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Scienze economiche e statistiche

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The second life of yttrium as a catalyser for the pharma industry

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Diapositiva 1

AM1 Antonio Massarutto; 25/11/2022

Recyclable Rare Earths from EEE

Electrical and electronic equipment	**Recyclable REEs**
PCB (Printed Circuit Board)	Pd, (Au), (Ag)
LCD (Liquid Crystal Display)	Y, Eu, (In)
CRT (Cathode Ray Tube)	Y, Eu, Ce, La, Tb
Batteries	Ce, La, Sm, Pr, Nd, (Co)
Lamps/ LED (Light Emitting Diodes)	La, Tb, Ga, Au
Speakers/Magnets	Nd, Dy, Pr, Gd, (Co)
Fluorescent lamps	Y, Ce, Ga, Eu, Tb, La

Source: our elaboration from various sources.
Note: in brackets the critical non-rare earth raw materials present in relevant quantities per type of WEEE.

Recycling rate of individual REMs still very low

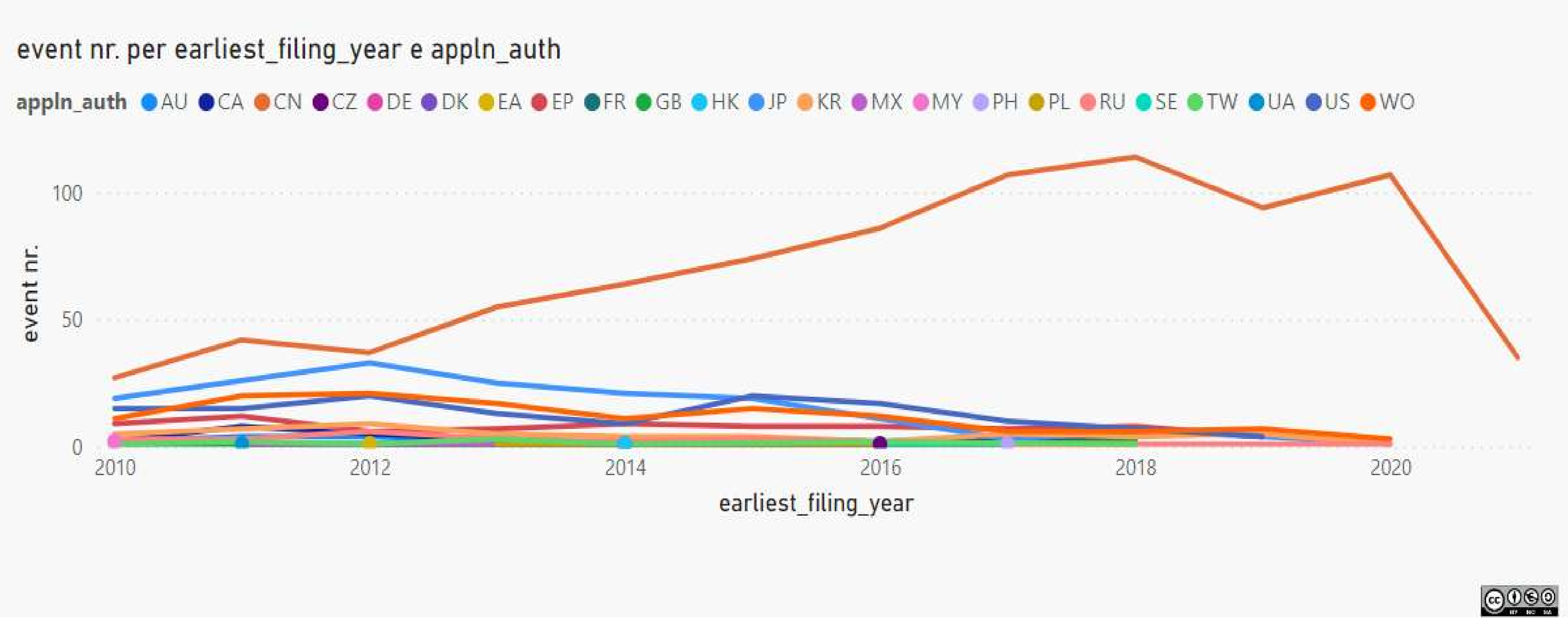
REE	**Recycling Input Rate from WEEE**
Light Rare Earth Elements	
Ce*	1%
La*	1%
Nd**	1%
Pr***	10%
Sm*	1%
Heavy Rare Earth Elements	
Dy**	0%
Er*	1%
Eu**	38%
Gd*	1%
Ho, Tm, Lu, Yb*	1%
Tb**	6%
Y**	31%

Source: : our elaboration of SCRREEN2 - European Union's Horizon 2020. Factsheet updates based on the EU Factsheets 2020. Rare Earth Elements.
Note: (*) UNEP, 2013; (**) Bio Intelligence Service, 2015; (***) BRGM, 2015

In terms of secondary supply, today the recycling input rate is still very low, usually less than 1%, especially in Europe, due to the lack of efficient collection systems and the prohibitive costs of building REE recycling capacity (Erecon, 2014, in SCRREEN2, 2020).

Higher recycling input rates for Europium, Yttrium and Terbium are only due to the recycling of fluorescent lamps: as it is estimated that there are still large volumes of these lamps that will reach end-of-life in the coming years, they represent a real 'mine' from which to recover with appropriate REE treatment to be redirected to the industrial sector.

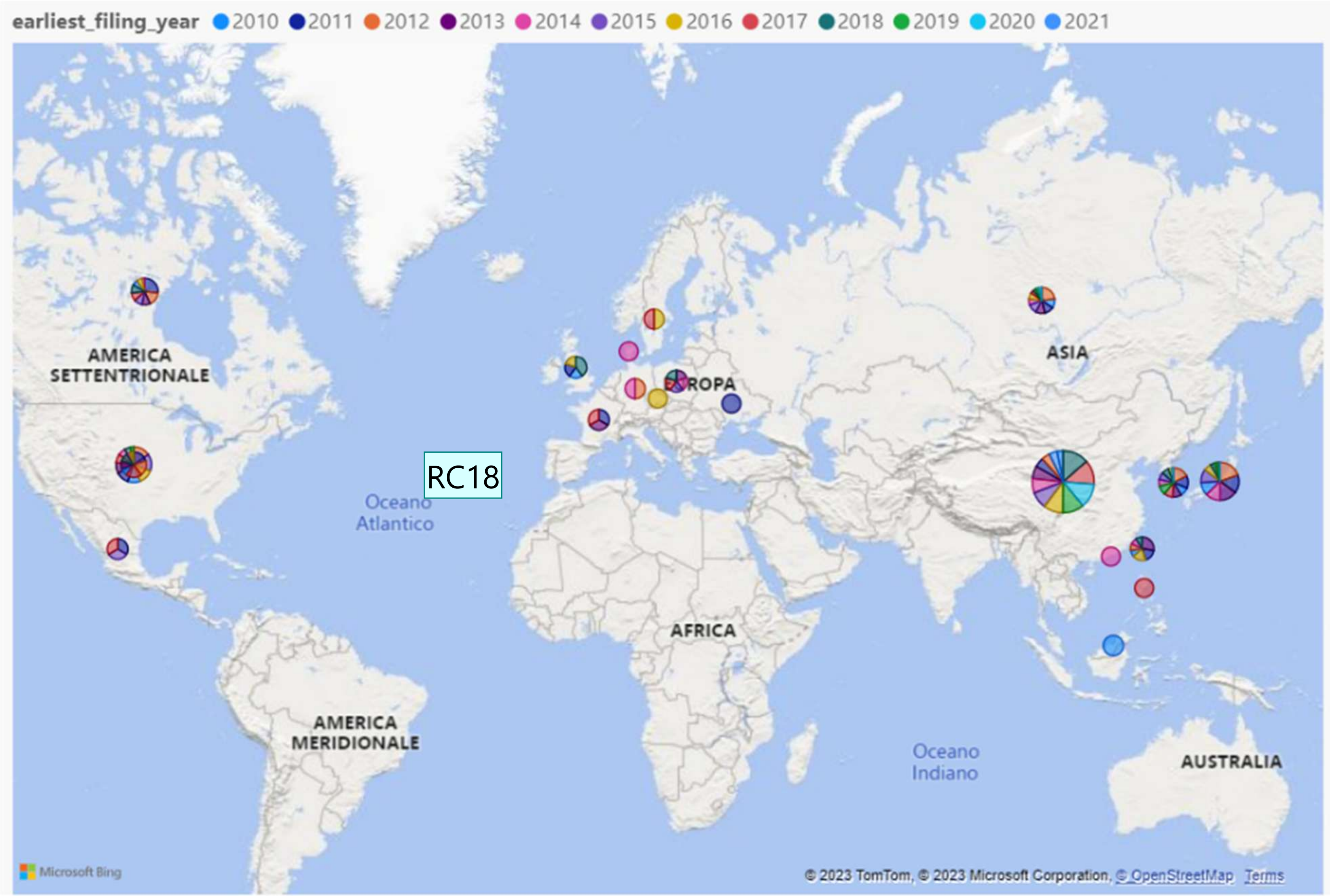
Patents for CRMs recycling from WEEE



REEs patent applications filed with national/supranational patent authorities (years 2010-2021) (China first actor)

Source: Favot, Priore, Compagnoni, 2023 "A descriptive study of innovativeness of Rare-Earth-Elements recycling sector based on patents" - IRTC 2024 Conference

Worldwide distribution of REEs patent applications (2010-2021)



Source : Favot, Priore, Compagnoni, 2023 “A descriptive study of innovativeness of Rare-Earth-Elements recycling sector based on patents” – IRTC 2024 Conference

Diapositiva 5

RC18 La ricerca brevettuale è stata effettuata su PATSTAT online (ed. Primavera 2022), utilizzando un elenco di codici verdi di riciclaggio dei RAEE (IPC o CPC) dalla metodologia ENV-TECH dell'OCSE [Rif.: 1, 2]. In una seconda fase si sono identificati i documenti brevettuali REEs utilizzando le parole chiave REE.

