Strategic Considerations of Critical Mineral Depletion, Recycling, and Substitution

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Oct. 2024

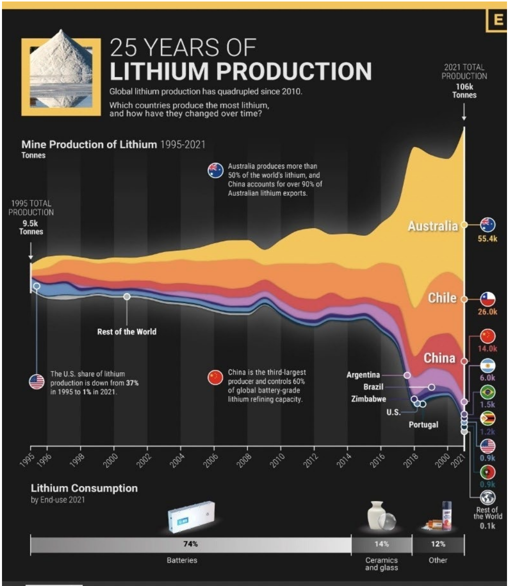
Increasing demand of Critical minerals

- May 2021, International Energy Agency (IEA): *a typical electric car requires* **six times** *the mineral inputs of a conventional car and an onshore wind plant requires* **nine times more** *mineral resources than a gas-fired plant.*
- To meet the Paris Agreement goals, the share of total demand rises significantly over the next two decades:
  - over 40% for copper and rare earth elements (REEs),
  - 60-70% for nickel and cobalt,
  - almost 90% for lithium – Imerys will contribute to it obviously.
- The United States Energy Act of 2020 defines " critical mineral" as a non-fuel mineral or mineral material essential to the economic or national security of the U.S. and which has a supply chain vulnerable to disruption. United States Geological Survey (USGS) 2022 listed 50 CMs.
- EU has similar definition: in 2011, First list of 14 CM; Fourth list in 2020 of 30 CMs.
- we focus only on energy transition related.

Supply chains of critical minerals

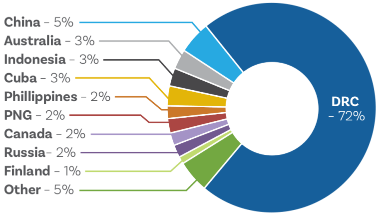
- International Renewable Energy Agency (2022): the majority of REE mining (58% in 2020) and purification (90%), permanent magnet production (90%) are concentrated in China.
- The United States Geological Survey(USGS) 2020:
  - 80% of U.S.'s refined REEs imports come from China.
  - production from titanium minerals is almost non-existent from 2021.
  - China and Russia supply 2/3 of world total titanium supply.
- European Union:
  - does not produce any REEs, 98% imports from China;
  - imports 78% of its lithium from Chile;
- IEA: nickel demand for use in batteries for electric vehicles and back-up energy storage will grow from 196,000 tons in 2020 to 3,804,000 tons by 2040.

Fact (1)– 25 years Lithium production

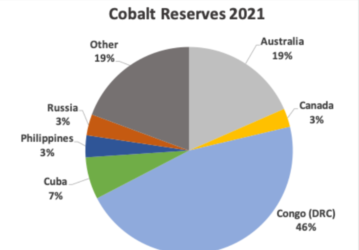


Fact (3)– global Cobalt production and reserve

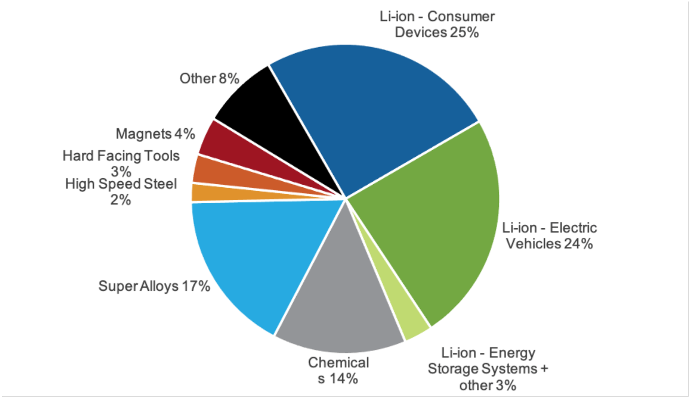
Figure 19 – **Global Cobalt Production – 2021**



