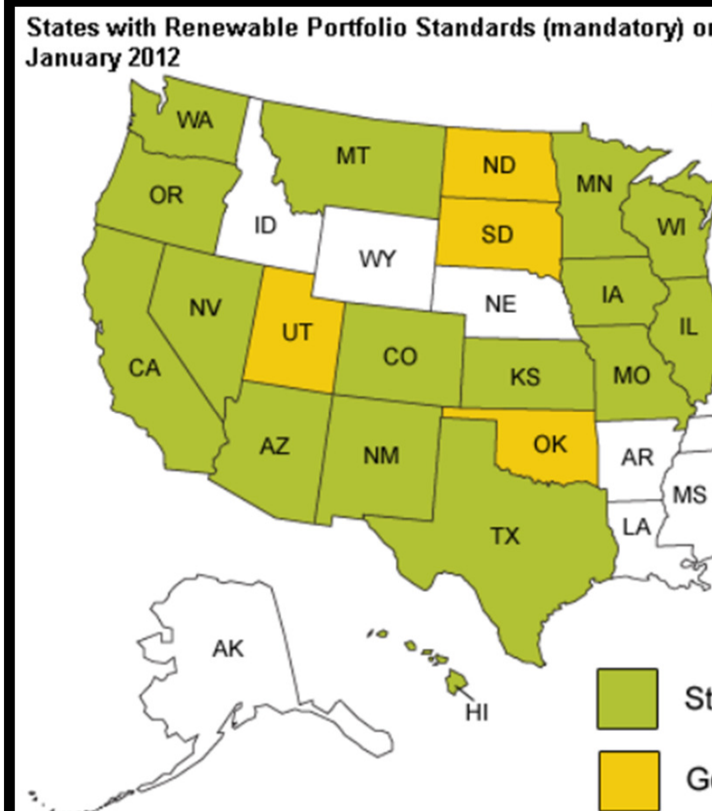
Extraction of each (Fisher-Pry)

