Reciclagem

Uso de Recursos e Impactes

As Nações Unidas calcularam que, em média, 1/3 dos danos ambientais globais estão ligados ao desperdício e sobre utilização de energia e 2/3 estão ligados à sobre-exploração e uso pouco produtivo dos materiais extraídos. Cerca de 67% das emissões de gases de estufa estão relacionadas com a produção de materiais básicos. E desde 2000 a produtividade material da economia tem diminuído – precisamos de mais recursos para gerar um euro de retorno.

Em 2050 cada cidadão irá exigir 70% mais recursos que no início do século e a procura energética será o dobro da atual. A transição para renovável irá exigir 10 vezes mais capacidade instalada: mais procura, mais produção, mais materiais …

A escassez de recursos poderá **até** não ser o principal constrangimento, mas certamente o mesmo não se poderá dizer dos impactes ambientais derivados da extração, consumo intensivo e uso ineficaz dos recursos.

- Modos de contornar o problema da escassez futura dos materiais:

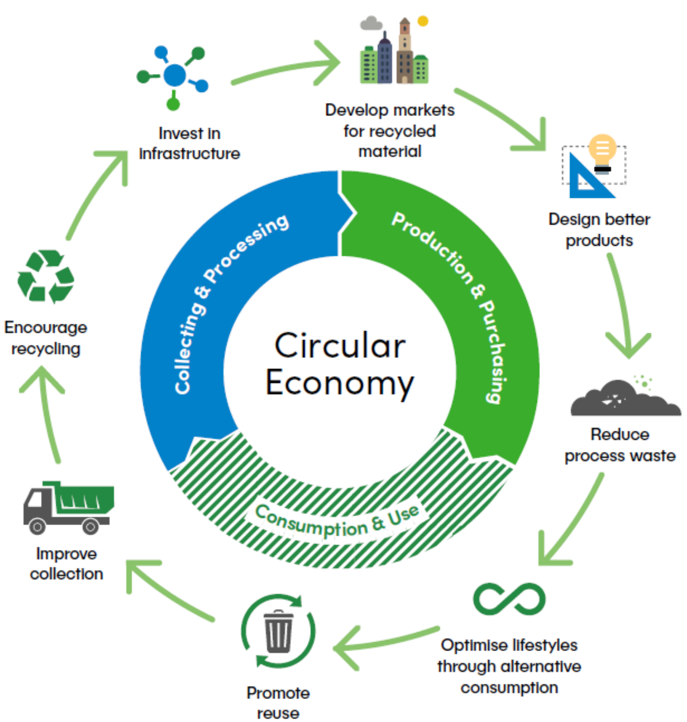
  - **Utilização** eficiente no projeto (e.g. filmes à superfície);
  - **Substituição** por material mais abundante (e.g. cobre por PE em canalizações);
  - **Reciclagem** envolve muita mão-de-obra, embora pouco capital e energia; se a energia e o capital começarem a escassear, o seu custo será comparável ao da mão-de-obra, e a reciclagem tornar-se-á muito mais atraente.

A reciclagem

Reciclagem (definição; fonte: infopédia):

"tratamento de resíduos ou materiais usados, de forma a poderem ser reutilizados ou transformados em novas matérias-primas e novos produtos".

Economia circular



O caminho

?