Roberta Curiazi; 29/11/2023

Our research questions

- Economic assessment of urban mining potential
  - Is «urban mining» a reliable source of CRM?
  - Is the value chain of recycling economically and financially sustainable?
  - What are the «participation constraints» faced by market players in the recycling industry?
  - What are the limiting factors of a more widespread development of recycling in this specific field?
- Implications for Public Policy
  - Can we do something to favour it? How?
  - What has been done so far? With which outcomes?
  - How long can we wait for the domestic industry to be ready?
  - Will the reliance on domestic sources of CRM (UM) jeopardise the competitiveness of EU industry?

SOME ECONOMICS OF THE CIRCULAR ECONOMY

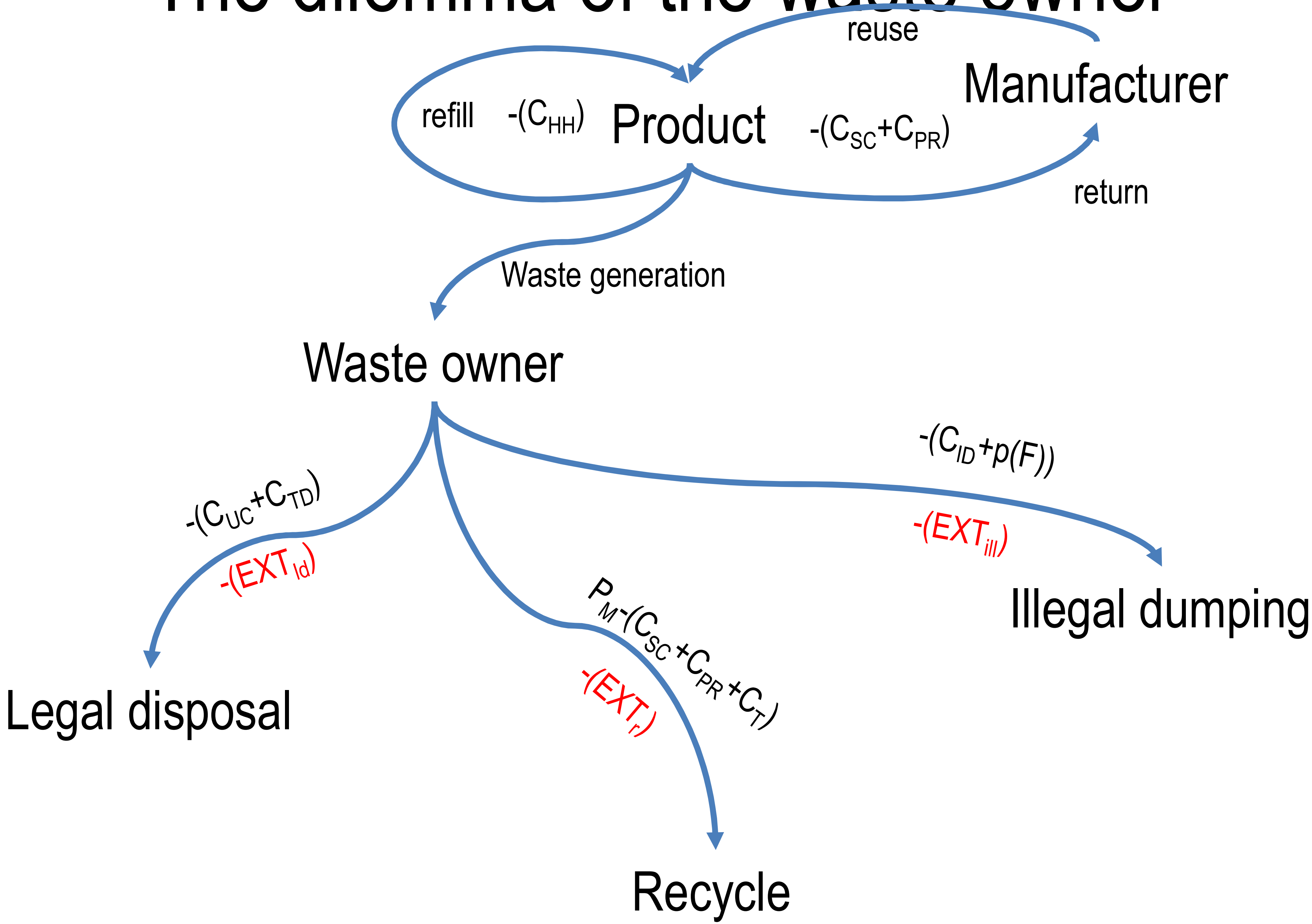
Two questions about circular economy

- The «circular narrative»
  - CE is «win-win» and desirable under any possible viewpoint
  - The reasons behind non-adoption are lazy thinking, cultural idleness and passive resistance of bad habits
  - The EU is a benign master that helps us in our interest, and in that of future generations
- If so, why aren't we doing it yet?
  - In a market economy, if something is profitable, it will eventually attract investors eager to exploit the related margin! (but information asymmetries may prevent it ⇔ role of the state: ***abate transaction costs arising from information asymmetries***)
  - Externalities and public goods (Role of the state: ***correct market signals***)
  - «We are all slaves of a distorted development model» (role of public policy: ***re-educate everyone and create an ethical state***)
  - «The market economy is unfit» (role of public policy: replace markets with a centralised planned economy)
  - «Someone having market power does not find it profitable» (role of public policy: combat globalised monopolies and the power of lobbies)
  - Because a «paradigm change» requires coordination that is still lacking (role of public policy: catalyse change)

Possible answers: CE is worth doing because …

- Weak sustainability arguments ⇔ use economic rationale
  - ***Private Cost-benefit*** of improving material efficiency above BAU > 0 ⇔ it is profitable to invest in circular economy because the market value of resources saved is higher than the cost (if not yet, it will soon ⇔ perspective private value)
  - ***Social cost-benefit*** of improving material efficiency above BAU > 0 ⇔ even if market prices do not reflect this, taking externalities into account
  - ***Transactions costs are significant***, and we can do a lot to reduce them through more efficient organization of «reverse value chains» ⇔ technology and organization of the value chain is governed by «inertial» forces ⇔ path-dependence
- Strong sustainability arguments ⇔ integrate non-economic arguments in the valuation (because market prices, even corrected, fail to reflect values)
  - ***Material resources are limited*** (in physical terms) ⇔ focus on material efficiency
  - ***Disposal sites are scarce*** ⇔ focus on landfill diversion
  - ***Other environmental sinks are scarce*** (climate change, diffused pollution, biodiversity) ⇔ focus on GHG emissions
  - ***Global interactions*** and full implications of material use still not well understood ⇔ focus on precautionary principle
  - ***Cultural, social and political dimensions*** ⇔«Waste is a sin» ⇔ focus on ethics

The dilemma of the waste owner



La struttura della filiera

- **L'utilizzatore del materiale di riciclo**
  - Vincolo di partecipazione: $P_R \leq$ WTPmax = $P_{mkt} = P_{mv} - C$
  - Obiettivo: min P_R
- **Il soggetto obbligato** (es. il produttore)
  - Obiettivo: min (CAC)
  - Vincolo: raggiungere target
- **Il gestore del servizio RU**
  - WTAmin = $P_{RD} \geq (CRD+CTR) - (CRT+CTS)$
- **Il gestore delle attività di trattamento e preparazione per il recupero**
  - Vincolo di partecipazione: $P_R \geq CTR$
- **Il sistema EPR**
  - Vincolo di partecipazione: $CAC \geq (P_R + CTR - P_{RD})$
  - Obiettivo: max $(CAC - (P_R + CTR - P_{RD}))$

Il margine di filiera

- Margine di filiera = P_R – $(C_{TR}+C_{RD}-(C_{RT}+C_{TS}))$ = $M_{UF}+M_{RU}+M_{PR}+M_{SO}$
- Vincoli di break-even:
  - Per il sistema EPR: CAC = max $(0; P_{RU}+P_{PR}-P_C)$
  - Per l'utilizzatore finale: $P_{RU} \leq P_{mkt}$
  - Per il gestore del RU: $P_{RU} \geq (C_{RD}+C_{TR} - (C_{RT}+C_{TS}))$
  - Per le imprese che svolgono attività di preparazione al riciclo: $P_{PR} \geq C_{PR}$
- Il margine di filiera, in astratto, può essere ripartito tra tutti questi soggetti, con il vincolo che ciascuno ottenga un ricavo almeno pari al suo vingolo di partecipazione
  - Margine dell'utilizzatore finale: MUF = Pmkt – PC
  - Margine del gestore RU: MRU = PRU - $(C_{RD}+C_{TR} - (C_{RT}+C_{TS}))$
  - Margine del riciclatore: MPR = PPR – CPR
  - Margine del sistema EPR: MSO = - CAC