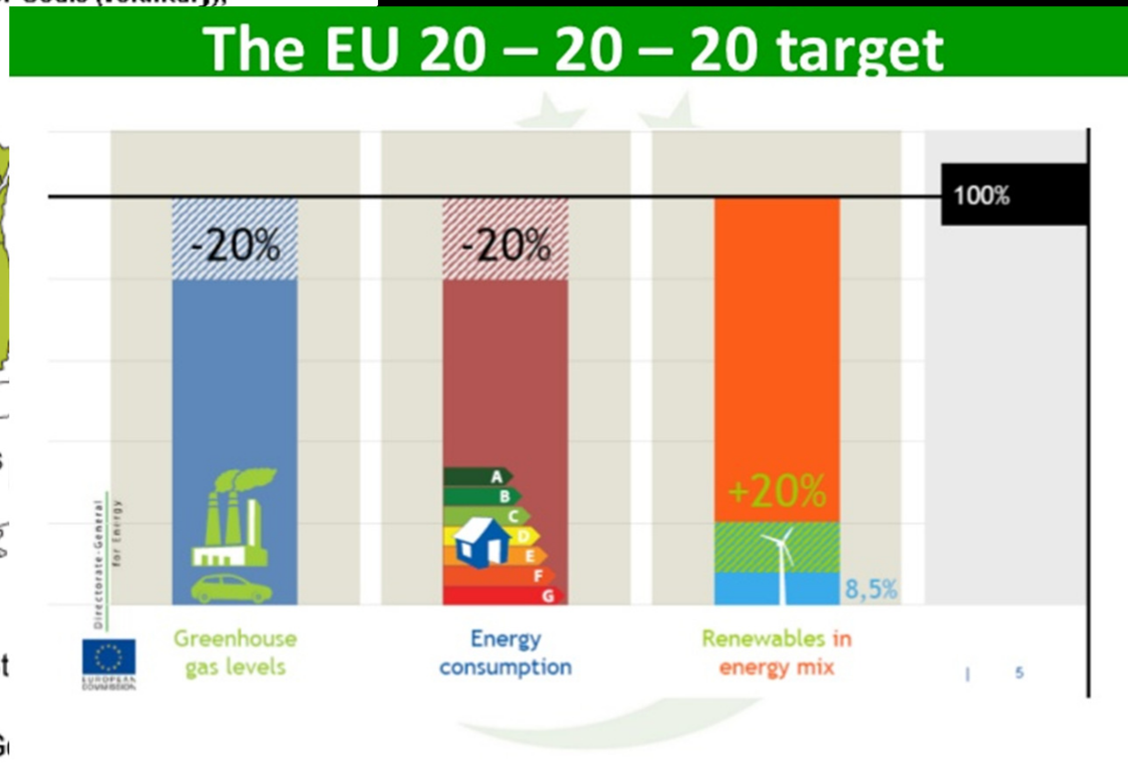


Extraction effort and research

Inducing a Transition to Reduce Greenhouse Gases

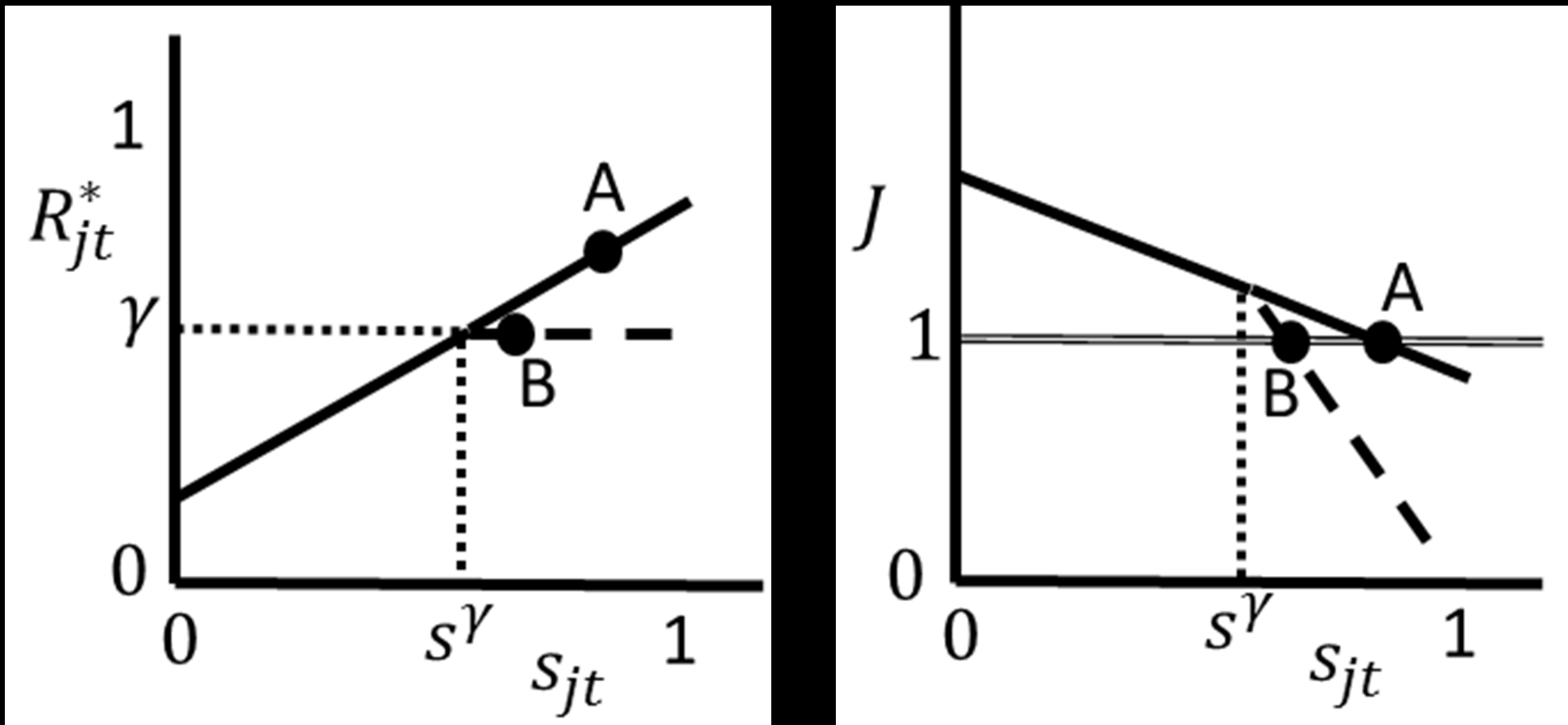
Despite economists' preference for emission prices and R&D subsidies, it has been far more common in practice to mandate or subsidize renewable energy.