Waste

Raw Material

Separation / Mixture

Homogeneity

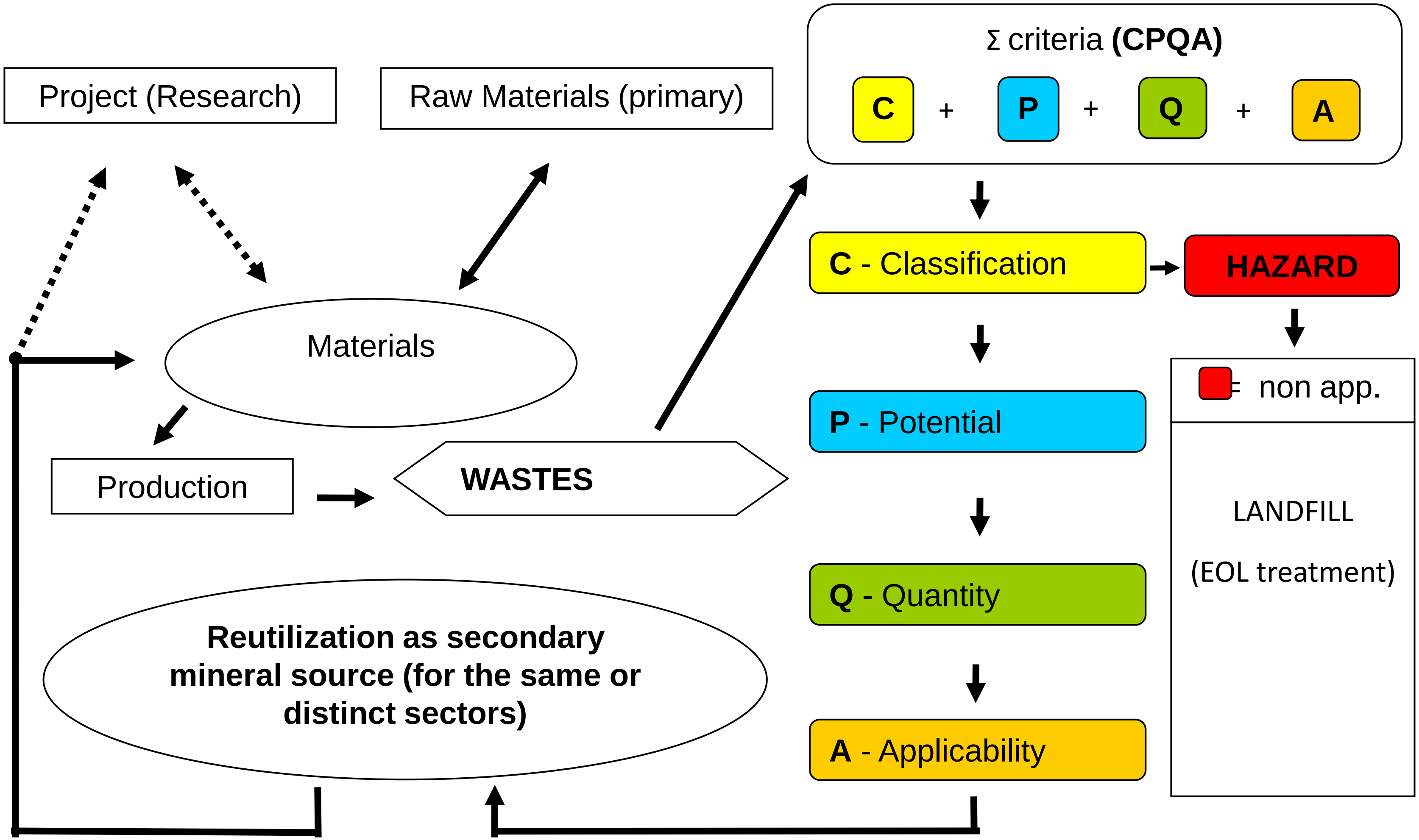
Milling ? Washing ? Drying ? Calcination ?

Raw Material “Re-design”

Incorporation in a common product (ceramic/cement matrix)

Novel Product

How to start ?



Project (Research)
Raw Materials (primary)
Σ criteria (CPQA)
C + P + Q + A
C - Classification
HAZARD
P - Potential
Q - Quantity
A - Applicability
= non app.
LANDFILL
(EOL treatment)
Materials
Production
WASTES
Reutilization as secondary mineral source (for the same or distinct sectors)

How to start ?

- Waste characterization

  The qualification of (industrial) waste might be established from the perspective of its value as a mineral source for possible application in manufacturing/engineering sectors (as inorganic materials). The criteria used to assess the waste potential were CPQA (for short):

- C - Classification (hazardousness);
- P - Potential mineral characteristics;
- Q - Quantity/availability and homogeneity of the waste at the source;
- A - Applicability of the material (alternative / recovery proposals).

How ?

Wastes characterization

(a) Chemical and mineralogical/phases (XRF/XRD);
(b) Thermal behavior (DTA/TG/DSC);
(c) Grain size distribution;
(d) Toxicity (leaching tests): **DIN 38414-S4**

Wastes pre-treatment/adaptation ?

(a) Collection of representative samples;
(b) Mixing and homogenization;
(c) Milling ? Drying ?
(d) …

Processing/Products characterization

(a) Technological requirements;
(b) Standartization (properties);

Overall cost/benefit analyses

Resíduos:
empecilho ou **oportunidade??**


Ambiente
Ar
Água
Resíduos
Ruído
Resíduos Hospitalares
Resíduos Urbanos
Resíduos Industriais

Resíduos por setor económico

Waste generation by economic activities and households, 2018
(% share of total waste)