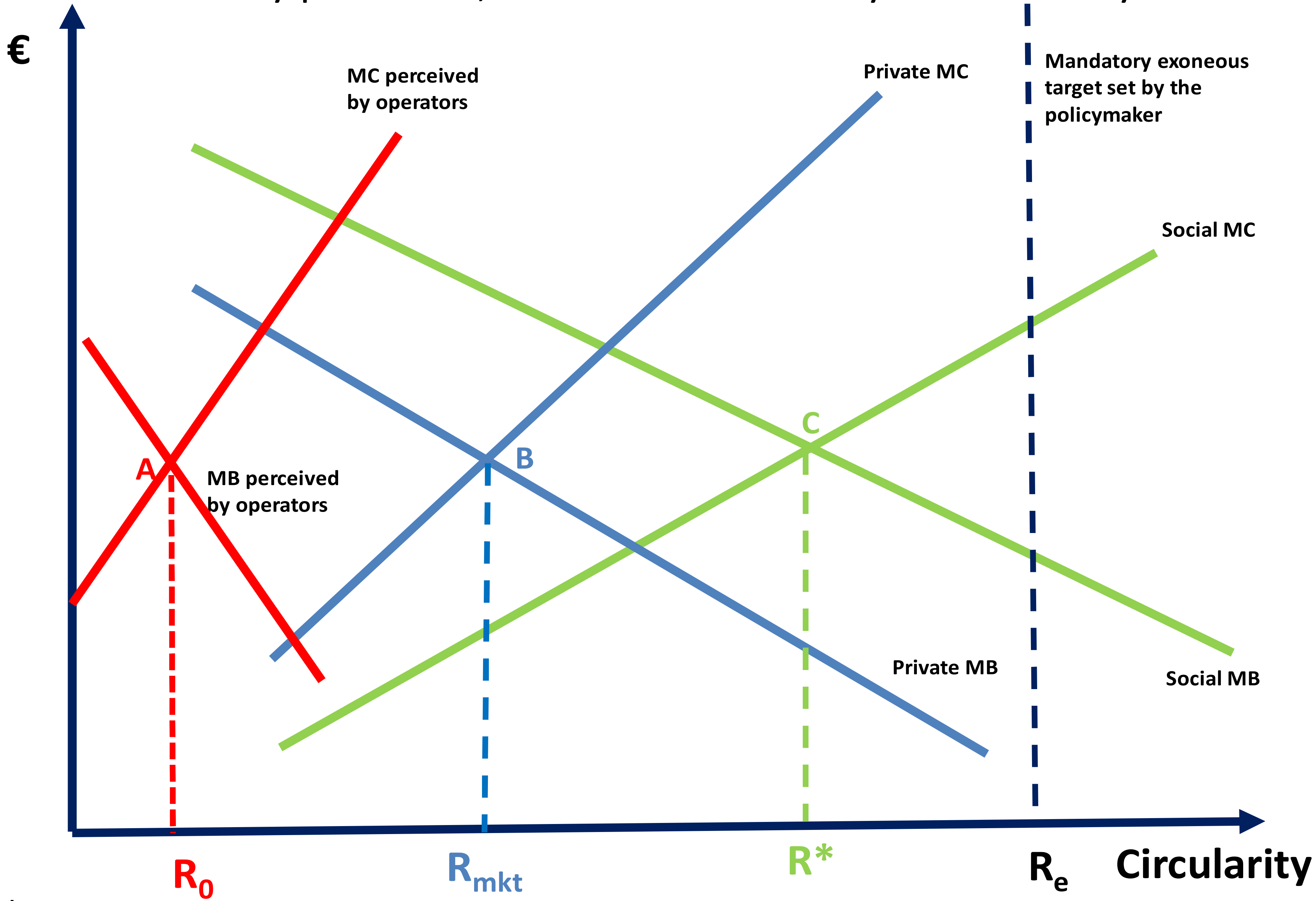
Desirability of CE targets

- $P_M > C_{SC} + C_{PR}$:
  - M would not be a waste! The market would spontaneously achieve recycling targets
  - this used to be the case in the past and still is in developing economies for many materials;
  - Not anymore in developed economies (but may be jeopardised by transactions costs)
  - Policy needs: market design; EPR to contrast TC;
- $P_M - (C_{SC} + C_{PR}) < 0$; $P_M - (CSC + CPR) < (C_{TD} + C_{UC})$
  - Recycling not economically sustainable on a stand-alone basis, but least cost waste management option ⇔ less costly than (legal) disposal
  - Incentive for waste owners to separate (but need stable market conditions on P_M)
  - Illegal disposal is still cheaper! Need to repress illegal dumping (and illegal export) effectively
- $P_M - (C_{SC} + C_{PR}) > (C_{TD} + C_{UC})$ but $P_M - (C_{SC} + C_{PR}) < (C_{TD}+C_{UC}+EXT+RC)$
  - Market signals not enough! Need active public policy to reconcile market signals with true cost/benefit
  - Public policy targets depend on the relative cost of sorting and successive treatment/preparation for recycling

Desirability of CE targets

- $P_M - C_{PR} > C_{TD}$
  - After separate collection has been made, it is more economical to recover materials than to dispose of it
  - Requires dedicated systems for SC; once materials have been collected, it is worth recycling them
  - Incentives may limit to SSC: e.g. mandatory targets, PAYT, DRS, ADF, nudging, rewards/penalties for operators
  - Problem: fake export provides a cost-effective alternative (e.g. WEEE) ⇔ EPR to guarantee destinations
- $P_M - C_{PR} < C_{TD}$, but $P_M - C_{PR} < C_{TD} + EXT + RC$
  - Setting SC targets is not enough! Even if someone else bears the cost of collection, disposal still cheaper
  - Provide subsidies and set mandatory targets for recycling, develop markets for recycled materials (e.g. green public procurement; public stockpile; mandatory content of recycled materials; phaseout of disposable packaging)

Paradox: If it is really profitable, how is it that nobody has noticed yet?



Possible answers:

- The market has not yet noticed it (but will do so sooner or later; and many are already becoming aware)
- Market prices are distorted and send erroneous signals, although it is socially beneficial to carry on
- **Market prices, even corrected, do not incorporate all valuable dimensions ⇔ extra-economic components are present**

Possible explanations of the paradox

- From R_0 to R_{mkt}
  - Market incompleteness (lack of coordination)
  - Transactions costs in the transition from an old to a new technological paradigm ⇔ critical mass needed to catalyze change
  - Market myopia ⇔ price system uncapable of anticipating future shortage
  - Possible remedies: actions aimed at speeding up transition and removing barriers (e.g. EPR; creation of markets; strict responsibility)
- From R_{mkt} to R^*
  - Market prices do not account for externalities
  - Environmental quality as a «public good» ⇔ everyone wishes to free-ride
  - Possible remedies: actions aimed at correcting prices; regulation
- From R^* to R_e
  - Economic evaluation implies that all values are tradable
  - Some are not (e.g. slavery is not ethically admitted)
  - Need to impose bans and obligations that descend from ethical norms

Policy instruments

- Instruments aimed at reducing transactions costs
  - Coordination of markets through technical standards and mandatory targets and deadlines
  - Liablity principles (EPR, PPP)
  - Facilitate cooperation via PPP
- Instruments aimed at modifying payoff of alternative actions
  - Improve separate collection rate
    - Volume charging (PAYT)
    - Advanced disposal fees (e.g. damage deposits; returnable deposits)
    - Improve the quality and availability of separate collection services
    - Design for the environment
  - Increase convenience of recycling over disposal
    - Taxes on virgin raw materials, shipping etc
    - Taxes on disposal
    - Mandatory quantitative targets with economic penalties
  - Increase the value of recycled materials
    - Public demand for recycled products (e.g. Green Procurement)
    - Mandatory standards (e.g. min content of recycled materials)
    - Nudging
- Combat illegal dumping to «waste havens»
  - Self-sufficiency principle
  - Include stewardship over the final destination of materials in EPR targets
  - Deposit-refund systems; advanced disposal fees

