Materials Scarcity and Recycling for Renewables

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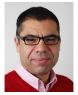
based on work with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Motivation: energy transition requires more minerals

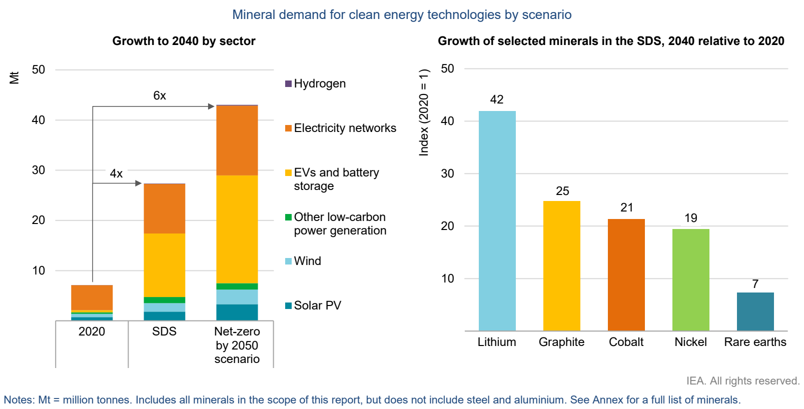
- The production of renewable sources of electricity requires relatively large amounts of mineral inputs
- Minerals are also major inputs for electricity storage and transmission

> *"The Life Cycle Assessments find that wind and solar power plants tend to require more bulk materials (namely, iron, copper, aluminum, and cement) than coal- and gas-based electricity per unit of generation. [...]"*
> Hertwich et al., *PNAS* (2015)

Offshore wind plants require thirteen times more mineral resources than a similarly sized gas-fired power plant
International Energy Agency (2021)

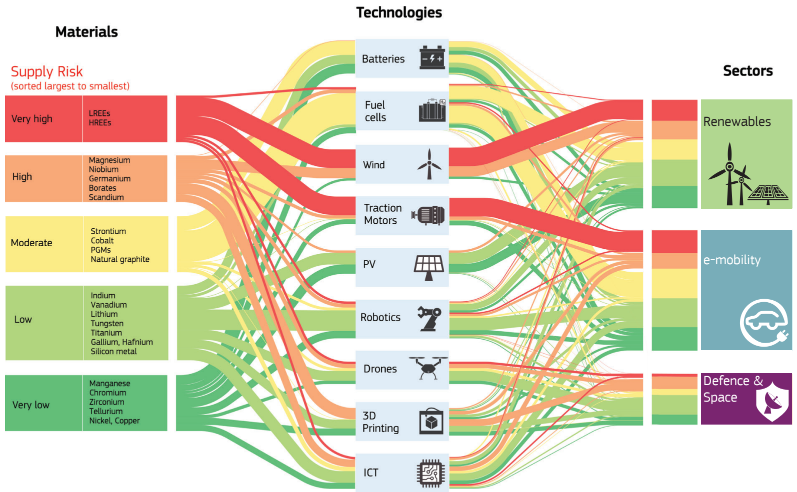
Motivation: energy transition requires more minerals

- Expected strong growth in demand



Source: International Energy Agency (2021), The Role of Critical Minerals in Clean Energy Transitions

Motivation: energy transition requires more minerals



Source: European Commission (2020), Critical materials for strategic technologies and sectors in the EU - a foresight study

Taking the issue into account

- The need of mineral resources to build the energy infrastructure essential to achieving greenhouse gas emission reduction targets is typically not taken into account in integrated assessment modelssupporting academic and public policy debate on the energy transition
- Shall we analyze the energy transition as moving from non renewable fossil resources (or carbon budget) to another non renewable resource, minerals, rather than to an unbounded flow of renewable resources, such as solar radiation?
- Yet there is a crucial asymmetry: minerals are stored in the stock of dedicated (green) capital, and can be recycled.
  - Implications of recycling for the timing of investment in renewables and for their share in the energy mix
  - Design of energy transition policy with endogenous recycling

Related literature

- Abundant literature of macro-dynamic models à la Hotelling where the renewable energy is modelled as an expensive backstop technology.
- A cost-effectiveness approach to climate change: the carbon budget constraint Chakravorty, Magné and Moreaux (2016)
- Here renewable energy differs from a backstop technology:
  - investment in renewable capacity is costly Amigues, Ayong Le Kama and Moreaux (2015)
  - and it requires scarce minerals.
- Introducing minerals and recycling is rare and recent.
  - Chazel, Bernard and Benchekroun (2020) extend Golosov, Hassler, Krusell, Tsyvinski (2014) to account for mineral resources constraints and recycling. Copper scarcity limits low-carbon energy production.
  - Luderer, Pehl, Arvesen et al. (2019): IAM derived demand for mineral resources and related emissions, without global resource constraint
- Macro-dynamic models with recycling: Pittel, Amigues and Kuhn (2010), Lafforgue and Rougé (2019), Zhou and Smulders (2021).