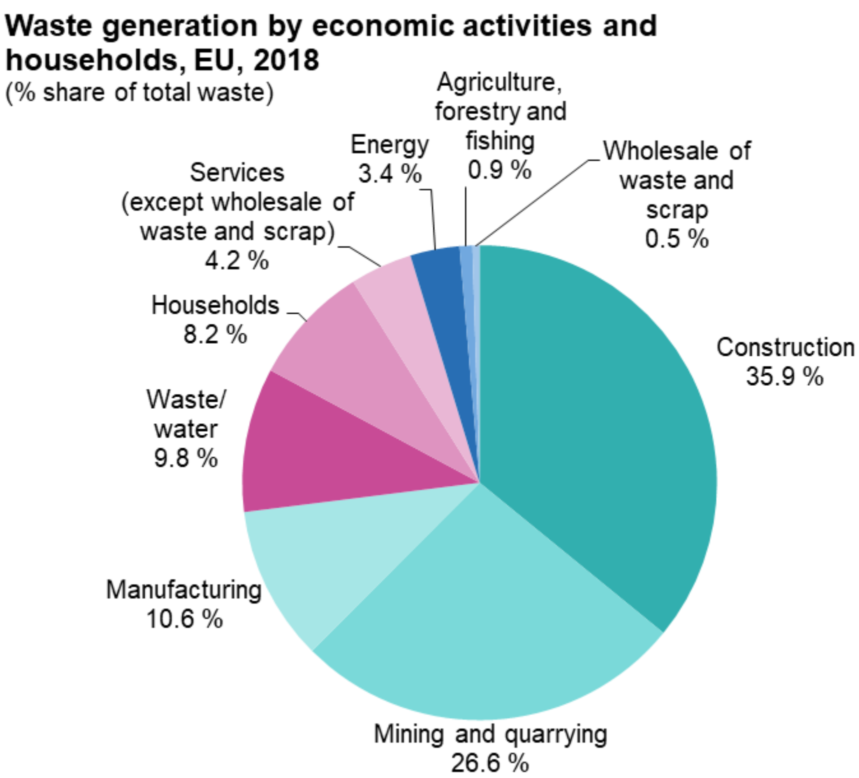
	Mining and quarrying	Manufacturing	Energy	Construction and demolition	Other economic activities	Households
EU	26.6	10.6	3.4	35.9	15.4	8.2
Belgium	0.1	24.9	1.2	33.5	33.1	7.2
Bulgaria	82.4	2.0	10.0	0.1	3.1	2.4
Czechia	0.2	14.6	1.5	41.7	26.7	15.3
Denmark	0.0	4.7	5.1	56.0	17.8	16.4
Germany	2.2	13.9	2.3	55.5	16.8	9.2
Estonia	29.5	18.8	32.3	9.5	7.6	2.4
Ireland	14.2	24.7	1.1	13.6	35.1	11.4
Greece	56.4	11.8	7.6	5.0	9.2	10.1
Spain	17.1	9.9	2.4	27.6	26.5	16.5
France	0.4	6.6	0.4	70.2	13.7	8.7
Croatia	12.0	8.9	1.3	22.7	31.7	23.3
Italy	0.8	16.5	1.3	35.3	28.7	17.5
Cyprus	6.6	16.3	0.1	45.8	14.5	16.8
Latvia	0.1	21.7	2.5	17.5	25.7	32.6
Lithuania	1.6	37.2	2.1	8.8	30.3	20.0
Luxembourg	0.0	6.9	0.1	81.2	9.7	2.1
Hungary	1.0	14.3	11.2	33.2	25.4	14.9
Malta	1.6	1.0	0.0	78.8	11.2	7.4
Netherlands	0.0	9.6	1.1	70.0	13.3	6.0
Austria	0.1	8.7	0.8	74.4	9.3	6.7
Poland	36.7	17.0	10.7	9.7	20.6	5.3
Portugal	0.2	19.0	1.1	8.8	38.1	32.8
Romania	88.0	3.9	3.4	0.3	2.4	2.1
Slovenia	0.2	20.2	11.8	8.1	51.9	7.8
Slovakia	2.2	27.5	7.9	4.4	39.8	18.2
Finland	74.9	6.7	1.0	12.3	3.5	1.6
Sweden	74.7	3.7	1.4	8.9	8.0	3.2
Iceland	0.0	24.4	0.0	3.9	31.5	40.2
Liechtenstein	1.6	1.5	0.0	88.6	1.6	6.7
Norway	1.2	12.8	1.5	40.0	27.4	17.1
United Kingdom	5.2	4.0	0.2	48.8	32.4	9.4
Montenegro	27.4	3.7	27.6	11.3	8.6	21.4
North Macedonia	14.2	46.6	0.5	3.1	35.6	0.0
Serbia	75.6	2.9	14.7	1.1	2.1	3.6
Turkey	17.9	:	26.1	0.0	7.1	28.9
Bosnia and Herzegovina	8.2	28.1	48.1	1.8	0.2	13.6
Kosovo (¹) (²)	93.5	2.0	3.4	0.1	0.0	1.0