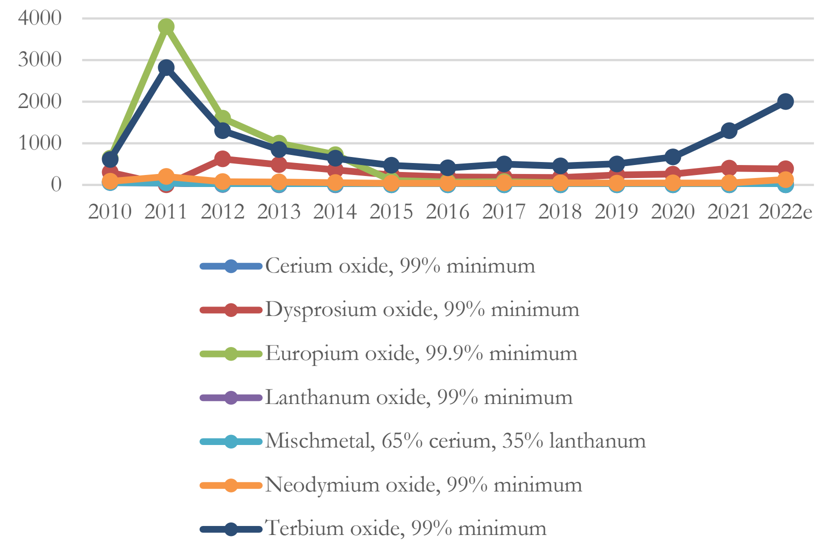
Discover Rare Earth Materials

A CASE STUDY: RECYCLING YTTRIUM FROM FLUORESCENT LAMPS

Treasure hunt

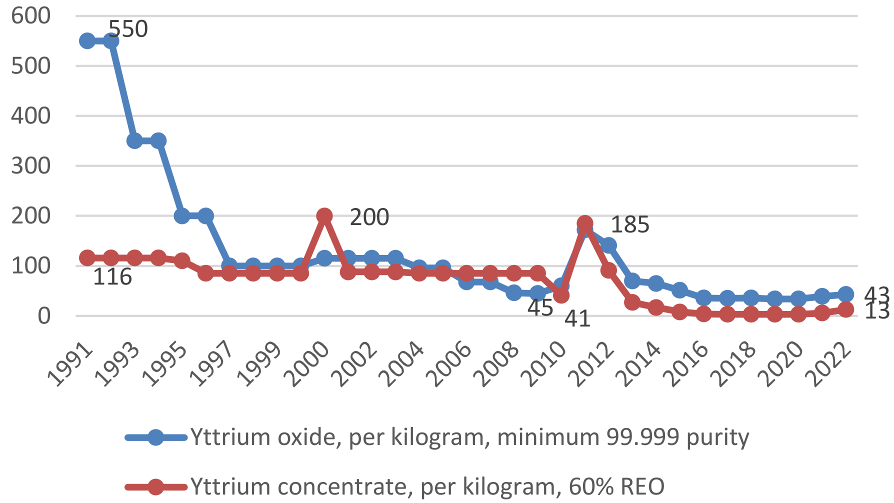
1 H hydrogen 1.008 [1.0078, 1.0082]																	2 He helium 4.0026
3 Li lithium 6.94 [6.938, 6.997]	4 Be beryllium 9.0122											5 B boron 10.81 [10.806, 10.821]	6 C carbon 12.011 [12.009, 12.012]	7 N nitrogen 14.007 [14.006, 14.008]	8 O oxygen 15.999 [15.999, 16.000]	9 F fluorine 18.998	10 Ne neon 20.180
11 Na sodium 22.990	12 Mg magnesium 24.305 [24.304, 24.307]											13 Al aluminium 26.982	14 Si silicon 28.085 [28.084, 28.086]	15 P phosphorus 30.974	16 S sulfur 32.06 [32.059, 32.076]	17 Cl chlorine 35.45 [35.446, 35.457]	18 Ar argon 39.948
19 K potassium 39.098	20 Ca calcium 40.078	21 Sc scandium 44.956	22 Ti titanium 47.867	23 V vanadium 50.942	24 Cr chromium 51.996	25 Mn manganese 54.938	26 Fe iron 55.845	27 Co cobalt 58.933	28 Ni nickel 58.693	29 Cu copper 63.546	30 Zn zinc 65.38	31 Ga gallium 69.723	32 Ge germanium 72.630	33 As arsenic 74.922	34 Se selenium 78.971	35 Br bromine 79.904 [79.901, 79.907]	36 Kr krypton 83.798
37 Rb rubidium 85.468	38 Sr strontium 87.62	39 Y yttrium 88.906	40 Zr zirconium 91.224	41 Nb niobium 92.906	42 Mo molybdenum 95.95	43 Tc technetium	44 Ru ruthenium 101.07	45 Rh rhodium 102.91	46 Pd palladium 106.42	47 Ag silver 107.87	48 Cd cadmium 112.41	49 In indium 114.82	50 Sn tin 118.71	51 Sb antimony 121.76	52 Te tellurium 127.60	53 I iodine 126.90	54 Xe xenon 131.29
55 Cs caesium 132.91	56 Ba barium 137.33	57-71 lanthanoids	72 Hf hafnium 178.49	73 Ta tantalum 180.95	74 W tungsten 183.84	75 Re rhenium 186.21	76 Os osmium 190.23	77 Ir iridium 192.22	78 Pt platinum 195.08	79 Au gold 196.97	80 Hg mercury 200.59	81 Tl thallium 204.38 [204.38, 204.39]	82 Pb lead 207.2	83 Bi bismuth 208.98	84 Po polonium	85 At astatine	86 Rn radon
87 Fr francium	88 Ra radium	89-103 actinoids	104 Rf rutherfordium	105 Db dubnium	106 Sg seaborgium	107 Bh bohrium	108 Hs hassium	109 Mt meitnerium	110 Ds darmstadtium	111 Rg roentgenium	112 Cn copernicium	113 Nh nihonium	114 Fl flerovium	115 Mc moscovium	116 Lv livermorium	117 Ts tennessine	118 Og oganesson
			57 La lanthanum 138.91	58 Ce cerium 140.12	59 Pr praseodymium 140.91	60 Nd neodymium 144.24	61 Pm promethium	62 Sm samarium 150.36	63 Eu europium 151.96	64 Gd gadolinium 157.25	65 Tb terbium 158.93	66 Dy dysprosium 162.50	67 Ho holmium 164.93	68 Er erbium 167.26	69 Tm thulium 168.93	70 Yb ytterbium 173.05	71 Lu lutetium 174.97

REE price time series (dollars/Kg), 2010-2022

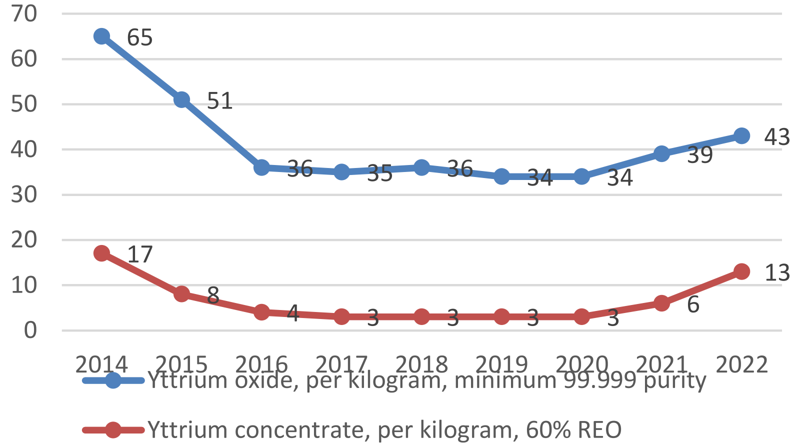


Source: our elaboration of USGS 1991 – 2022.

Yttrium price time series (dollars/Kg), 1991-2022

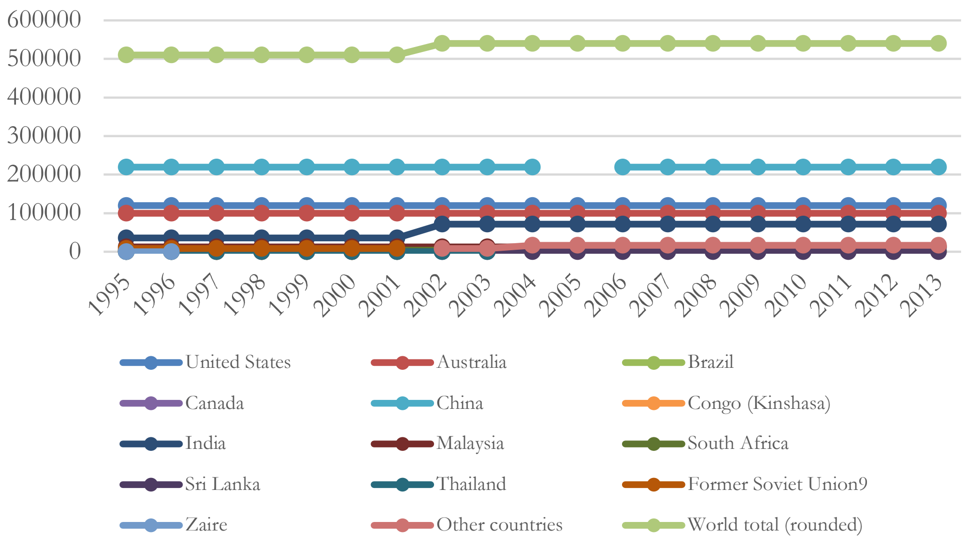


Yttrium price time series (dollars/Kg), 2014-2022



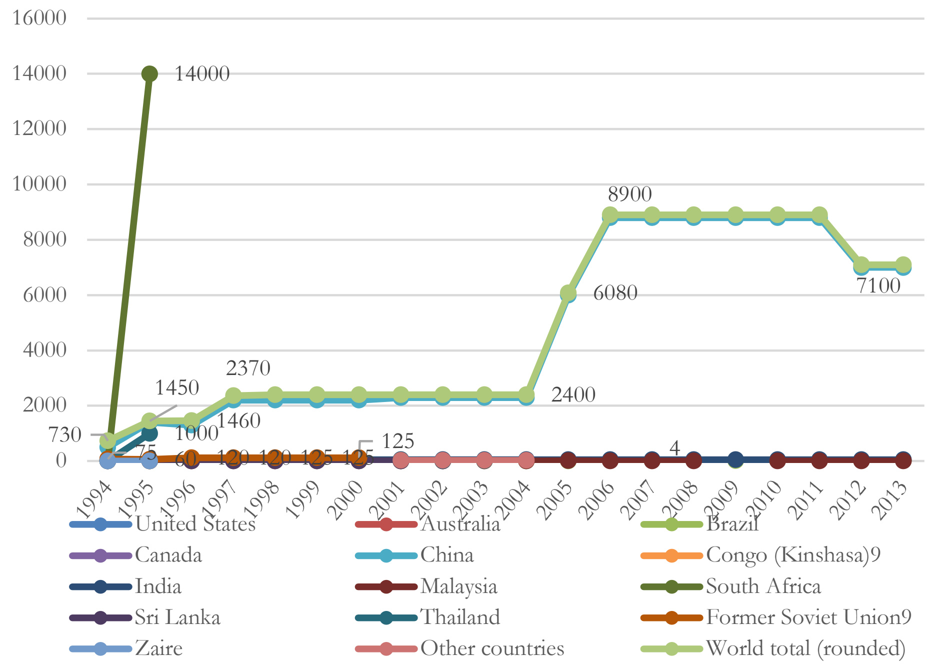
Source: our elaboration of USGS 1991 – 2022.

Yttrium world reserves (tons)



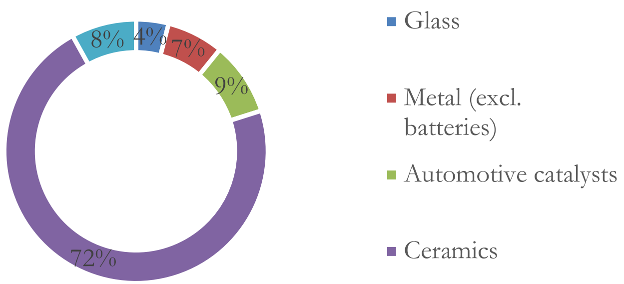
Source: our elaboration of USGS, 1995-2013

Yttrium world production of (in tons)