Outline

The centralized optimal trajectory: main trade-offs

I. Exploring the role of recycling without climate problem nor backstop technology

II. Endogenous costly recycling under carbon budget and with a backstop technology

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In the papers also:

- decentralized equilibrium and policy (optimal, constrained and myopic)

  Pommeret, Ricci and Schubert (2021), Critical raw materials for the energy transition, *European Economic Review* forthcoming
- alternative determinants of the timing of investment in renewables

  Fabre, Fodha and Ricci (2020), Mineral resources for renewable energy: Optimal timing of energy production, *Resource and Energy Economics*

Mineral for renewables: optimal timing

- Utility from the consumption of energy services q_t

$$u(q_t) = \frac{1}{1-\varepsilon} q_t^{1-\varepsilon}$$

- Energy services from two sources

$$q_t = x_t^{\gamma} y_t^{1-\gamma} \qquad \gamma \in (0,1)$$

  - a flow x_t from non-renewable resources (conventional power),
  - a flow y_t from renewable sources (wind power)
- conventional power is produced out of a NRR, the "fossil"resource f_t

$$x_t = f_t$$

- No extraction costs
- The quantity of fossil resources is limited

$$\sum_{t \geq 0} f_t \leq F$$

Mineral for renewables: optimal timing

- y_t wind power is produced employing a stock of “green”capital K_t

$$y_t = \phi K_t$$

- Green capital K_t encompasses currently extracted minerals (the primary resource m_t) and the stock of secondary minerals recycled from previous period's green capital δK_{t-1}, with $\delta \in [0,1]$ **exogenous**
- No extraction costs
- Assuming perfect substitutability between primary and secondary mineral resources, and infinite recycling

$$K_t = \sum_{\tau=0}^{t} m_\tau \delta^{t-\tau} + K_{-1}\delta^{t+1}$$

- The quantity of mineral resources is limited crucial

$$\sum_{t\geq 0} m_t \leq M$$

Mineral for renewables: optimal timing

A benevolent planner chooses the path of resource extraction to solve

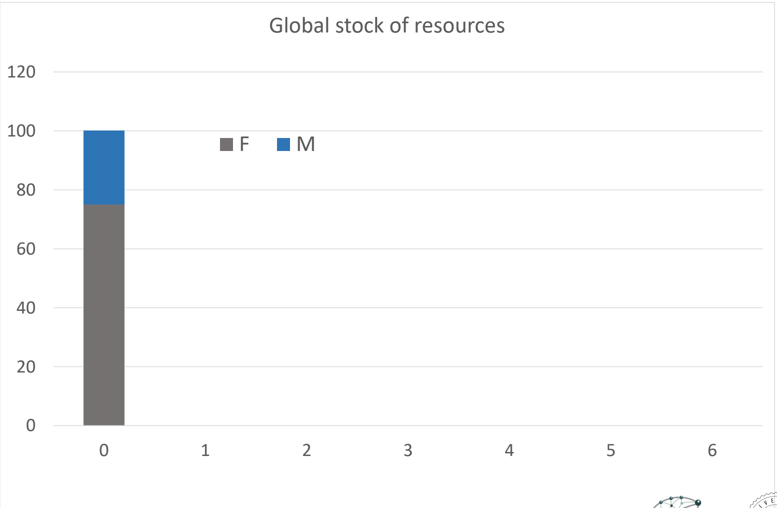
$$\max \sum_{t\geq 0} \left(\frac{1}{1+\rho}\right)^t \frac{1}{1-\varepsilon} q_t^{1-\varepsilon}$$

$$st \begin{cases} q_t = (f_t)^\gamma (K_t)^{1-\gamma} \\ K_t = K_{-1}\delta^{t+1} + \sum_{\tau=0}^{t} m_\tau \delta^{t-\tau} \\ F \geq \sum_{t\geq 0} f_t \\ M \geq \sum_{t\geq 0} m_t \end{cases}$$

