Critical raw materials for the energy transition

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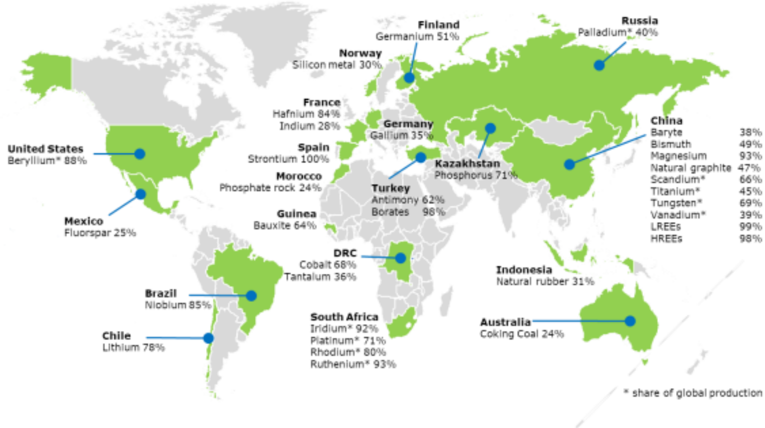
Motivation: energy transition requires CRMs

- CRMs are raw materials of economic and strategic high importance for the economy and whose supply is associated with a high risk (European Commission, 2017):
  - they are scarce,
  - there is no substitutes with current technologies,
  - consumer countries are dependent on imports,
  - supply is dominated by one or a few producers.
- European list of CRMs:

2020 Critical Raw Materials (new as compared to 2017 in bold)		
Antimony	Hafnium	Phosphorus
Baryte	Heavy Rare Earth Elements	Scandium
Beryllium	Light Rare Earth Elements	Silicon metal
Bismuth	Indium	Tantalum
Borate	Magnesium	Tungsten
Cobalt	Natural Graphite	Vanadium
Coking Coal	Natural Rubber	**Bauxite**
Fluorspar	Niobium	**Lithium**
Gallium	Platinum Group Metals	**Titanium**
Germanium	Phosphate rock	**Strontium**

Figure 1: biggest supplier countries of CRMs to the EU



Source: European Commission report on the 2020 criticality assessment

- EU: for electric vehicle batteries and energy storage, up to 18 times more lithium and 5 times more cobalt is needed in 2030 compared to now, and almost 60 times more lithium and 15 times more cobalt in 2050.
- EU: demand for rare earths used in permanent magnets, e.g. for electric vehicles, digital technologies or wind generators, could increase tenfold by 2050.
- The demand for CRMs increases rapidly with climate ambition. Example of electric storage batteries: demand for aluminium, cobalt, iron, lead, lithium, manganese and nickel could grow by more than 1000% by 2050 (World Bank, 2020).

Examples of minerals that are both crucial for the energy transition and suffering from geological scarcity:

- Silver is significantly mobilized in crystalline technologies.
  - PV is the third largest user of silver.
  - There is a real tension on the availability of the material.
  - There is no possibility of substitution in the short term (for metallisation, copper has been unsuccessfully studied and moreover, silver is not only used in metallisation).

- Cobalt is essential
  - for permanent magnets (in wind turbines)
  - in lithium-ion batteries (note that Tesla is announcing cobalt-free lithium-iron-phosphate batteries, Reuters 30/9/20), with a strongly increasing demand: less than 30% of total demand in 2000 and 60% in 2019.

  Reserves are concentrated in Congo.

- There is a need to mobilize more mineral resources to build the energy infrastructure essential to achieving greenhouse gas emission reduction targets

  → generally not taken into account by public policy driving the energy transition,

  → while some of them may be critical (UN International Resource Panel, 2020, World Bank, 2017, 202, European Commission, 2017, 2020).
- Does the energy transition simply push the boundaries of scarcity? From fossil fuels scarcity to carbon budget scarcity to mineral scarcity.
- The solution: to reduce the dependence of energy transition on CRMs through recycling or through the discovery of technologies that do not rely on CRMs.

What we do

- We build a model where the timing and other main features of the energy transition depend on
  - the relative strength of the two constraints –carbon budget and minerals' scarcity– weighting on the economy,
  - the minerals' recycling possibilities,
  - the existence (or not) of a backstop technology for CRMs.

- We take into account
  - political economy: the optimal carbon tax may not be feasible
  - regulator's myopia: the regulator may take his decisions as if minerals were abundant.

→ How much do cumulative emissions overshoot the carbon budget?

→ How much is the expected date of fossil phase-out mistaken?