Source: our elaboration of USGS, 1994-2013

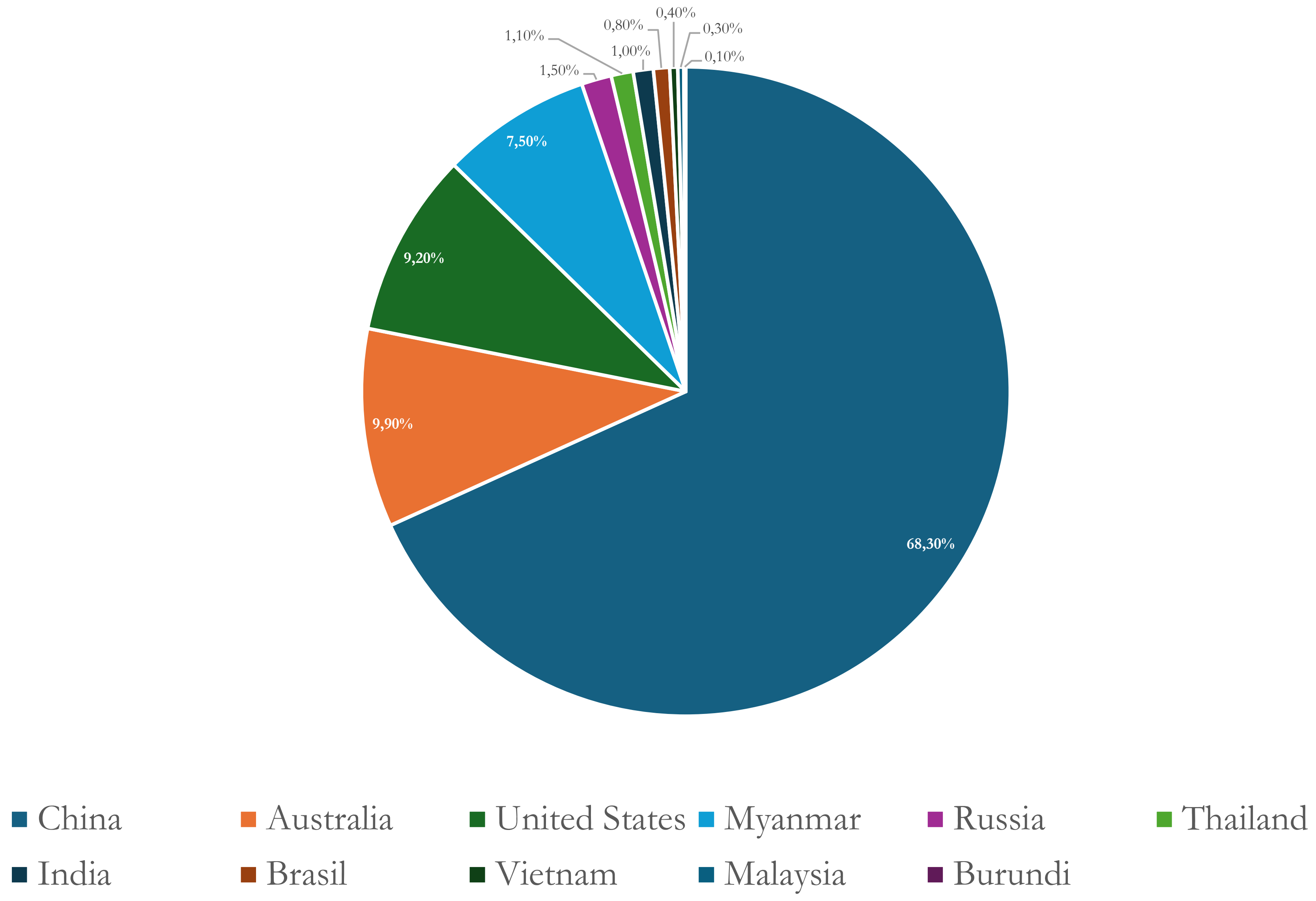
Applicazioni Yttrium (Y)



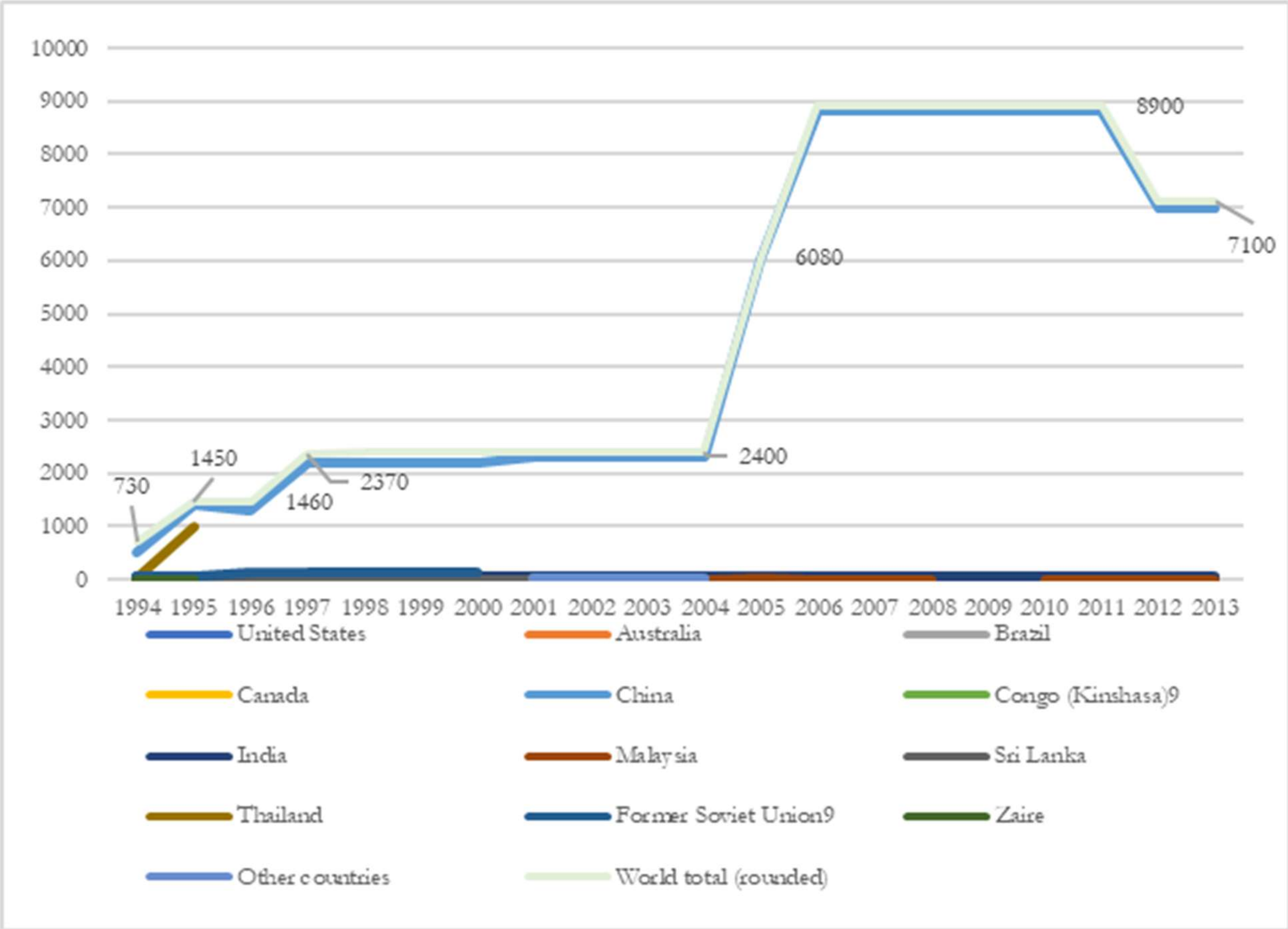
Source: elaborazione autori da SCRREEN2, 2020

- ✓ From the graph above, the almost perfect coincidence between Chinese and global yttrium production is clear, with a nearly complete overlap of the two curves.
- ✓ The EU consumed, on average, about 56 tons per year of yttrium in all forms (metal equivalent) in magnets and lighting applications (SCREEN2, 2020).