Source: Wood Mackenzie



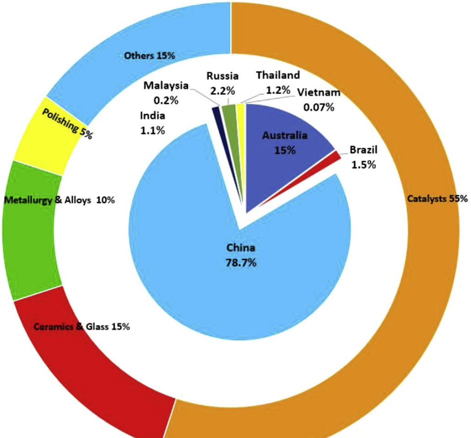
Fact (4)– the use of Cobalt



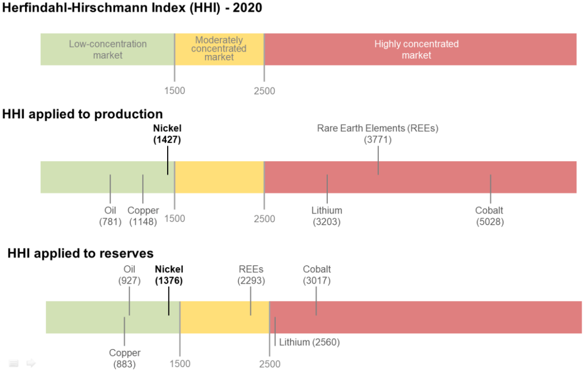
Fact (5)– global REEs production and use

Rare Earth Metals Market Outlook 2031

The **global rare earth metals market** was valued at **US$ 10.6 Bn** in **2021**
It is estimated to grow at a CAGR of **7.4%** from 2022 to 2031
The **global rare earth metals market value** is expected to reach **US$ 21.7 Bn** by the end of **2031**



Fact (6)– Concentration of Cobalt, Lithium and REE

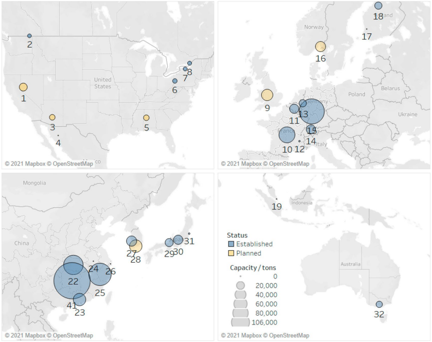


Recycling technology of critical mineral

- Some metals, ex aluminium, copper, iron and even platinum, are frequently recycled.
- Only 1% percent of Lithium-ion batteries (LIB) get recycled in US and EU (Worldwide, it is less than 5%), but nearly 99% Lead-acid batteries get recycled (Yanamandra et al, 2022).
- Cobalt has better rates of recycling than lithium, with an estimated end-of-life recycling rate of 32 per cent (OECD, 2019b).

- LIB recycling technology is partly ready.
- By 2040, 58% of all cars sold worldwide are anticipated to be electric vehicles (EVs) worldwide. (BloombergNEF. "Electric Vehicle Outlook 2021")
- IEA: EVs produced in 2019 alone generated 500,000 tons of LIB waste, and by 2040 could be as much as 8 million tons.

Recycling of lithium-ion batteries (LIB)



Established and planned global Li-ion battery recycling facilities as of November 2021.(27−42,57)

DOI: (10.1021/acsenergylett.1c02602)

Recycling of lithium-ion batteries

- More than two-thirds of the current recycling capacity is in China;
- The largest battery recycling facility in the world, with 100,000 ton capacity, is operated by Brunp Recycling Technologies in Hunan Province, China.
- Approximately 90% of recycling capacity is concentrated in Europe and East Asia.

- In steel and aluminum industries recycling leads to 60–75 per cent and 90–97 per cent energy savings, respectively, compared to primary mining (Johansson, 2016).