$$f_t, m_t \geq 0 \ , \ M, F, K_{-1} \text{ given}$$

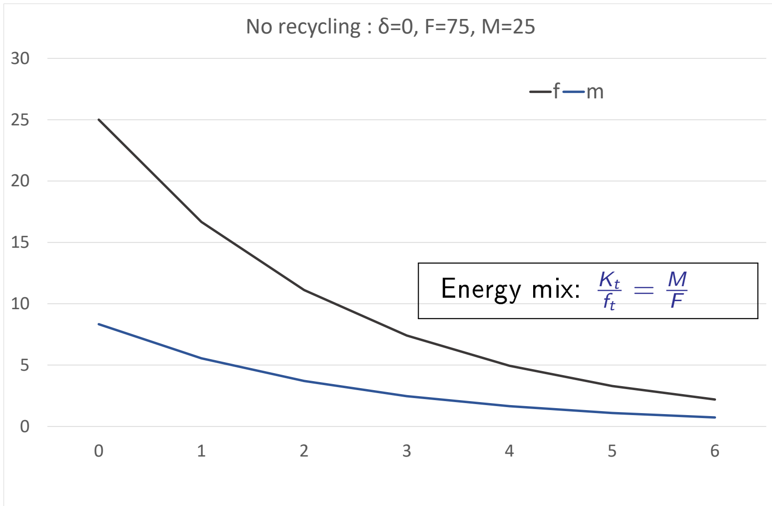
Mineral for renewables: optimal timing

- Let $K_{-1} = 0$ and $\delta = 0$: two cakes of different size



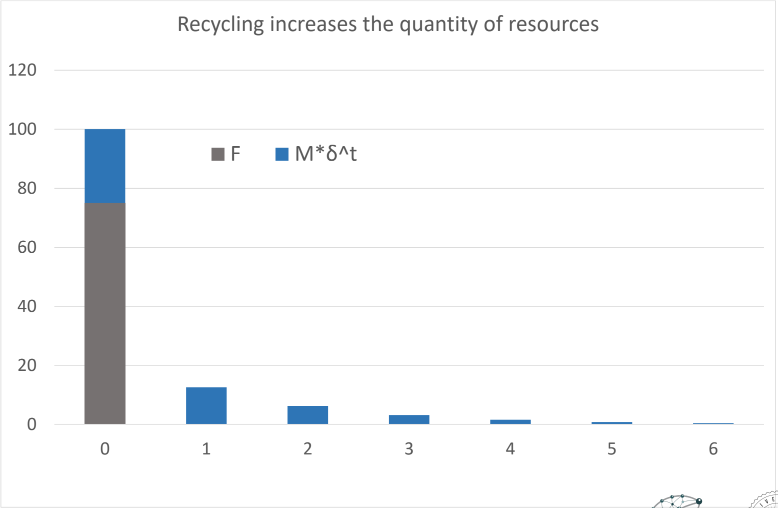
Mineral for renewables: optimal timing

- Let $K_{-1} = 0$ and $\delta = 0$: according to $r \equiv \left(\frac{1}{1+\rho}\right)^{\frac{1}{\varepsilon}}$



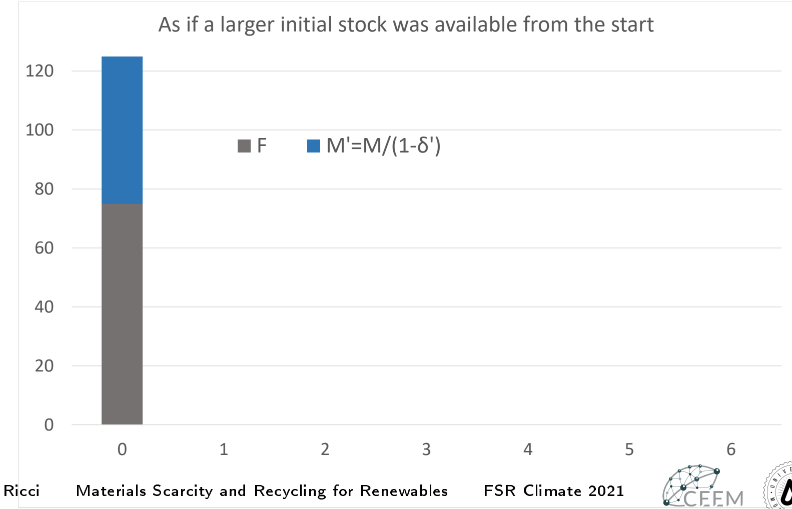
Mineral for renewables: optimal timing

- Let $K_{-1} = 0$ and $\delta > 0$: more abundant resources



Mineral for renewables: optimal timing

- Let $K_{-1} = 0$ and $\delta > 0$: a wealth effect, as if $\delta = 0$ but $M' > M$