Global reserves of Yttrium



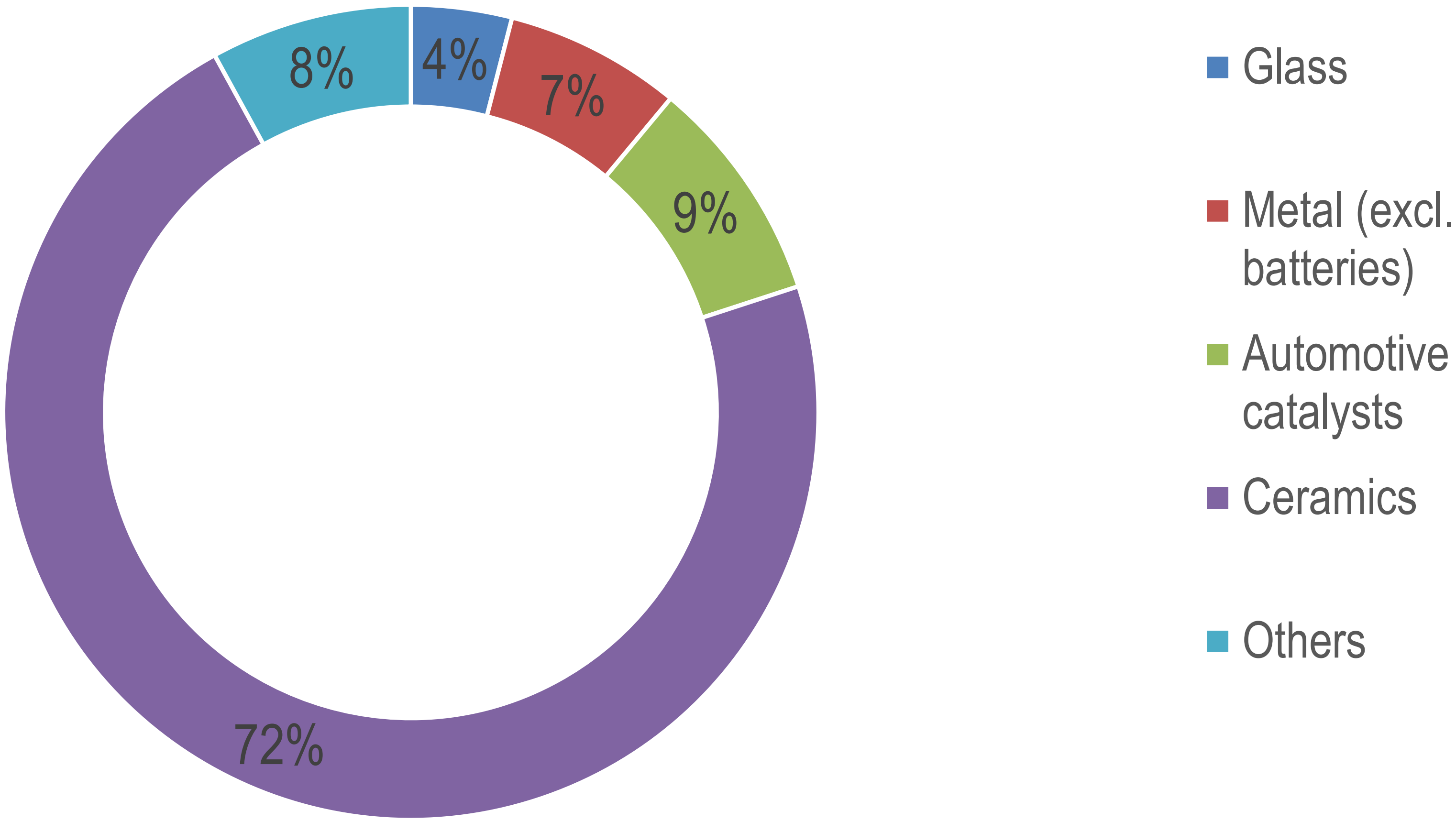
Global Yearly Production of Yttrium



Yttrium applications worldwide

Year	*USD mln*	*Mt*	*By application*							
			Phosphors		*Ceramics*		*Glass additives*		*Others*	
			USD mln	Mt	*USD mln*	Mt	*USD mln*	Mt	*USD mln*	Mt
2019	62,53	20.865,12	26,38	8.920,77	29,24	9.652,38	1,19	414,08	5,72	1.877,89
2020	58,66	19.640,88	23,29	7.933,15	28,62	9.462,92	1,17	409,30	5,58	1.835,50
2021	63,90	21.296,15	26,11	8.850,74	30,56	10.053,79	1,22	424,33	6,01	1.967,30
2026	101,59	33.004,10	47,48	15.658,01	43,61	13.964,56	1,53	516,14	8,97	2.865,40
CAGR (2021-2026)	9,72	9,16%	12,70	12,09	7,37	6,79	4,60	3,99	8,35	7,81

Utilizzo di ittrio per settore



OUR STUDY N.1

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Research article

Rare-earth elements in the circular economy: The case of yttrium

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ABSTRACT

This paper discusses the economic rationale of recycling exhaustible raw materials and assesses how a circular economy perspective can improve the sustainable use of critical raw materials (CRMs). We use the case study of yttrium, a rare-earth element (REE) on the EU list of CRMs, given its widespread use in the electronics industry and the geopolitical concentration of its supply. Even if recycling REEs from waste electric and electronic equipment is a valid alternative to extraction from mines, as proposed by the circular economy paradigm, less than 1% of REEs used today are recycled. Nevertheless, studies on the economic benefits of recovery REEs are very limited. In this paper, we present the business case of an Italian recycling company, Relight Ltd., and its HydroWEEE project, to recycle REEs such as yttrium, from spent lamps. In environmental terms, recycling REEs has a much lower impact than their extraction from virgin source. In economic terms, it is profitable to recycle yttrium if its market price is above 14€/kg, and above 9.54€/kg taking in consideration the external costs of mining. Therefore, in 2012 and 2013, recycling was profitable thanks to the high price of yttrium, while between 2014 and 2016 recycling was not cost effective. In these cases, policymakers must incentivize recovery and recycling solutions with appropriate policies.

An application to rare-earth materials (REM): Yttrium

- Background information about yttrium
  - Use sectors: florescent lamps, CRT televisions, plasma display panels, energy efficient lighting (such as LEDs), phosphor powders for low-energy lighting, optical glasses and batteries, as well as for high-tech applications, such as lasers, superconductors, nuclear reactors and electronic components for missile defence systems
  - «Rare» means «costly to mine» due to low concentration
  - Market monopolised by China (≈99% of global production)
  - In 2011, export ban + export tariffs caused world market price to jump to nearly 200 €/kg (previously constant around 15-20)
  - Alternative source: urban mining
- The study
  - Research Questions:
    - what is the minimum price to activate private initiative?
    - what is the min price to make recycling convenient from a social CBA viewpoint?
  - Methodology: social CBA
  - Data sources
    - Pilot plant extracting yttrium from exhausted fluorescent lamps
    - Obtained data about the process cost for extracting Y directly from manufacturers
    - Use reference official sources for other + benefit transfer (e.g. GHG; external cost of mining)

Market price that makes recycling economical

Table 2
Economic evaluation of recovery Y oxide from fluorescent lamps (€/kg).

Year	2012	2013	2014	2015	2016
SC for R5*	€ 1.3519	€ 1.3540	€ 1.9870	€ 1.3930	€ 1.5560
TR	€ 12.4477	€ 12.4477	€ 12.4477	€ 12.4477	€ 12.4477
UC*	€ 0.0976	€ 0.0993	€ 0.1015	€ 0.1010	€ 0.1050
TD*	€ 0.1053	€ 0.1107	€ 0.1169	€ 0.1191	€ 0.1244
PR Equation (1)	€ 14.0025	€ 14.0117	€ 14.6531	€ 14.0608	€ 14.2331
EXT	-€ 4.4600	-€ 4.4600	-€ 4.4600	-€ 4.4600	-€ 4.4600
PR Equation (2)	€ 9.5425	€ 9.5517	€ 10.1931	€ 9.6008	€ 9.7731

«Urban mining» of yttrium is economically convenient for a price not lower than 14 €/kg
During the past years, price has been stably higher
However, due to recent significant discoveries (>200 years of stocks), p has dropped far below

Accounting for externalities, the policy support to recycling is desirable if p < 9,5 €/kg)
Willingness to reduce dependence from China may provide further justifications

Since SC cost is 1,5 €/kg, if EPR systems bear the cost of SC, price limits lower to 12,7 – 8,2 €/kg respectively

OUR STUDY N.2

Yttrium Recycling Steps from WEEE

In nature, yttrium is found pure in phosphates or carbonates (most common) or as yttrium oxide (uncommon); this depends on the mineral from which it is extracted.

In WEEE, it is mainly found in fluorescent bulbs and screens with low concentrations.

*CRT-type Screens (Cathode Ray Tube) → 0.0002 % (Battelle, 2023)

*LED/LCD Screens (Monitors and Notebooks) → 3.2-16.0 mg or 1.6-1.8 mg (our elaboration from Delice et al., 2023)

*LED- Light Emitting Diode /LCD- Liquid Crystal Display Screens (Televisions and Other) → 4.9-110 mg

** Fluorescent lamps (40 W) → 2.97-0.72 g

PHASE 1 - Calcination process

The 'crudest' and most economical phase: oxides (yttrium oxide) are obtained in the form of a mixture called 'purification crude' (containing n-elements of the periodic table, almost all oxides, with low Y content - e.g. 4% as in the test mixture)

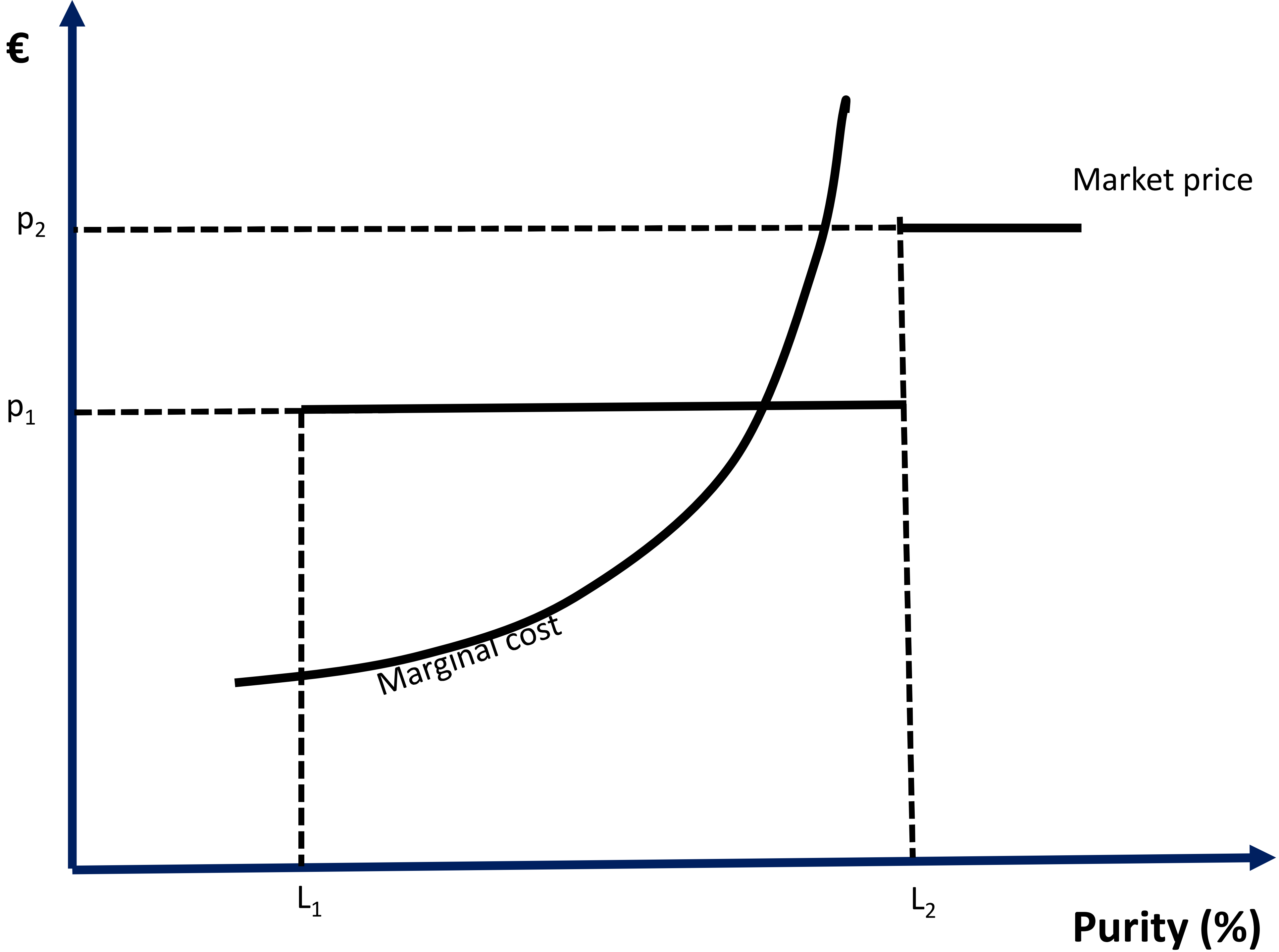
PHASE 2 - Complex and costly chemical-physical processes to separate the rare earth being purified in various forms (e.g. as pure yttrium or yttrium oxide or yttrium carbonate or yttrium triflate), possibly also isolating the other elements

versus

PHASE 2 - REEMIX process

Change from yttrium oxide (insoluble), adding triflic acid diluted by 50%, to yttrium triflate (soluble), to be used as a catalyst in other reactions in the pharmaceutical industry

$$Y_2O_3 + 6CF_3SO_3H_{(aq)} \xrightarrow[100°C,1h]{} 2Y(OTf)_3 + 3H_2O$$


€
p_2
p_1
Market price
Marginal cost
L_1
L_2
Purity (%)