(¹) 2016
(²) This designation is without prejudice to positions on status, and is in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo Declaration of Independence.
Source: Eurostat (online data code: env_wasgen)

eurostat

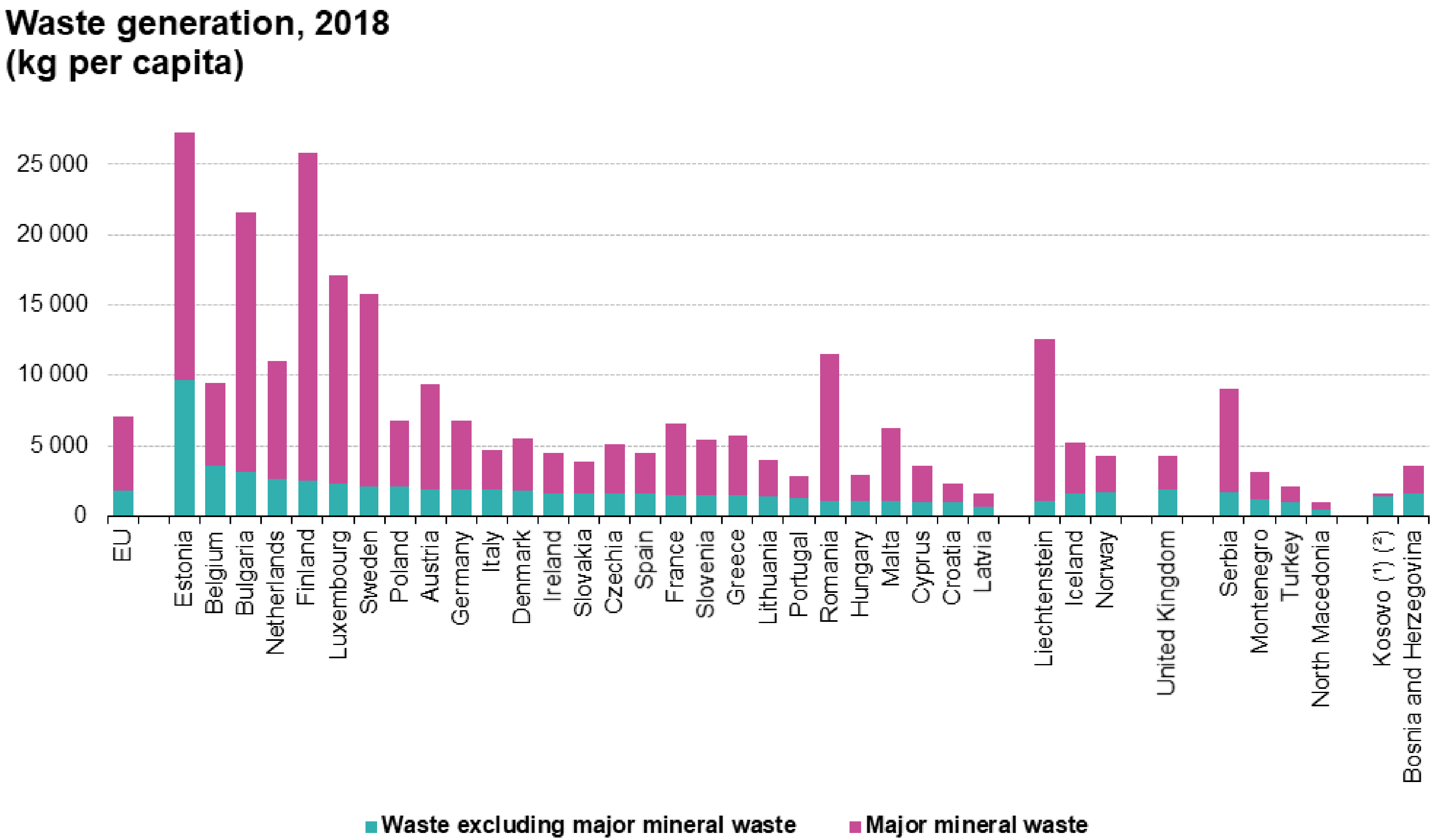
Resíduos por setor económico

In 2018, the total waste generated in the EU by all economic activities and households amounted to 2 337 million tonnes.