Mineral for renewables: optimal timing

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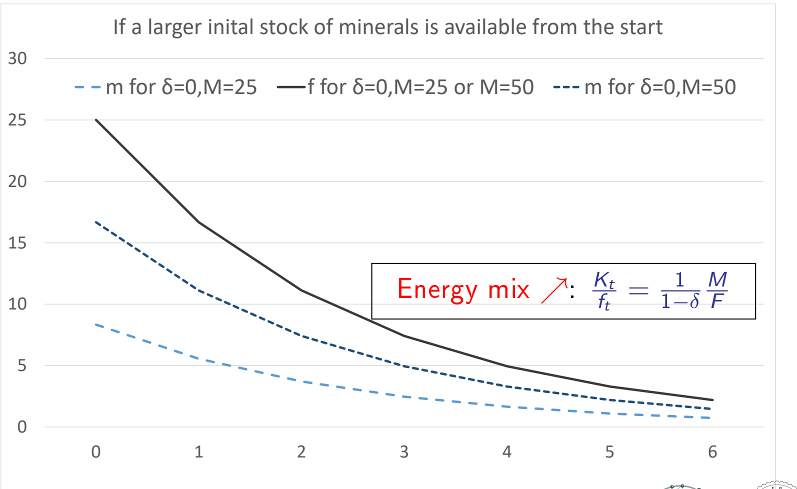
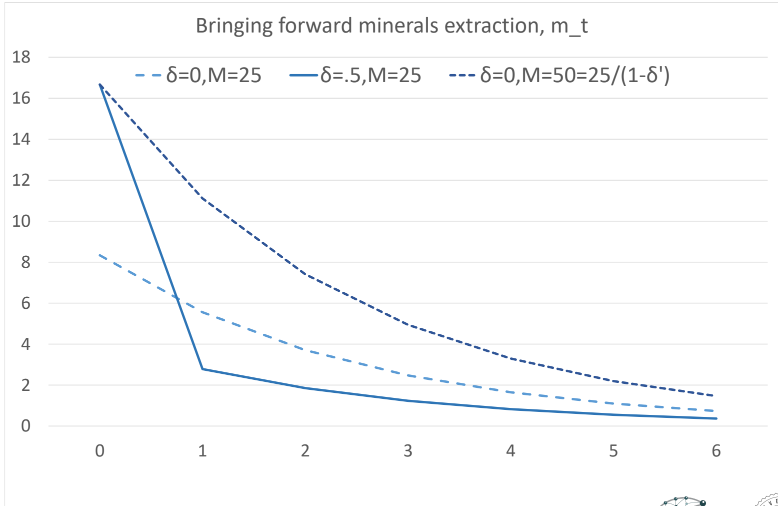


Mineral for renewables: optimal timing

- Let $K_{-1} = 0$ and $\delta > 0$: adjust the mineral extraction path



Mineral for renewables: optimal timing

Result

When there is no endowment of green capital $K_{-1} = 0$ and the recycling rate is below the social discount rate $\delta < r$, the optimal trajectories imply that

the larger is the recycling rate $\delta \in [0, r)$

- the more intensive in renewable energy is the constant input ratio
- the greater is the extraction of minerals in the first period
- the larger is green capital at every period

$$\forall t \geq 0 \ \frac{x_t}{y_t} = \frac{f_t}{K_t} = \frac{1}{1-\delta}\frac{F}{M}$$

$$m_0 = \frac{1-r}{1-\delta}M$$

$$\forall t \geq 1 \ \frac{f_t}{m_t} = \frac{r}{r-\delta}(1-\delta)\frac{F}{M}$$

Take home message

- ♠ The **pessimistic stance**:
  Since green capital relies on mineral inputs, its potential contribution to help overcoming the scarcity of conventional energy sources is weaker than generally though
- Yet minerals can be recycled, while fossil resources cannot, therefore:
- ♡ An original **pro-renewable energy argument**:
  The energy mix shall be the more intensive in renewables, the more so the higher the productivity of recycling
- ♡ An original **pro active argument**:
  Investment in green capital to produce energy from renewable sources shall be brought forward the more so the higher the productivity of recycling

Fabre, Fodha and Ricci (2020), Mineral resources for renewable energy: Optimal timing of energy production, *Resource and Energy Economics*

Next

How to choose the recycling rate?