Substitution- (I) alternative

- Sodium is abundant– thus cheaper and reducing the dependency on other countries.

  So far

- A sodium battery will be bigger and heavier than a lithium one of the same capacity.
- Sodium batteries could work for grid-scale storage, home storage and heavy forms of transport, such as lorries and ships.
- Sodium batteries are less durable than their Li-ion counterparts.

Substitution- (II) China

1. Volkswagen predicted that by 2025 half of all cars sold in China would be electric.
2. China (since 2021)
   - At least 36 Chinese companies that are either making or investigating sodium batteries:
   - The leading one CATL, the world's largest maker of Li-ion vehicle batteries. In 2021 it announced the world's first sodium battery for electric vehicles.
   - Chery, a Chinese carmaker, will use sodium batteries, alongside some lithium ones, in its iCAR brand, to be launched shortly.
   - April 2023 at the Shanghai Auto Show, BYD's Seagull hatchback will soon be equipped with sodium batteries.

Substitution- (III) Europe

European Sodium-ion Battery initiatives:

- SIMBA project: nearly 20 research institutes,universities, and companies across Europe. The primary goal is to develop a home Sodium-ion Battery.
- NAIMA project: from December 2019 to May 2023, brought together companies, research institutions, and universities from various European countries.
- German ENTISE: Led by German battery supplier Varta, aims to develop industrial-scale Sodium-ion Battery technology.
- Fraunhofer ISI (Europe's largest application oriented research organization, based in Karlsruhe) has explored alternative battery technologies up to 2045, with focus on Metal-Ion related Batteries.
- Tiamat Energy (located in Amiens) is planning a factory for sodium-ion battery cells with an annual capacity of 5 GWh in northern France.
- Altris, in Sweden, developer and prototype manufacturer of sodium-ion batteries.
- ...

Substitution- (IV) Other parts

- Eos Energy works on zinc-powered energy storage. They recently received a nearly $400 million loan from the US Department of Energy, focusing on Zinc batteries.
- Natron Energy, of Santa Clara, California, to build $1.4B sodium-ion battery plant in North Carolina
- ...

Questions

- What is the optimal strategy for an exporting country supplying the market?
- What is the recycling or substitution rate required of the importing country in order to reduce its dependency on the exporting country

- When is it the best moment to start recycling or substitution?
- Should recycling and substitution coexit, or one and only one exits in the importing countries?

- What if exporting countries also use the critical mineral expect exporting?
- What if exporting countries also develop substitutions?

Related Literature (I) recycling

- (Aluminum market) **Monopoly** of Aluminium with **competitive recycling**. Gaskins (1974, JET), Swan (1980, JPE) and Martin (1982, J Indu E)...
- (Phosphorus market) Weihard and Seyhand (2009, EE) and Seyhand et al (2012, RCR): recycling and distribution of Phosphorus.
- Weigl and Young (2023, RCR) recycling of the Lithium-Ion Battery in the USA. – **No competition**.

Related Literature (II) Backstop substitution

- Dasgupta and Stiglitz (1981, 1982), Dasgupata, Gilbert and Stiglitz (1983, Econometria)...competition between importing and exporting countries: Constant marginal production cost in substitute - regime change immediately
- Hung and Quyen (1993): Variable cost, the regime change is not immediate, rather takes some time. The setting is closer to ours. But ONE country model. The optimal time is not when the innovation should take place, rather when the R&D should start.

- We consider the choice between substitution and recycling: The Importing country could invests in R&D for recycling the imported critical mineral or development of a backstop substitution, such as Sodium battery to replace lithium battery.
- Before substitution is ready for the market, the minerals are **not only essential but critical** for the energy transition.

General assumptions

- Two players: $i-$-importer; $j-$exporter of critical mineral.
- Before recycling (or backstop substitute) supplies to the market, player i imports critical mineral from country j and invests in R&D for recycling and/or backstop substitution.
- T_l the moment when the invention l starts to supply the market, $l = r, s$
- Dasgupta et al (1983) and Hung and Quyen (1993): the arrival date of invention, $\widehat{T}_l$, requires a commitment of investment cost $I_l(\widehat{T}_l)$ at date $t = 0$ with $I_l(0) = \infty$ and $I_l(\infty) = 0$.