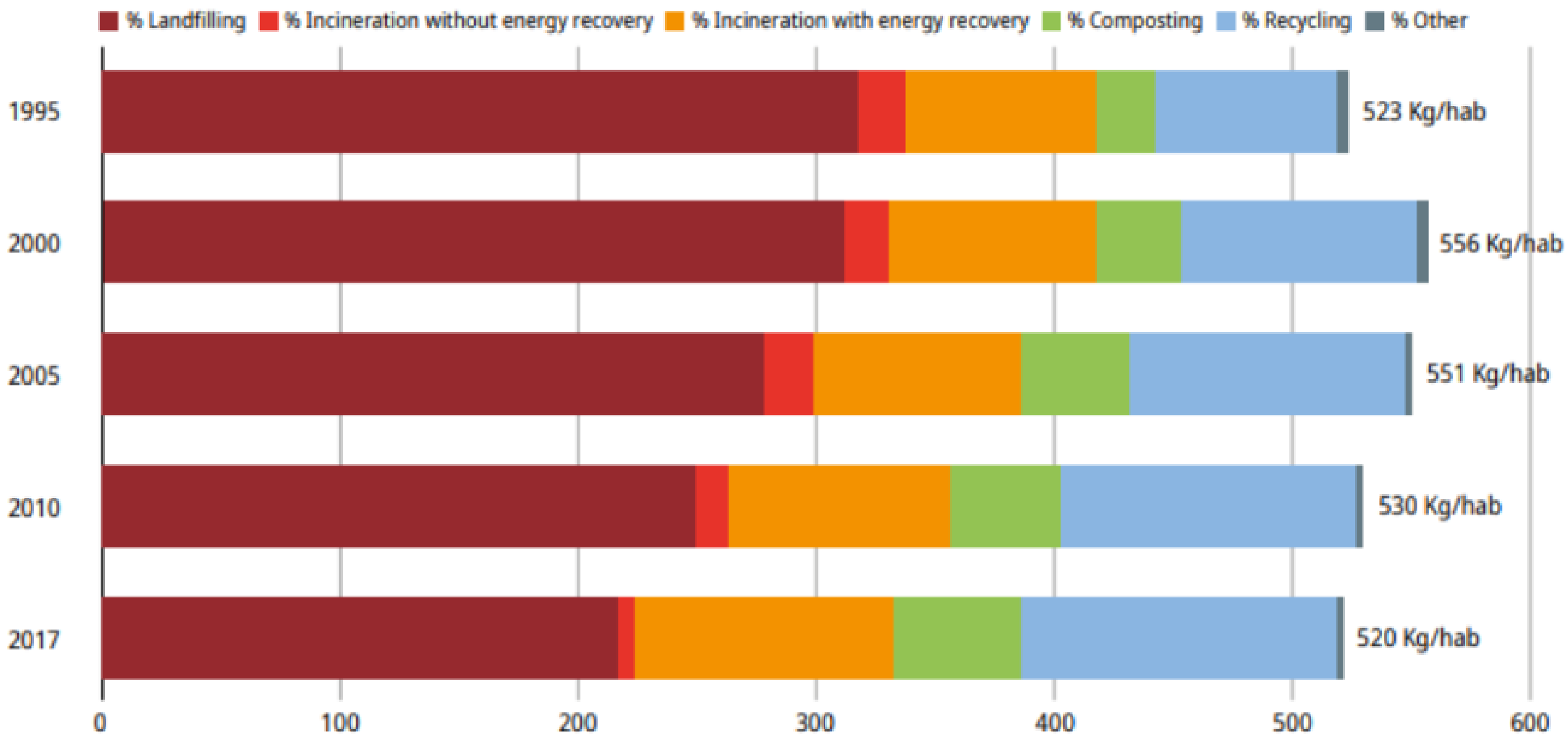
Source: Eurostat (online data code: env_wasgen)

Total de resíduos per capita: distinção entre “mineral waste” e “outros”



Note: sorted on total waste generated.
(¹) This designation is without prejudice to positions on status, and is in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo Declaration of Independence.
(²) 2016.
Source: Eurostat (online data code: env_wasgen)