II. Endogenous costly recycling under carbon budget and with a backstop technology

- Pommeret, Ricci and Schubert (2021), Critical raw materials for the energy transition, *European Economic Review* forthcoming

Energy transition with optimal minerals recycling

Stylized dynamic deterministic model of the optimal choice of the electricity mix – fossil and renewables with storage (Pommeret and Schubert, 2021)

- energy consumption q_t based on fossil and/or renewables
- fossil energy, x_t, is abundant but emits CO_2, εx_t
- there is a carbon budget on cumulative emissions $X_t \leq \overline{X}$
- renewable energy, y_t, is clean
- coal and solar are available at zero variable costs
- coal-fired power plants already exist (no capacity constraint)
- the initial renewables capacity K_0 is small so that investment I_t is required in order to build up capacity $\dot{K}_t$,

Energy transition with optimal minerals recycling

- Investment in renewables capacity K_t

  implies adjustment costs $C(I_t)$

  and requires:
  - minerals, m_t, available in finite stock M_0
  - or an inexhaustible expensive backstop input, b_t, at unit cost ν
  - or recycled green capital
    - $\alpha_t \in [0,1]$: rate of recycling of the depreciated green capital δK_t.
    - cost of recycling: $R(\alpha_t, \delta K_t) \equiv \eta(\alpha_t)\delta K_t$
    - $\eta(\alpha) \geq 0$, $\eta'(\alpha) \geq 0$ and $\eta''(\alpha) \geq 0$
    - $\eta'(1) \geq \nu$, the cost of perfect recycling (i.e. $\alpha_t = 1$) is larger than the cost of using the backstop
    - $\eta'(0) > \zeta(0) > 0$, initially minerals are not enough valuable to make any recycling worthy technology instead

Energy transition with optimal minerals recycling

The planner's problem:

$$\max \int_0^{\infty} e^{-\rho t}\left[u(q_t) - C(I_t) - \nu b_t - \eta(\alpha_t)\delta K_t\right] dt$$

$q_t = x_t + \phi K_t$		energy consumption
$\dot{X}_t = \varepsilon x_t$	value: $\lambda_t \geq 0$	carbon stock
$\dot{K}_t = I_t - \delta K_t$	value: $\mu_t \geq 0$	green capital
$I_t = m_t + b_t + \alpha_t \delta K_t$		investment
$\dot{M}_t = -m_t$	value: $\zeta_t \geq 0$	minerals' stock

$$X_t \leq \overline{X}, \quad M_t \geq 0, \quad x_t \geq 0, \quad m_t \geq 0, \quad b_t \geq 0, \quad 0 \leq \alpha_t \leq 1$$

$$X(0) = X_0 \geq 0, \quad Y(0) = Y_0 \geq 0 \text{ and } M(0) = M_0 \geq 0 \text{ given}$$

Sequence of phases

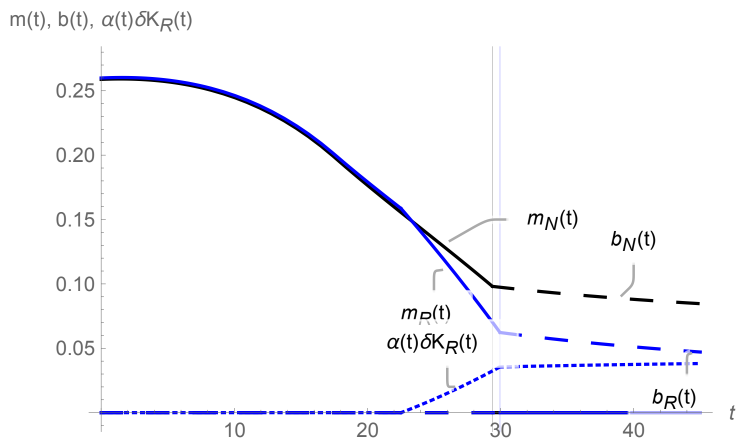
T_X date at which the carbon budget is exhausted
T_α date at which recycling begins
T_M date at which the minerals stock is exhausted
T_b date at which the backstop starts being used