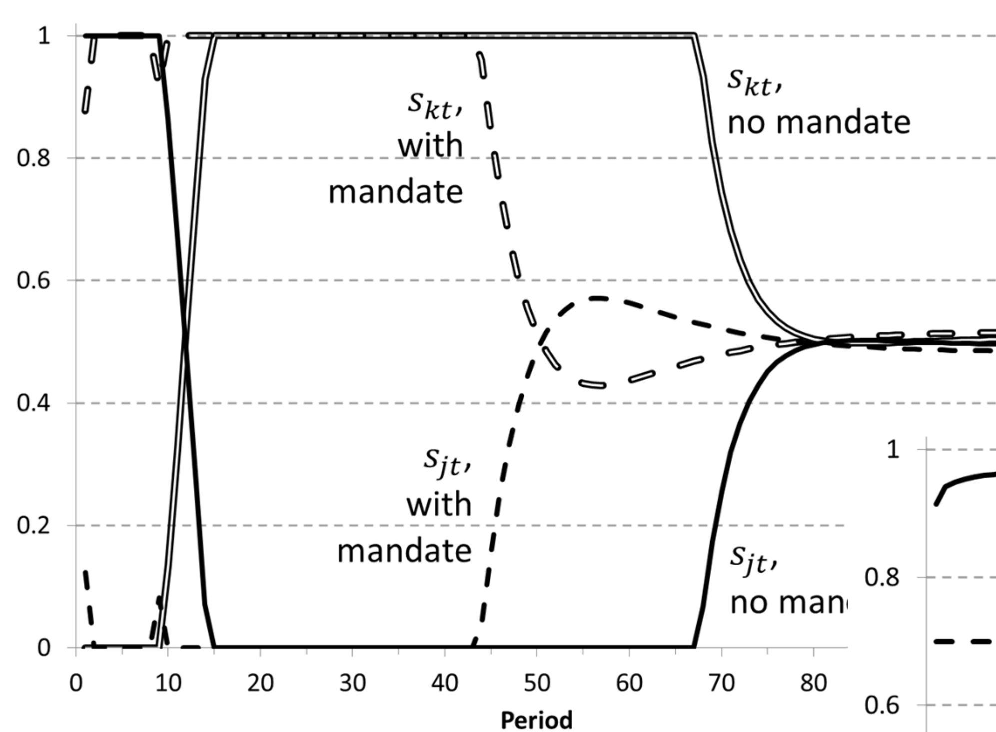
By accounting for complementarities between resources and the machines for using them, the present setting includes a novel <u>market transformation motive</u> that captures stories some advocates tell about escaping lock-in.

Let resource *k* be the clean resource. Consider a policy begun in time *t* that mandates that resource *k* have at least share γ of the market. Equilibrium changes from A to B.