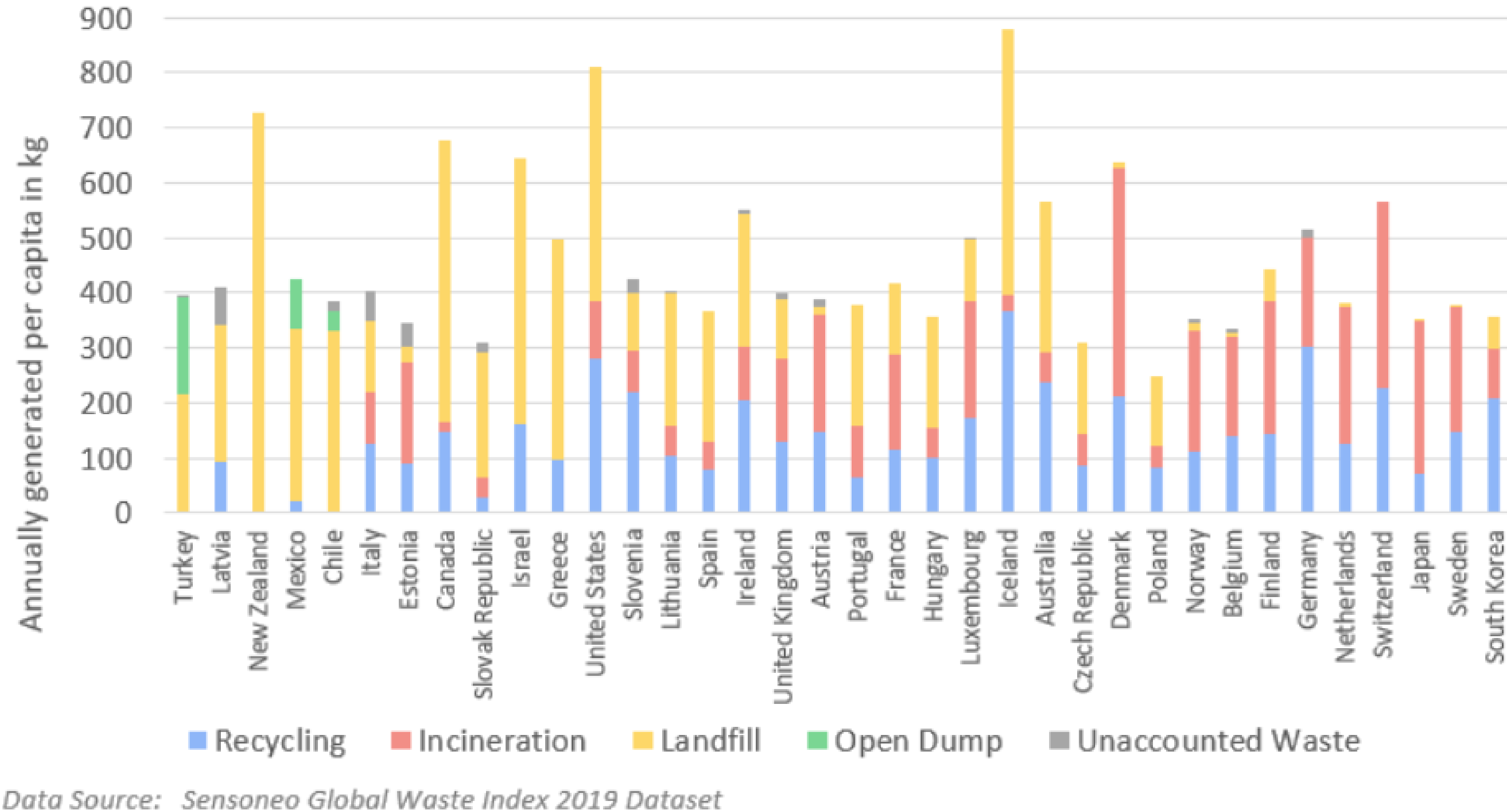
Resíduos Urbanos: ponto da situação na EU



Source: OECD (2019), "Waste: Municipal waste", *OECD Environment Statistics* (database).