Notation

- $x(t)(\geq 0) =$ depletion of non-renewable critical mineral at time t.
- $S_0(> 0) =$ initial reserve and $S(t) =$ reserve of natural resource at t: $\dot{S}(t) = -x(t)$.
- $X(t) = \int_0^t x(\tau)d\tau =$ accumulated extraction – supplied to the market.
- When $t \geq T_r$, $y(t) =$ recycling at t of critical mineral. Cost $R(y)$: $R(0) = 0, R'(0) = 0,\ R'(y) > 0,\ R''(y) \geq 0$.
- $Y(t) = \int_T^t y(\tau)d\tau =$ accumulated recycled mineral.
- $t \geq T_s$, the perfect substitution, z starts to supply to the market: $z(t) \geq 0$. Cost of production $Z(z)$: $Z(0) = 0, Z'(0) = 0,\ Z'(z) > 0$, $Z''(z) \geq 0$.

The game

- The optimal control problem for player j is:

$$W^j(S_0) = \max_{x(t)} \int_0^\infty \left[P(x(t)+y(t))x(t) - C(X,x)\right] e^{-rt} dt$$

$$= \int_0^{T_r} \left[P(x)x(t) - C(X,x)\right] e^{-rt} dt + \int_{T_r}^\infty \left[P(x(t)+y(t))x(t) - C(X,x)\right] e^{-rt} d$$

- subject to $x(t) \geq 0$ and $x(t) \geq x_{min}$ for $t \in [0, T_r]$
- and $0 < X \leq S_0$.
- Player i's optimal control

$$W^i(S_0) = \max_{y,z,T_r,T_s} \int_0^\infty \left[U(x,y,z] - P(x)x - R(y) - Z(z)\right] e^{-rt} dt - I_r(T_r) - I_s(T_s)$$

subject to $y(t) \geq 0$, $z(t) \geq 0$, and minimum market demand:

$$x + y \geq x_{min} > 0 \quad t \in [0, T_r].$$

HJB equations

- Let $m = n, r, s$, and b for modes, n represents neither recycling nor backstop technologies are activated, r recycling is ready; s substitution starts to supply the market; b both exist.
- $V_m^i(X)$ and $V_m^j(X)$ value functions in Modes m of Players i and j, respectively, when the accumulated extraction is X.
- $U_n(x)$, $U_r(x, y)$, $U_s(x, z)$, and $U_b(x, y, z)$ the importer's instantaneous utility in Mode n, r, s, and b, respectively.
- Mode n

$$rV_n^i(X) = U_n(x_n^*) - x_n^* P(x_n^*) + x_n^* \left(V_n^i\right)'(X),$$
$$rV_n^j(X) = P(x_n^*) x_n^* - C(X, x_n^*) + x_n^* \left(V_n^j\right)'(X)$$

- where

$$x_r^* = \arg\max_{x \geq x_{min}} \left\{ P(x + y_r^*) x - C(X, x) + x \left(V_r^j\right)'(X) \right\},$$

HJB equations

- Mode r

$$
\begin{aligned}
rV_r^i(X) &= U_r(x_r^*, y_r^*) - R(y_r^*) - x_r^* P(x_r^* + y_r^*) + x_r^* \left(V_r^i\right)'(X), \\
rV_r^j(X) &= P(x_r^* + y_r^*)\, x_r^* - C(X, x_r^*) + x_r^* \left(V_r^j\right)'(X),
\end{aligned}
$$

- where

$$
\begin{aligned}
x_r^* &= \arg\max_{x \geq 0} \left\{ P(x + y_r^*)\, x - C(X, x) + x \left(V_r^j\right)'(X) \right\}, \\
y_r^* &= \arg\max_{\max\left\{x_{\min} - x_r^*, 0\right\} \leq y \leq \eta X} \left\{ U_r(x_r^*, y) - x_r^* P(x_r^* + y) - R(y) \right\}.
\end{aligned}
$$

- Mode s ......
- Mode b ......