Results for one specific sequence:

0 (T_x, T_m) → T_X	T_X → T_α	T_α → T_M, T_b	T_M, T_b → t
$x_t > 0$	$x_t = 0$	$x_t = 0$	$x_t = 0$
$m_t > 0$	$m_t > 0$	$m_t > 0$	$m_t = 0$
$b_t = 0$	$b_t = 0$	$b_t = 0$	$b_t > 0$
$\alpha_t =$	$\alpha_t = 0$	$\alpha_t > 0$	$\alpha_t > 0$

Solution method

Comparing the optimum with and without recycling



Comparing the optimum with and without recycling

Fairyland: $K^* \nearrow$

With recycling there is more green capital at steady sate

- This means that we choose larger investment δK^*

  which implies higher capital adjustment costs $C(I)$
- In fact, the unit cost of the investment "input" is lower
  - it equals ν without recycling, i.e. the "input" is 100% backstop
  - but with recycling, it equals a weighted average of ν and $\eta(\alpha^*)$, i.e. of the costs of the backstop technology and of recycling

♠ this feature limits the comparability and it's due to the assumption that the backstop is recycled too

Comparing the optimum with and without recycling

Better off: $q \nearrow$

With recycling energy consumption is always higher

- This reflects the positive income effect

  due to the less stringent constraint of natural resources scarcity
  - aside from recycling the backstop, if you extract all the mineral at date 0 and recycle at constant rate $\tilde{\alpha}$, you can use $\frac{M_0}{1-\tilde{\alpha}}$ mineral inputs for investment instead of M_0
  - green capital, mineral and fossil resources' values fall

♡ Developing recycling technologies is welfare improving

figure

Comparing the optimum with and without recycling

Green paradox: $x_0 \nearrow$, $T_X \searrow$

Recycling induces earlier use of fossil resources and their exhaustion

- Initially, fossil resource use increases

  in order to increase the initial electricity consumption (q_0), since
  - the initial stock of green capital is given (K_0)
  - and it is preferable to smooth investment in green capital ($C(I)$)
  - while fossil resource use ifs fully flexible
    (no extraction costs, no capacity constraint)

♣ This green paradox implies no welfare loss (carbon budget framework)

Comparing the optimum with and without recycling

Timing of the energy transition: $T_X \searrow$, $T_M = T_b \nearrow$

With recycling fossil phase-out is brought forward, and the adoption of the backstop technology (thus mineral exhaustion) is postponed.

Several mechanisms are at work.

Abstract from investment costs (set $C(I) = 0$)

- without recycling, two non renewable resources available at no cost, vs a costly backstop

  in line with the Herfindahl principle of *least cost first*: exhaust first fossils and minerals, then at some date T_b switch to the backstop
- with recycling
  - “as if” more abundant natural resources
    $\Rightarrow$ postpone the use of the backstop: $T'_b > T_b$
  - moreover, recycling is a technology that is asymmetric with respect to time ...

Comparing the optimum with and without recycling

Timing of the energy transition: $T_X \searrow$, $T_M = T_b \nearrow$

With recycling fossil phase-out is brought forward, and the adoption of the backstop technology (thus mineral exhaustion) is postponed.

Several mechanisms are at work.

Abstract from investment costs (set $C(I) = 0$)

- with recycling, carefully design when using fossils rather than minerals
  - recycling is asymmetric with respect to time, but not fossils
  - as in Fabre et al. (2020), put forward extraction to initially build up the green capital stock
  - here also relevant when switching to backstop, T_b:

    just before T_b it is preferable to produce with green capital than fossils, because the former allows to substitute the costly backstop with recycled inputs just after T_b, while fossils do not

◇ A novel policy precept: build up a large green capital stock

Take home message

- Minerals embedded in green capital influence the energy transition: the date of fossil phase-out, investment in green capital, the level of the carbon tax.
- Planning the energy transition as if minerals were abundant is misleading.
- Recycling improves welfare, and affects the timing of green capital investment.

Pommeret, Ricci and Schubert (2021), Critical raw materials for the energy transition, *European Economic Review* forthcoming

Road ahead

- 2021-25 Interdisciplinary project sponsored by the Agence Nationale de la Recherche
- Inspecting mineral recycling
- Equity and efficiency issues
- Dynamic trade-technology strategic interdependence
- Quantitative prospective modeling

Thank you !

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