Related literature

- Abundant literature of macro-dynamic models à la Hotelling where the renewable energy is modelled as an expensive backstop technology.
- Here renewable energy differs from a backstop technology:
  - production requires costly investment in capacity, but variable costs are nil,
  - investment in renewable capacity requires scarce minerals.
- Introducing minerals and recycling is rare and recent.
  - Fabre et al. (2020): the reliance of renewable energy on minerals that can be recycled favors large and early investment in green capital.
  - Lafforgue and Rouge (2019): recycling urges a more intense exploitation of the resource.
  - Chazel et al. (2020) extend Golosov et al. (2014) to account for mineral resources constraints and recycling. Copper scarcity limits low-carbon energy production.

Model's main assumptions

Stylized dynamic deterministic model of the optimal choice of the electricity mix –fossil and renewables with storage (see Pommeret and Schubert, 2019).

- fossil energy, e.g. coal, is abundant but emits CO_2,
- renewable energy, e.g. solar, is clean,
- the issue of the intermittency of renewables is solved thanks to an electricity storage technology,
- coal and solar are available at zero variable costs,
- coal-fired power plants already exist (no capacity constraint),
- the initial solar plus storage capacity is small so that investments are to be made in order to build up a sizable capacity,
  - requiring CRMs,
  - which can be recycled (to a certain extent),
  - or replaced by an expensive backstop.

Outline

- Optimal energy transition under mineral's scarcity: we solve the social planner's program under the constraint of a carbon budget that cannot be exceeded. There is therefore a trade-off between using:
    - polluting fossil energy
    - clean renewable energy requiring costly investment in green capital, which relies on
        - CRMs that are being depleted
        - or a costly backstop technology.
- We analyze the optimal trajectories considering different potential successions of phases: minerals may be exhausted before or after the carbon budget is reached, depending on the relative size of the two stocks.

- Public policy for the energy transition under mineral's scarcity: we study a decentralized version of the economy and compute
  - the optimal policy
  - the consequences for the energy transition of a suboptimal policy consisting in a constant carbon tax and a feed-in premium with balanced budget, in case the optimal carbon tax is not feasible (acceptability constraint)
  - the consequences of a myopic regulation where the regulator sets a constant carbon tax in the aim of respecting the carbon budget, and does so as if minerals were abundant

  $\rightarrow$ how much do cumulative emissions overshoot the carbon budget?

  $\rightarrow$ How much is the expected date of fossil phase-out mistaken?
- We account for the possibility of recycling.

The optimal solution: social planner's programme

$$\max \int_0^\infty e^{-\rho t}[u(e(t)) - C(I(t)) - \nu b(t)]dt$$

$$e(t) = x(t) + \phi Y(t)$$

$$I(t) = \chi m(t) + b(t)$$

$$\dot{X}(t) = \varepsilon x(t) \qquad (\lambda(t))$$

$$\dot{Y}(t) = I(t) - \delta Y(t) \qquad (\mu(t))$$

$$\dot{M}(t) = -m(t) \qquad (\zeta(t))$$

$$X(t) \leq \overline{X}, \quad x(t) \geq 0, \quad M(t) \geq 0, \quad m(t) \geq 0, \quad b(t) \geq 0$$

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

Solving for the succession of phases when the carbon budget is more constraining than minerals' scarcity

First phase: $x > 0$, $m > 0$, $b = 0$. Carbon ceiling and minerals' scarcity not binding.

FOCs yield:

- $u'(x + \phi Y) = \varepsilon\lambda$: fossil is used, and marginal utility of electricity consumption is equal to the carbon value.
- $C'(m) + \zeta = \mu$: total marginal cost of using minerals to invest in green capital is equal to the shadow value of green capital. Relevant iff $\mu > \zeta$, i.e. the value of green capital is higher than the value of the mineral stock under the ground.
- $\zeta < \nu$: the scarcity rent of the mineral stock is smaller than the marginal cost of the backstop, which explains why the backstop is not used.

- The Hotelling rule applies to the carbon value and to the scarcity rent of minerals:

$$\lambda(t) = \lambda(0)e^{\rho t} \quad \text{and} \quad \zeta(t) = \zeta(0)e^{\rho t}$$

- Dynamic system in $Y(t)$ and $\mu(t)$, the renewable capacity and its shadow price.
- The first phase ends at date T_X, such that for the first time $x(t) = 0$, and $X(T_X) = \overline{X}$. T_X is defined by:

$$u'(\phi Y(T_X)) = \varepsilon\lambda(T_X)$$

and

$$\int_0^{T_X} x(t)dt = \overline{X}/\varepsilon$$

provides $\lambda(0)$.

Second phase: $x = 0$, $m > 0$, $b = 0$. Electricity production is totally clean. Minerals' scarcity is not binding.

- Dynamic system in $Y(t)$ and $\mu(t)$.
- At the end of the second phase, costs of mineral and backstop are equal, the mineral stock is exhausted and minerals are replaced by the backstop. This occurs at date T_M defined by $\zeta(T_M) = \nu$, when

  $$C'(I(T_M)) + \nu = \mu(T_M) \quad \text{with} \quad I(T_M) = m(T_M^-) = b(T_M^+)$$

  and

  $$\int_0^{T_M} m(t)dt = M_0$$

  provides $\zeta(0)$.