Simplified HJB

- x_m^* is a function of X and $\left(V_m^j\right)'$ and y_m^* and z_m^* are functions of X and x_m^*.
- Thus, we can write

$$x_m^* = \xi_m \Big(X, \big(V_m^j\big)' \Big), \quad y_m^* = \eta_m \Big(X, \big(V_m^j\big)' \Big), \quad z_m^* = \zeta_m \Big(X, \big(V_m^j\big)'$$

- Hence, the HJB equations

$$rV_m^i = H_m^i \Big(X, \big(V_m^i\big)', \big(V_m^j\big)' \Big), \qquad rV_m^j = H_m^j \Big(X, \big(V_m^j\big)' \Big).$$

Terminal conditions

- At $X = S_0$, Player j no longer has resource to extract and export:

$$V_m^j(S_0) = 0 \qquad \text{for } m = n, r, s, b.$$

- Player i can still use recycling and/or backstop technologies if available.
-
$$V_n^i(S_0) = 0,$$
-
$$V_r^i(S_0) = \max_{y(\cdot)} \int_0^\infty e^{-rt} \left[U_r(0, y(t)) - R(y(t))\right] dt,$$
-
$$V_s^i(S_0) = \max_{z(\cdot)} \int_0^\infty e^{-rt} \left[U_s(0, z(t)) - Z(z(t))\right] dt,$$
-
$$V_b^i(S_0) = \max_{y(\cdot), z(\cdot)} \int_0^\infty e^{-rt} \left[U_b(0, y(t), z(t)) - R(y(t)) - Z(z(t))\right] dt.$$

The switching condition—impulse control

- At the moment when Player i activates a new technology, she pays the expenses $I_m(X_m)$ of developing that technology.
  - $$V_n^i(X_r) = V_r^i(X_r) - I_r(X_r), \qquad V_n^i(X_s) = V_s^i(X_s) - I_s(X_s),$$
  - $$V_r^i(X_s) = V_b^i(X_s) - I_s(X_s), \qquad V_s^i(X_r) = V_b^i(X_r) - I_r(X_r).$$
- Activation of new technologies does not change the exporter's value:
  - $$V_n^j(X_r) = V_r^j(X_r), \qquad V_n^j(X_s) = V_s^j(X_s),$$
  - $$V_r^j(X_s) = V_b^j(X_s), \qquad V_s^j(X_r) = V_b^j(X_r)$$

The main proposition–impulse control

Suppose Player i activates Technology k to cause the mode change $m \longmapsto m'$ when the state is X_k. Assume that $0 < X_k < S_0$. Also assume that the equation

$$rV^i = H^i_m\left(X, P^i, P^j\right)$$

can be solved uniquely for P^i so that

$$P^i = G^i_m\left(X, V^i, P^j\right)$$

for some function G^m_i, and that the limit

$$\lim_{X \uparrow X_k} \left(V^j_m\right)'(X)$$

exist. Then, X_k satisfies

$$r\left[V^i_{m'} - I_k\right](X_k) = H^i_m\left(X_k, \left[V^i_{m'} - I_k\right]'(X_k), \hat{P}^j_{m'}\right),$$

and $\hat{P}^j_{m'}$ satisfies

$$rV^j_{m'}(X_k) = H^j_m\left(X_k, \hat{P}^j_{m'}\right).$$

Player i's utility functions

- Player i's utility

  $$U(x, y, z) = (x + y)^{\alpha} + z^{\alpha},$$

  with $0 < \alpha < 1$ and $\frac{1}{1-\alpha}$ the elasticity of demand.

- $$U_n(x) = x^{\alpha}, \quad U_r(x, y) = (x + y)^{\alpha},$$

- $$U_s(x, z) = x^{\alpha} + z^{\alpha}, \quad U_b = U.$$

Cost functions

- Stiglitz (1976), the invest demand function:

$$P(x(t)+y(t)) = \begin{cases} p_0 x(t)^{\alpha-1}, & 0 \le t \le T_r, \\ p_0(x(t)+y(t))^{\alpha-1}, & t \ge T_r, \end{cases}$$

  with p_0 a positive constant.
- Minimum requirement: $0 < t < \min\{T_r, T_s\}$.
  $x + y \ge x_{min} > 0$.
- Recycling cost: $R(x, y, t) = R_0 y$. (Could decrease with $Y-$ learning effects.)
- Extraction cost $C(X, x)$ checks: $C_x > 0$, $C_X > 0$, i.e., considering degradation or stock effects.