Fonte: https://earth.org/data_visualization/waste-management-and-recycling/

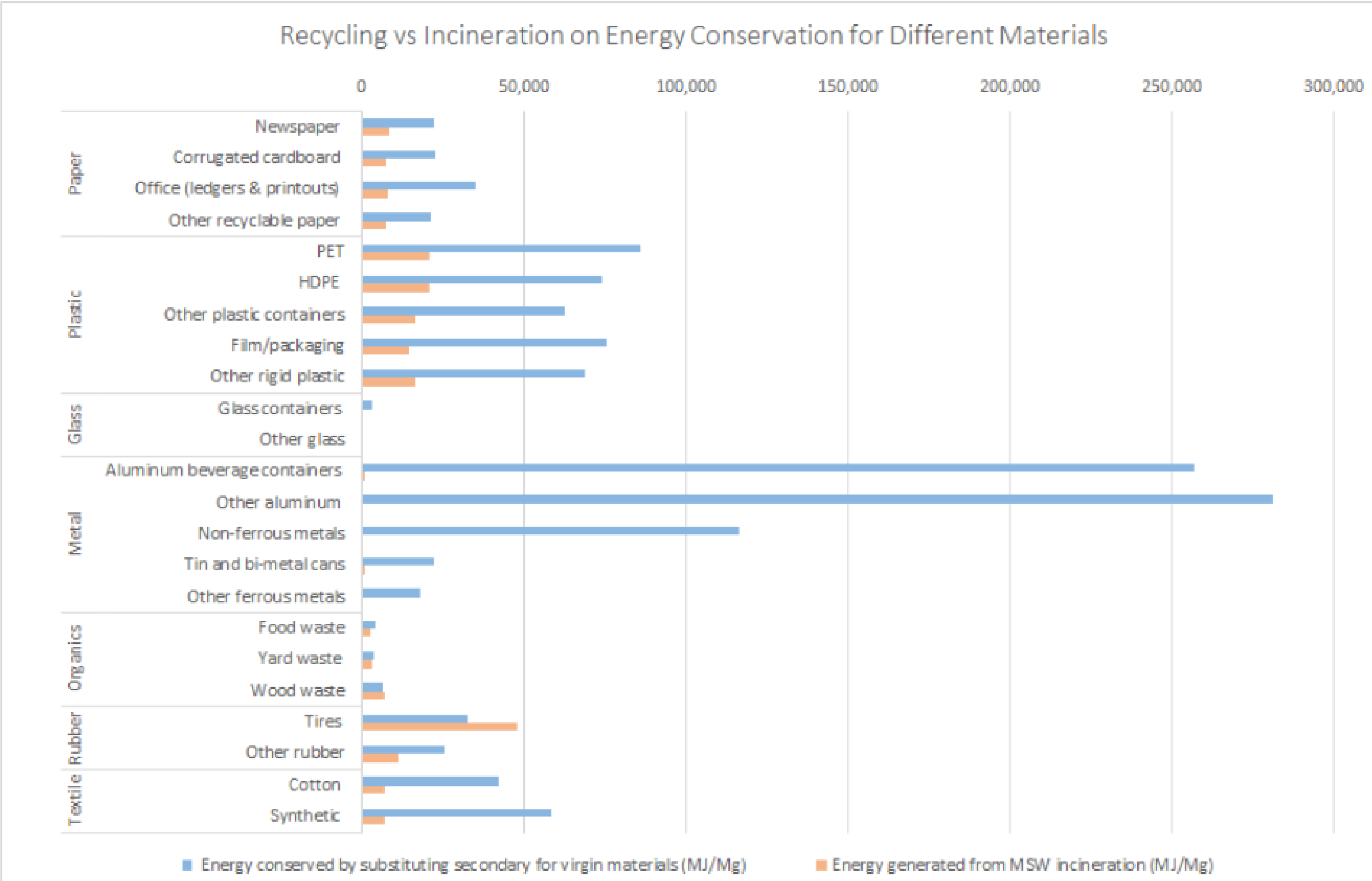
Resíduos Urbanos: ponto da situação



Data Source: Sensoneo Global Waste Index 2019 Dataset

Fonte: https://earth.org/data_visualization/waste-management-and-recycling/

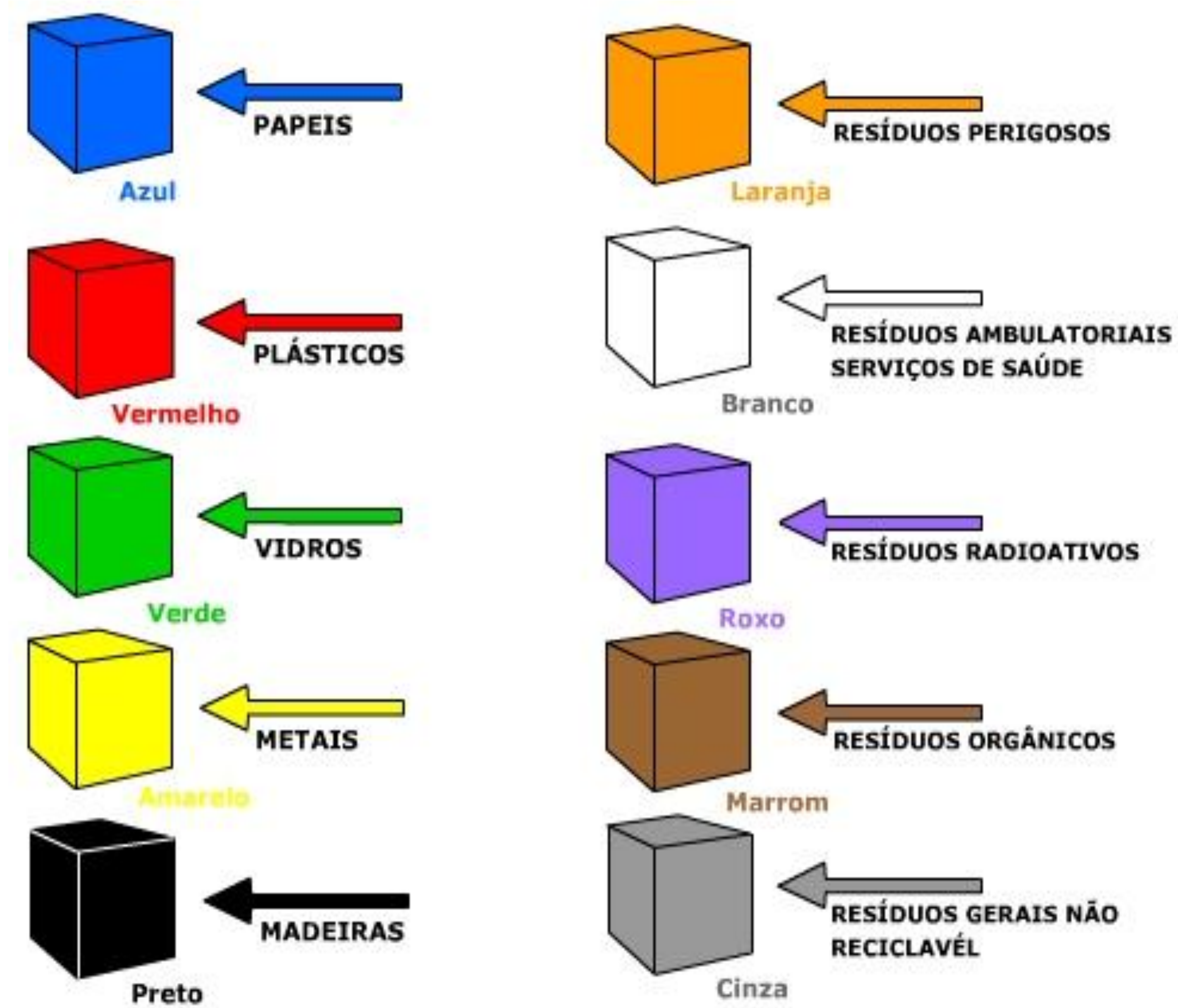
Resíduos Urbanos: ponto da situação



Fonte: https://earth.org/data_visualization/waste-management-and-recycling/

➢ O eterno problema da separação

No limite “TUDO” é reciclável



Nem sempre os resíduos são um problema…

- **Casos de sucesso:**
  - Reciclagem de latas de alumínio
  - Reciclagem de vidro de embalagem (garrafas e fracos de vidro)
  - Reciclagem de papel
  - Aparas de madeira e/ou serragem
  - …
- **Outros resíduos com potencialidades:**
  - Resíduos da construção e demolição (RCD)