Third phase: $x = m = 0$, $b > 0$.

Green investment consists exclusively of the backstop technology. The dynamic system in $Y(t)$ and $\mu(t)$ converges to a steady state (μ^*, Y^*), defined by:

$$\begin{cases} (\rho + \delta)\mu^* = \phi u'(\phi Y^*) \\ C'^{-1}(\mu^* - \nu) = \delta Y^* \end{cases}$$

The steady state is saddle path.

This sequence is optimal for a relatively stringent climate policy, large minerals stock and small initial green capacity, and for a specific configuration of the costs.

Decentralized economy

- Agents:
  - a representative electricity consumer,
  - utilities producing electricity from either fossil resources or green capital, that they own,
  - owners of mineral resources,
  - owners of fossil resources,
  - regulator.
- Investment in green capital by utilities mobilizes either mineral resources or the backstop technology, available in-house at a constant cost, ν.
- All markets are perfectly competitive.
- Policy tools:
  - tax on carbon emissions, τ,
  - feed-in-premium (FIP) for electricity produced from green capital, σ,
  - lump sum transfer to the household, $\mathcal{T}$.

Behaviours

Electricity consumer

She faces a purchaser price of electricity P_e.
Electricity demand schedule given by:

$$u'(e(t)) = P_e(t)$$

Fossil producers
No extraction costs and no scarcity: $P_x(t) = 0, \forall t \geq 0$

CRMs producers

No extraction cost but limited stock: $P_m(t) = \zeta_d(t)$, with ζ_d the scarcity rent, following the Hotelling rule, and

$$\int_0^{T_M} m(t)dt = M_0$$

Power producer

Solves an intertemporal program, based on the expected evolution of the electricity price P_e, the prices of the inputs, fossil P_x and minerals P_m, and policy tools:

$$\max_{x(t),m(t),b(t)} \int_0^\infty [P_e(t)x(t) + (P_e(t)+\sigma(t))\,\phi Y(t) - (P_x(t)+\varepsilon\tau(t))\,x(t) - C(I(t)) - P_m(t)m(t) - \nu b(t)]\,e^{-rt}dt$$

$$\dot{Y}(t) = I(t) - \delta Y(t) \qquad (\mu_d(t))$$

$$I(t) = m(t) + b(t)$$

$$x(t) \geq 0,\;\; m(t) \geq 0,\;\; b(t) \geq 0$$

FOC:

$$P_e(t) \leq P_x(t) + \varepsilon\tau(t)$$

$$P_m(t) + C'(I(t)) \geq \mu_d(t)$$

$$\nu + C'(I(t)) \geq \mu_d(t)$$

$+$ dynamic system in $Y(t)$ and $\mu_d(t)$.

Equilibrium

At equilibrium again three phases:

- electricity produced with fossil complemented by renewables, investment in renewable capacity using minerals
- electricity produced with renewables only, investment in renewable capacity using minerals
- electricity produced with renewables only, investment in renewable capacity using the backstop technology.

Optimal policy

The government maximizes social welfare under the climate constraint $\overline{X}$.

With

- a carbon tax equal to the optimal value of carbon $\tau(t) = \lambda(t)$
- and tax revenue transferred lump-sum at each date to the consumer,

the economy evolves along the optimal trajectory.

Constant carbon tax and FIP with balanced budget

- Real world policy making: the regulator is constrained on the choice of the policy instruments.
- Suboptimal policy studied here: constant carbon tax with proceeds used to subsidize investment in renewable energy.
- Thus only choice keft to the regulator is the one of the carbon tax level, the FIP being then determined by the balanced budget condition:

$$\tau \varepsilon x(t) = \sigma(t)\phi Y(t)$$

- Implies that when fossil is phased out the FIP becomes nil.
- Carbon tax set at the level ensuring the respect of the carbon budget.

Illustrative numerical simulations

Specifications:

$$u(e) \equiv \gamma \ln e$$

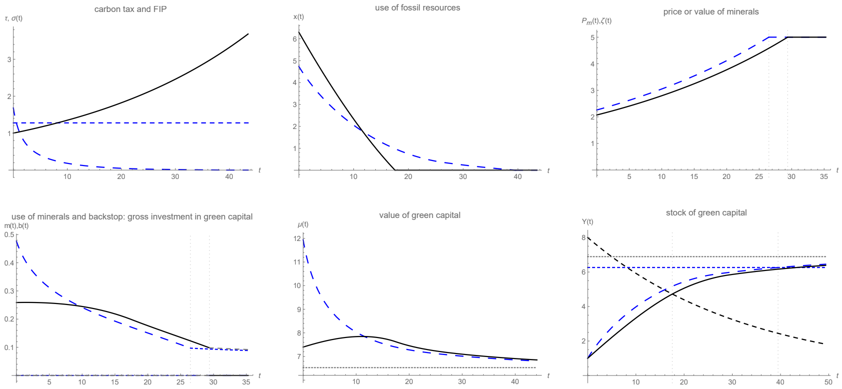
and

$$C(I) \equiv c_1 I + \frac{c_2}{2} I^2$$

Parameters:

ϕ	ρ	δ	ε	γ	ν	c_1	c_2	Y_0	M_0	$\overline{X}$
0.9	0.03	0.01	0.25	1.8	5	0.15	20	1	6	203.28

Optimal versus suboptimal policies.
(Dashed blue lines for the suboptimal case)



Initial carbon tax higher than at the optimum. Acceptability???

Myopic regulation

- The regulator (and only her) is not aware that minerals used for investment in green capital are scarce.
  $\rightarrow$ exogenous price $\hat{P}_m$ + does not imagine that the electricity producer will ever want to use the backstop technology.
- First step: we model the economy as the regulator does.
  $\rightarrow$ we can determine the constant carbon tax to which the regulator commits from the start, as function of the initial observed price of minerals.
- Second step: we consider how this policy affects the agents in the economy, when they are aware of mineral resource scarcity, by injecting this level of the constant carbon tax in the solution analyzed previously (note that $\hat{P}_m = P_m(0)$.)

- Main mechanism: ignoring minerals' exhaustibility boils down to under-estimating their real cost, hence that of the energy transition.
- The regulator undersizes environmental policy.
- Fossil use is higher.
- Cumulative carbon emissions overshoot the target,

Compararison of the scenarii

	optimal policy	suboptimal policy	myopic forecast	myopic regulation
Welfare	39.8	37.1	44.8	37.7†
Initial carbon tax	1	1.277	1.248	1.248
Carbon tax growth rate	0.03	0	0	0
Initial FIP	0	1.681	1.737	1.688
Steady state green capital	6.89	6.89	10.14	6.89
Fossil phase-out date	17.55	39.47	27.06	46.65
Minerals exhaustion date	29.39	26.49	-	26.49
Initial price of minerals	2.07	2.26	2.26	2.26
Initial value of green capital	7.397	11.939	11.577	11.939

† Cumulative carbon emissions overshoot the carbon budget at no social cost.

Recycling minerals

- If CRMs play an important role for the energy transition, recycling them represents a potentially interesting opportunity.
- $\alpha(t) \in [0,1]$: rate of recycling of the depreciated green capital $\delta Y(t)$.
- Cost of recycling:

$$R(\alpha(t), \delta Y(t)) \equiv r(\alpha(t))\delta Y(t)$$

  with $r(\alpha) \geq 0$, $r'(\alpha) \geq 0$ and $r''(\alpha) \geq 0$
- To focus on plausible cases where recycling is limited, we assume that the cost of perfect recycling (i.e. $\alpha(t) = 1$) is larger than the cost of using the backstop technology instead.

Optimal energy transition with minerals recycling

Planner's problem:

$$\max \int_0^{\infty} e^{-\rho t}[u(e(t)) - C(I(t)) - \nu b(t) - r(\alpha(t))\delta Y(t)]dt$$

$$e(t) = x(t) + \phi Y(t)$$

$$I(t) = m(t) + b(t) + \alpha(t)\delta Y(t)$$

$$\dot{X}(t) = \varepsilon x(t)$$

$$\dot{Y}(t) = I(t) - \delta Y(t)$$

$$\dot{M}(t) = -m(t)$$

$$X(t) \leq \overline{X}, \quad x(t) \geq 0, \quad M(t) \geq 0, \quad m(t) \geq 0, \quad b(t) \geq 0, \quad 0 \leq \alpha(t) \leq 1$$

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

Succession of phases when the carbon budget is more constraining than minerals' scarcity

The transition is achieved in four phases:

1. Electricity produced with fossil fuels complemented by renewables, while the renewable capacity is built up using minerals, no recycling;

High recycling cost

2. Electricity totally clean, investment in renewable capacity using minerals, no recycling;
3. Electricity totally clean, investment in renewable capacity using minerals, recycling starts;

Low recycling cost

2. Electricity produced with fossil fuels and renewables, investment in renewable capacity using minerals, recycling starts;
3. Electricity totally clean, investment in renewable capacity using minerals, recycling;

4. Electricity totally clean, investment in renewable capacity uses the backstop technology, up to the steady state.

Comparison with the optimum without recycling

- Smaller initial carbon value, hence more fossil fuel used in the short run.
- Fossil phased out sooner.
- Mineral stock exhausted later.
- Higher steady state renewable capacity, allowing higher electricity consumption in the long run.

The lower the cost of recycling the larger these effects