Extraction cost

- Extraction cost is a crucial element in decision-making when facing recycling and/or backstop substitution.
- Livernois and Martin (2001): with linear extraction and linear backstop technology costs, the central planner faces a dichotomous choice: either the resource or the backstop technology.
- Hung and Quyen (1993): even with zero extraction cost but convex substitute production cost, there are periods where both the resource and the backstop are used simultaneously.
- Levhari and Liviatan (1977), Seyhan et al. (2012), and Ruan and Zou (2024) etc.: extraction costs increase with depletion, but the marginal extraction cost remains constant and independent of the resource stock.
- $$C(X,x,t) = C(X,x) = c(X)x + \frac{c_2x^2}{2} = c_1xX + \frac{c_2x^2}{2}$$

Mode n

- $$rV_n^i(X) = (1 - p_0)(x_n^*)^\alpha + x_n^* \left(V_n^i\right)'(X);$$
- $$rV_n^j(X) = p_0 (x_n^*)^\alpha - \left[c_1 x_n^* X + \frac{c_2}{2}(x_n^*)^2\right] + x_n^* \left(V_n^j\right)'(X),$$
- where
$$x_n^* = \underset{x \geq x_{\min}}{\arg\max} \left\{ p_0 x^\alpha - \left[c_1 x X + c_2 \frac{x^2}{2}\right] + x \left(V_n^j\right)'(X) \right\}.$$
- $$x_n^* = \xi_n \left(X, \left(V_n^j\right)'(X)\right),$$
- where
$$\xi_n\left(X, P^j\right) = \max\left\{\phi\left(c_1 X - P^j\right), x_{\min}\right\} \qquad \text{for } 0 \leq X \leq S_0, \quad P^j \leq 0.$$

Calculation in Mode n

- Denote $P_n^j(t) = \left(V_n^j\right)'(X(t))$.
- Dynamical system for X and P_n^j:

$$\dot{X} = x_n^*, \qquad \dot{P}_n^j = rP_n^j + c_1 x_n^*.$$

- Let $Y_n = c_1 X - P_n^j$.
- $$\dot{Y}_n = -rP_n^j, \qquad \dot{P}_n^j = rP_n^j + c_1 \max\left\{\phi\left(Y_n\right), x_{\min}\right\}.$$

Solution in Mode n

- After solving Y_n and P_n^j,

$$X(t) = \frac{1}{c_1}\left[Y_n(t) + P_n^j(t)\right], \qquad x_n^*(t) = \max\left\{\phi\left(Y_n(t)\right), x_{\min}\right\},$$

- $V^i(X)$ checks

$$\frac{dV_n^i(X(t))}{dt} = rV_n^i(X(t)) - (1-p_0)\, x_n^*(t)^{\alpha},$$

- with the terminal condition

$$V_n^i(X(T_s)) = V_s^i(X_s) - I_s(X_s).$$

mode n to mode s

- $$V_n^i(X(t)) = e^{-r(T_s - t)}\left[V_s^i(X_s) - I_s(X_s)\right] + (1 - p_0)\, e^{rt} \int_t^{T_s} e^{-r\tau} x_n^*(\tau)^\alpha \, d\tau.$$
- Similar calculation as in Mode n, in mode s, we have
- $$V_s^i(X(t)) = V_s^i(S_0) + (1 - p_0)\, e^{rt} \int_t^{\infty} \phi(Y_s(\tau))^\alpha \, e^{-r\tau} \, d\tau,$$
- $Y_s(\tau)$, $\phi(Y_s(\tau))$ are known.