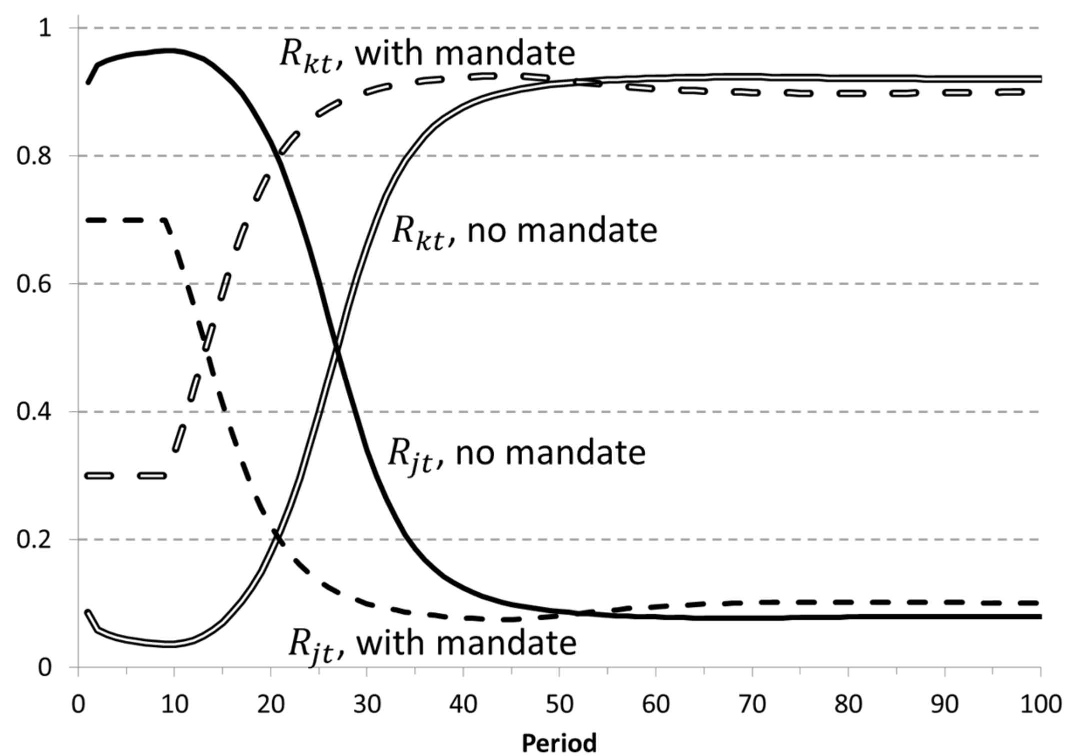


The mandate introduces a kink at s^γ.
Research and extraction both shift towards resource *k*.

When both resources receive equal weight in final-good production, we see a 30% mandate generate an immediate research transition and make extraction transition much earlier. The mandate makes itself nonbinding.