REEMIX recycling process

Quantities treated/treated in the laboratory:

1 g yttrium oxide + 4.0704 g triflic acid = **4.7 g yttrium triflate** + 2.4 ml water to be disposed

Max: 200 g yttrium oxide + 814.08 g triflic acid = 940 g yttrium triflate + 480 ml water to be disposed of

STEP 1 – The two reagents are mixed and heated on a hotplate for one hour at 100°C
Option A: use of the metal plates on which the flask is installed
Option B: use of the silicone oil bath in which the flask is immersed

STEP 2 – Filtration: The resulting product $+ 3H_2O$ is filtered to separate the triflated yttrium from the liquid solution

STEP 3 – Water removal: Yttrium is placed in a high vacuum 'diaphragm pump' at 10-2 millibars to completely evaporate the water

OUTPUT: crude mixture containing yttrium triflate
This 'impure' catalyst can be sold on the market in pharmaceuticals (in organic chemistry synthesis processes) as a substitute for the 'pure' catalyst.

Economic evaluation of 'REEMIX'

Triphyllic Acid(*)	
Supplier	*Price/gr*
Merck	6,48 €
TCI	2,09 €
Strem	4,84 €
Fluorochem	**0,40 €**
ChemPUR	7,32 €
abcr	0,48 €

Source: our elaboration, data 2024

Treatment costs (TR) of the WEEE mix to produce one gram of yttrium triflate	
Step 1: Catalyst synthesis	1,69
Step 2: Filtration	0,04
Step 3: Water removal	2,15
Total costs	**3,88**

Triflate Yttrium(*) (98% purity)	
Supplier	*Price/gr*
Merck	14,32 €
TCI	7,80 €
Strem	10,52 €
REEMIX PROJECT	**3,88 €**

(*) Prices in March 2024

Note: the prices of both products vary considerably over time and depend more than proportionally on the quantities purchased

Conditions for the economic sustainability of REEMIX

PR – (SC+TR) > UC + TD

PR= list price of catalyst purchasable by pharmaceutical companies
SC= cost for "separated collection" (specific cost for e-waste, source ISPRA)
TR= treatment and recovery cost (REEMIX process)
UC= "unsorted collection" cost (source ISPRA)
TD= “treatment and disposal", landfill or waste-to-energy cost (source: ISPRA)

Also including negative externalities:
PR - EXT > (SC + TR) + (UC + TD)

EXT= negative externalities of virgin raw material mining

Conditions for the economic sustainability of REEMIX

Table 1: Municipal waste management costs undifferentiated fraction, year 2019		
Sorted waste COST	*€/ kg*	*€ / gr*
UC = unsorted collection and transport	0,12300 €	0,00012 €
TD = treatmeant and disposal	0,14550 €	0,00015 €
OC = other costs	0,02330 €	0,00002 €
TMG = total management cost of usorted waste	0,29180 €	0,00029 €
Source: our reworking of ISPRA data, 2020 - Municipal Waste Report. Table 5.4 (Regional averages of specific costs per kg of waste year 2019. Sample of 85.84% of inhabitants)		

Conditions for the economic sustainability of REEMIX

Table 2: Management costs of municipal waste WEEE fraction, year 2019		
WEEE sorted waste COSTS	*€/ kg*	*€ / gr*
SC= cost separated collection	0,15505 €	0,00016 €
TR-e = treatment cost of e-waste	0,02898 €	0,00003 €
TC = total cost	0,18403 €	0,00018 €
Source: our reworking of Ispra 2020 data. Municipal waste report. Table 5.41 (Quantity and costs of separate collection of WEEE, average between hazardous and non-hazardous WEEE, year 2019. Sample of 12% of inhabitants)		

Table 3: Economic viability of the REEMIX compound of one gram yttrium triflate					
PR	SC	TR (REEMIX)	UC	TD	PR-(SC+TR)-(UC+TD)>0
14,32 €	0,000155 €	3,88 €	0,00012 €	0,00015 €	10,43 €
7,80 €	0,000155 €	3,88 €	0,00012 €	0,00015 €	3,91 €
10,52 €	0,000155 €	3,88 €	0,00012 €	0,00015 €	6,63 €
Source: market data and our elaboration, year 2024.					

From private to social cost and Benefit: accounting for externalities

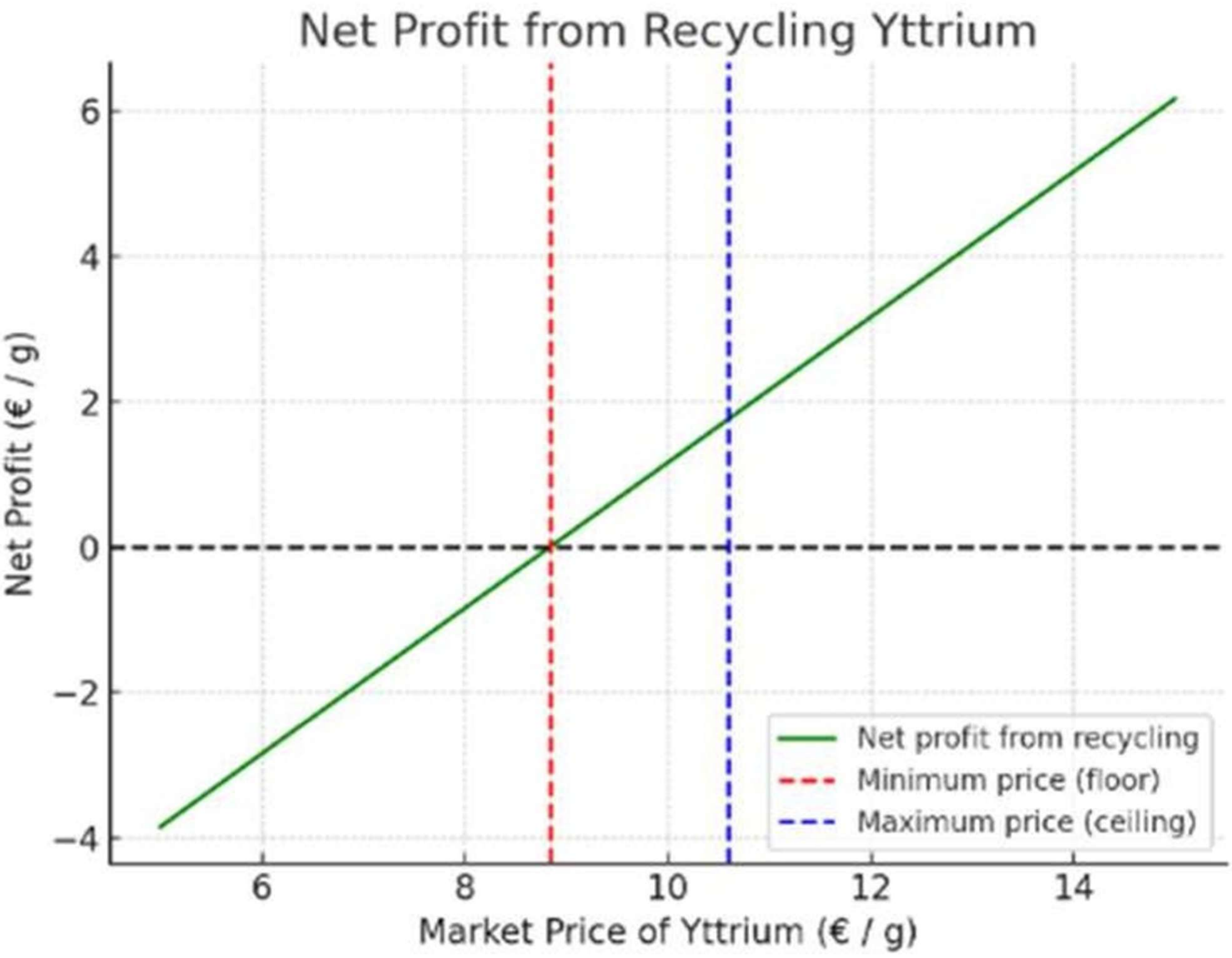
Table 1. The annual external cost of production of one metric ton of REO at Bayan Obo in 2013.