Proposition 2 – Time to substitute

- The point X_s at which the mode change from n to s for satisfies the equation

$$r\left[V_s^i\left(X_s\right)-I_s\left(X_s\right)\right]=\left(1-p_0\right)\xi_n\left(X_s,\hat{P}_s^j\right)^\alpha+\xi_n\left(X_s,\hat{P}_s^j\right)\left[V_s^i-I_s\right]'\left(X_s\right)$$

where $\hat{P}_s^j$ is given by

$$\hat{P}_s^j=\left(V_s^j\right)'\left(X_s\right)\qquad\text{if }\xi_s\left(X_s,\left(V_s^j\right)'\left(X_s\right)\right)\geq x_{\min}$$

and otherwise,

$$\hat{P}_s^j=\frac{1}{x_{\min}}\left\{rV_s^j\left(X_s\right)-p_0x_{\min}^\alpha+c_1X_sx_{\min}+\frac{c_2}{2}x_{\min}^2\right\}.$$

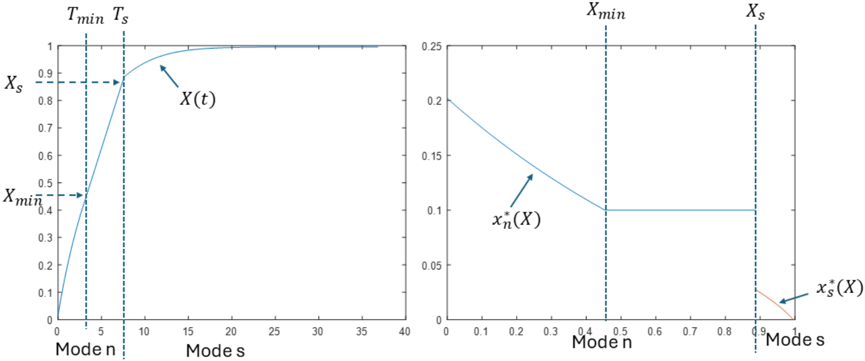


Figure 7: Left: The accumulation of the extracted resource and the change of mode with respect to time. Right: Markovian strategy of the supplier.

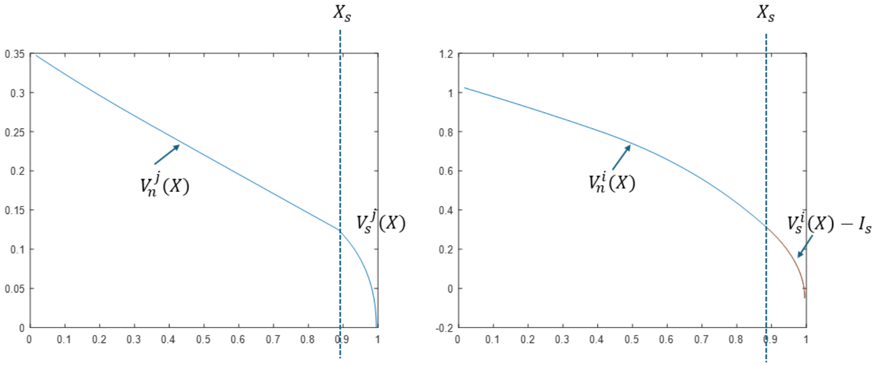


Figure 8: Left: The value functions for Player j. Right: The value functions for Player i.

Mode n to r

- The terminal condition is
$$V_r^j(S_0) = 0$$
- $$V_r^i(S_0) = \max_{x_{\min} \leq y(\cdot) \leq \eta S_0} \int_0^\infty e^{-rt} \left[y(t)^\alpha - R_0 y(t) \right] dt.$$
- It is easy to see that
$$V_r^i(S_0) = \frac{1}{r} \left[\bar{y}^\alpha - R_0 \bar{y} \right]$$
- where
$$\bar{y} = \begin{cases} \eta S_0 & \text{if } (\alpha/R_0)^{1/(1-\alpha)} > \eta S_0, \\ (\alpha/R_0)^{1/(1-\alpha)} & \text{if } x_{\min} \leq (\alpha/R_0)^{1/(1-\alpha)} \leq \eta S_0, \\ x_{\min} & \text{if } (\alpha/R_0)^{1/(1-\alpha)} < x_{\min}. \end{cases}$$

The optimal time to start recycling

There are three cases:

- $$y_r^* = x_{\min} - x_r^* > 0$$

  or

  $$y_r^* = 0;$$

- $$y_r^* = \eta X;$$

- $$\max\{x_{\min} - x_r^*, 0\} < y_r^* < \eta X.$$

- Consider two cases:

  (1) recycling from the beginning or the game;

  (2) optimal time of recycling.