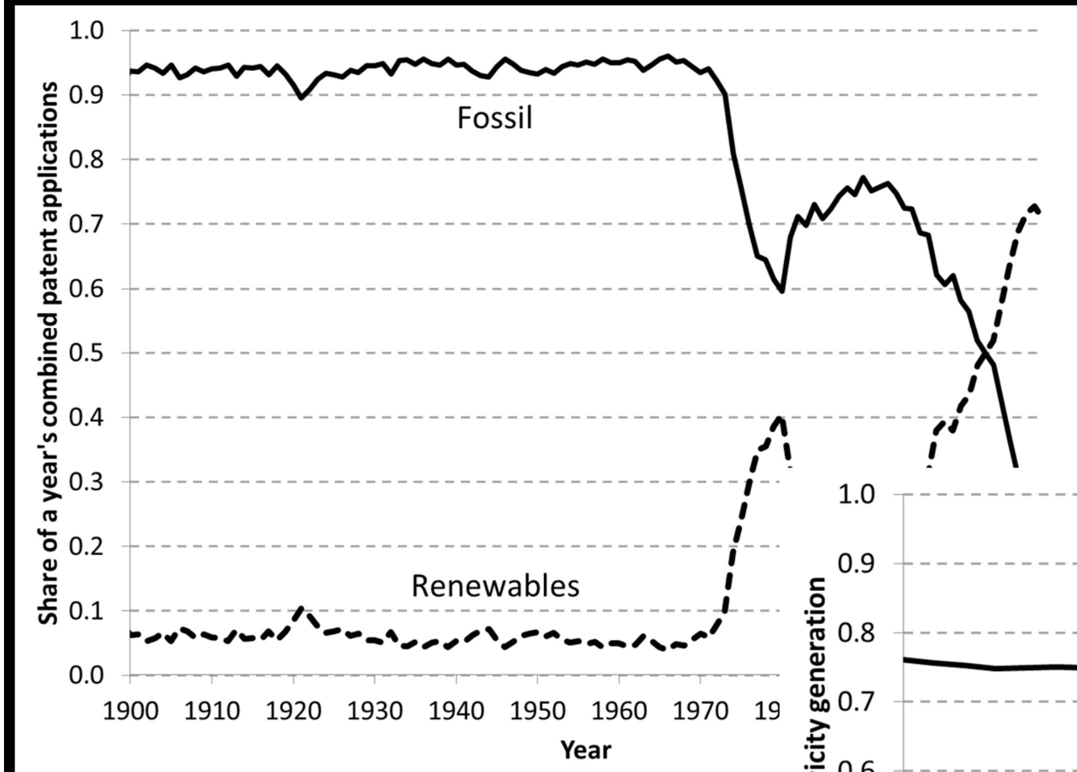


Research transitions immediately



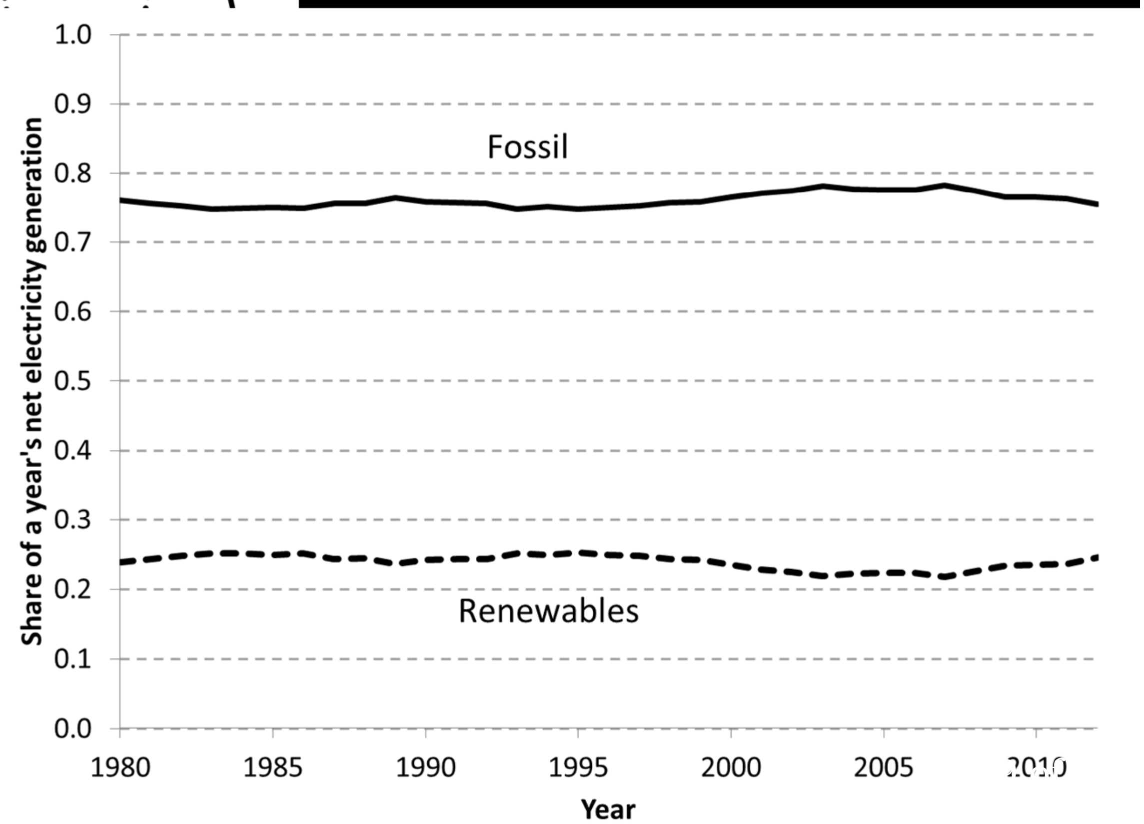
Extraction is bound by the mandate at first and transitions once technology has improved

This pattern is consistent with recent experience.



Research has transitioned.

Calculated from EIA data.



Patent data from
Antoine Dechezlepretre

Extraction has not transitioned.
Perhaps it has just begun?

Conclusion

I have integrated directed innovation and directed extraction into a setting that can match stylized facts from past energy transitions.

In previous settings, innovation incentives were independent of the allocation of extraction.

Here, complementarities between resources and the machines for using them generate market size effects, which tend to direct research towards sectors with high extraction and vice versa.

Both innovation and depletion are necessary to explain the regularity of past transitions.

I describe a novel market transformation motive for renewable energy mandates: by redirecting research effort towards renewables, they change future technology and thereby make themselves nonbinding.