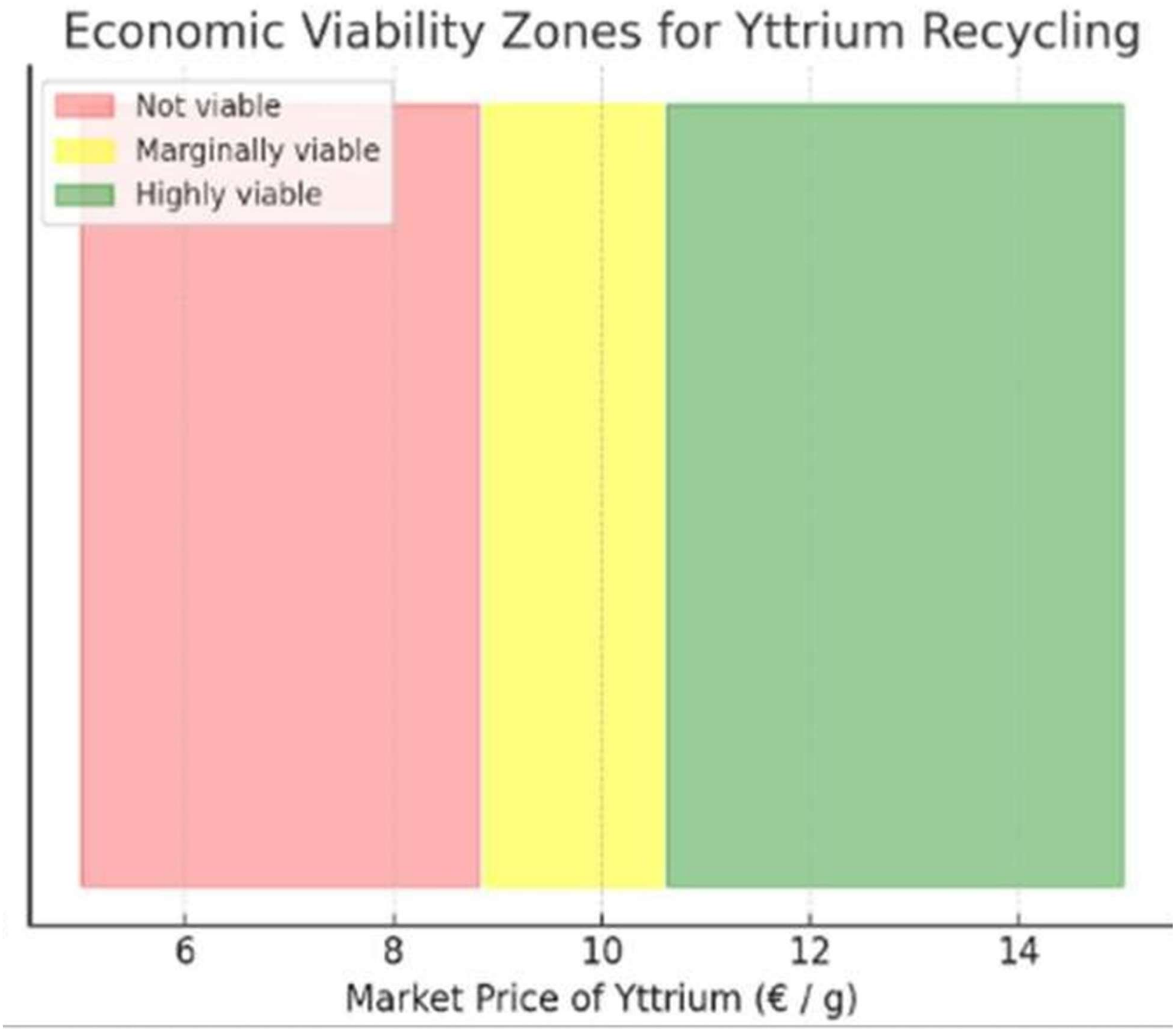
Category	External cost (CNY)
Damage to natural capital – waste water	14945
Damage to natural capital – waste gas	12515
Damage to natural capital – radioactive substance	1400
Damage to natural resource – rare earth resources	3199
Damage to ecological system – land occupation	2680
Total	34739

Source: Zhou et al., 2017.

The external cost of production of REO at Bayan Obo 2013			
CNY per kg	*Exchange rate at June 2024*	*€ per kg*	***€ per g***
34739	0.12682	4.41	**0.0044**

Being gram quantities, the costs related to negative externalities for producing Rare Earth Oxides (REO) from mining are negligible for the REEMIX project.


Net Profit from Recycling Yttrium
Net Profit (€ / g)
Market Price of Yttrium (€ / g)
6
4
2
0
−2
−4
6
8
10
12
14
Net profit from recycling
Minimum price (floor)
Maximum price (ceiling)


Economic Viability Zones for Yttrium Recycling
Not viable
Marginally viable
Highly viable
6
8
10
12
14
Market Price of Yttrium (€ / g)

Conclusions of the economic evaluation

- The chemical process works, and, in the laboratory, is economically sustainable provided that the prices of the catalyst that substitute will remain high
- The “REEMIX product” needs to be “validated” to be sold in the pharmaceutical market
- The industrial phase needs to be tested
- The market demand is fundamental to sustain the investment and operational costs

Lessons learned

- Empirical evidence vs «Malthusian» scenarios
  - «criticality» is essentially due to geopolitical reasons; industrial policy may consider import tariffs or quotas to sustain the internal price up to the level that makes UM profitable
  - EU industry can survive an increase in prices, even unilateral, but cannot survive a sudden collapse of supply ⇔ very low and even negligible impact of the price of Y on the value chain ⇔ higher cost of Y should not jeopardise the competitiveness of EU production
  - Still unclear what will be the market share that UM will be able to cover (EEE is only a minor destination of Y; most Y is used by ceramic and glass industries
- «Downcycling» is a promising opportunity
  - So far, applications of REE use materials of the highest purity since this is how they are supplied on the market, without an effective need for all applications
  - UM obtains REE at varying concentrations; even very low concentrations may be enough for many industrial processes
  - Once selective collection of appliances has been done, the cost of processes that extract low-concentration mixtures is much lower and can be calibrated depending on the degree of purity required by end uses
  - High-concentration sources can be reserved to the more demanding uses

Lessons learned

- Reserves, mining and refinement
  - Global reserves arguably very high (including deep sea)
  - Actual mining concentrated in China (also because other countries are reluctant because of high external costs)
  - Refinement capacity almost entirely controlled by China ⇔ developing alternative sources of raw material useless, until refinement capacity problem remains unsolved
- Urban mining potential
  - Y used in EU mostly for ceramics and automotive
  - Fluorescent lamps and screens in WEEE represent potentially an interesting source (globally, phosphors have the same order of magnitude as ceramics, ≈ 40%
  - However, these products are being abandoned at least in EU and replaced with higher performance substitutes (LED) that do not contain Y (or contain only limited quantities)

Lessons learned

- Crucial importance of EPR
  - The key to effective recycling is sorting of sources of CRM
  - Selective collection needed
  - Critical mass for implementing standardised separate collection schemes (e.g. equipped delivery points + encourage return systems operated by industry
  - The critical step of the value chain is located upstream ⇔ once WEEE flows have been effectively sorted, recycling costs are low compared to the market value
  - EPR also effective for catalysing RTD and share innovation costs among industrial players
  - Need to extend EPR to the industries where the use of Y is more intensive (EEE only a negligible share of the market!!)
- Policy instruments
  - Tariffs on import of CRM and/or products containing them
  - PPPs for pilot technologies (local start-ups, innovation incubators) either recycling processes or innovative destination processes
  - Green procurement
  - Subsidized stocks
  - Critical materials innovation hub (Ames Institute USA)
  - A policy aimed at recovering CRM from WEEE needs coordinated action at the EU level

Ongoing projects and sources of funding

CREDITS

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REEMIX project – "Apply ladder of chemical circularity"

Fondazione CARIPLO

PRIN "Climbing the Waste Hierarchy: enabling factors and policies (CLIWEP)", Bando 2022, Prot. 2022K5PSNP

Finanziato dall'Unione europea
NextGenerationEU

REPVBBLICA ITALIANA

Ministero dell'Università e della Ricerca

- ✓ Project title: "Apply ladder of chemical circularity: recycling rare earth elements, from electronic waste to drugs."

  Acronym: **REEMIX**

- ✓ Background:

  

  - ✓ World supply of Critical Raw Materials dominated by China; concerns for future availability
  - ✓ CRM are used especially in electronic products, a significant part of which is still disposed of as waste
  - ✓ "Urban mining" as an opportunity to create an alternative source of supply
- ✓ Research question:
  - ✓ Is UM financially and economically sustainable?
  - ✓ Is an industrial policy needed?
- ✓ Aims:
  - ▪ To study the use of the raw mixtures of REE recovered by E-waste in new chemical applications as catalysts that promote the synthesis of precious compounds.
  - ▪ Advantage: save cost of the purification process

- ✓ Hypotesis: If successful, the project would represent an innovative and outstanding REUSE of REE, by avoiding the required steps and expenses necessary for the recycling of REE in the electronic industry, and enhancing the value of raw materials, employed in a totally different field, as key players for the synthesis of highly functionalized (chiral) molecules, including biologically active compounds, with a potential large economic impact.

- **<u>PRIN</u> "Climbing the Waste Hierarchy: Enabling Factors and Policies (CLIWEP)"**
- <u>Background</u>: The "EU waste hierarchy" (EUWH) is a cornerstone of European environmental policy. It establishes a priority ladder of waste management practices with the aim of reaching a "circular economy"
- Research question: identifying proper ways to evaluate the progress of MS towards CE; understanding enabling factors and obstacles; design policies to facilitate progress

<u>Aims</u>:

- identify and apply effective performance indicators to measure the compliance of countries, municipalities, and waste utilities to WH, using state-of-the-art methods for performance assessment and policy evaluation
- identify and understand trade-offs among different steps of the ladder, i.e., understand the systemic relations across the whole management system of material throughputs and identify cases in which optimising a single step of the ladder may prevent optimising other scales
- provide an integrated economic analysis of the enabling factors (regulatory instruments and performance indicators, value chains creation and development, etc.) and existing bottlenecks (lack of incentives for reduction, reuse, and recycling, normative constraints, etc.) regarding the waste management and its role in the effective transition towards the CE
- identify best practices, governance models, regulatory tools, and policy actions and designs to provide policymakers support to define future country-, municipal-, and firm-level strategies to effectively implement the EUWH to realise the CE transition