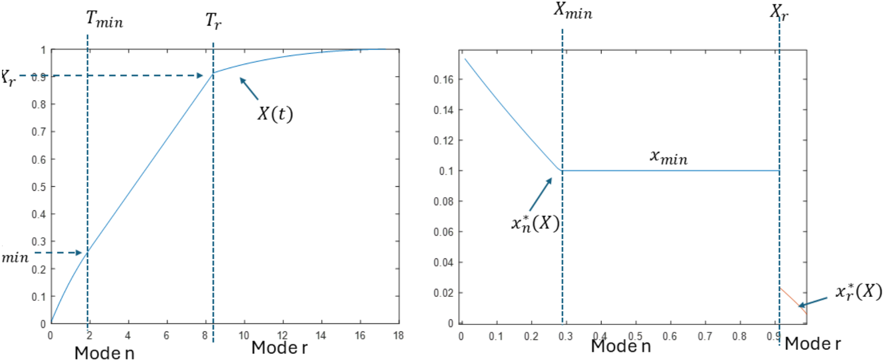


Figure 9: Left: The accumulation of the extracted resource and the change of mode with respect to time. Right: Markovian strategy of the supplier.

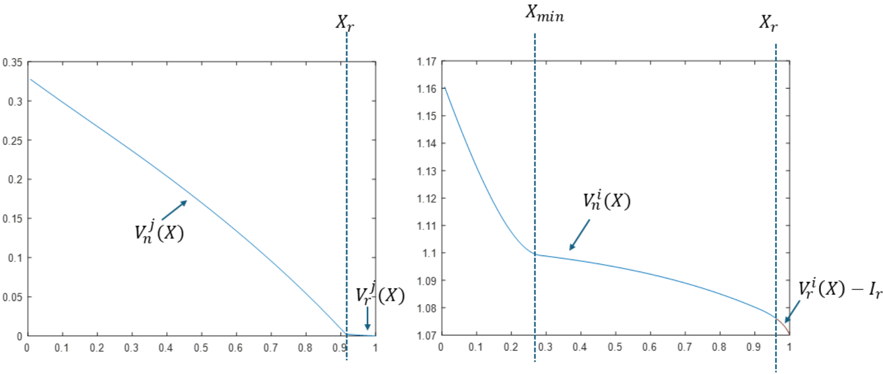


Figure 10: Left: The value functions for Player j. Right: The value functions for Player i.

Discussion

- Minimum demand: $x + y \geq x_{min}e^{mt}$ with $m > 0$ and $m < 0$; or more complicated case $m > 0$ in the short-run and $m \geq 0$ in the long-run, the equilibria established in remain the similar.
- Increasing reserve: In many mineral exploitation situations, reserves may change or even increase over time. IEA (2022), lithium reserves increased by 40% between 2011 and 2019; copper reserves rose by 30% in the last decade. Despite increasing production, the global reserve of REEs has remained nearly constant over the last 15 years.
  (1) $S_0 = \infty$- unrealistic. Both resources are abundant, either monopoly or duopoly, as previous proposition.
  (2) $S_0 = S_0(t) \leq \overline{S} < \infty$, the quantitative results still hold.
-

Results

- We could provide clear information when substitution should take place if no recycling.
- If no substitution, there may be no Nash equilibrium if the recyclable resource is exhausted while the virgin resource is still available, regardless the market structure.
- Critically important for the policymaker of the importing country in deciding when the recycling technology should be ready for use.

- Calibrate the model— most important for policy recommendation.
- The exporting countries may engage in recycling or using critical mineral.
- Uncertainty regarding when recycling, new resources, or substitution technology will be available.

Thank You