  - Escórias de alto forno (principalmente as de elevado teor em Ca)
  - Cinzas volantes
  - ….

Os casos mais complexos:

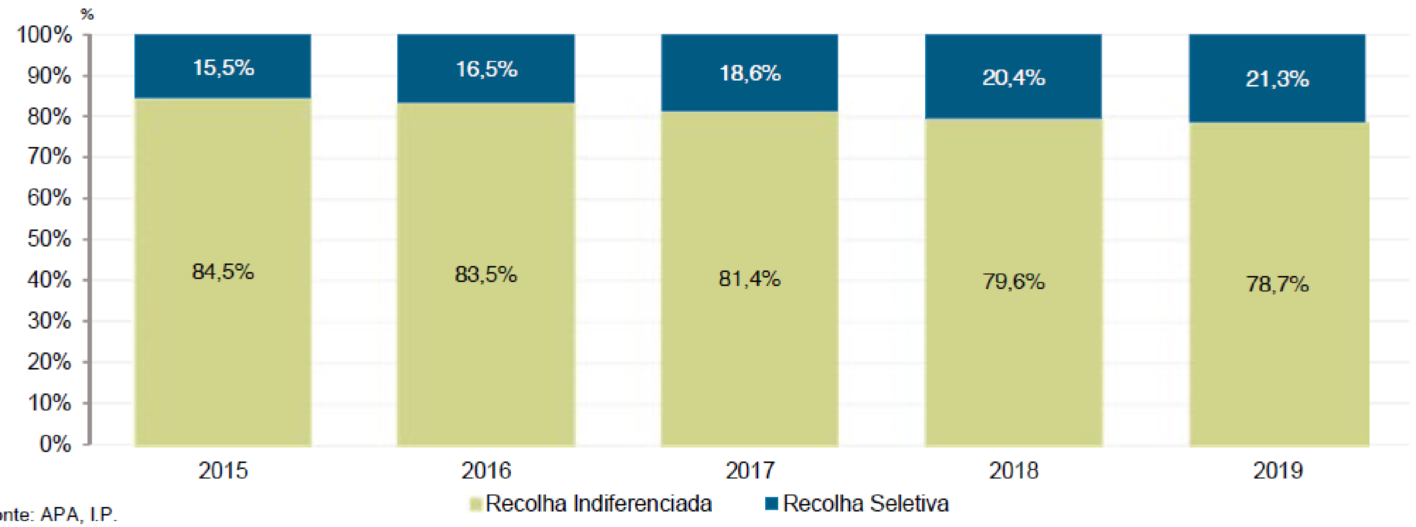
- **Eletrónica e eletrodomésticos**
  - Diferentes tipos de materiais (plásticos, cerâmicos e metais)
  - Alguns materiais de levada toxicidade (chumbo, mercúrio,…)
  - Separação/triagem complicada
  - Métodos de extração ainda pouco eficientes

- **Resíduos Hospitalares**
- **Resíduos das centrais nucleares**
- **Baterias (exceto Pb-ácido)**
- **Resíduos sólidos urbanos (RSU)**
  - A queima pode ser uma solução para a fração orgânica
  - Separação difícil

A reciclagem

Contexto em Portugal

Figura 5.3 >> Proporção da recolha indiferenciada e seletiva de resíduos urbanos sobre o total de RU recolhidos, em Portugal



Fonte: APA, I.P.

Em 2019 foram recolhidos de forma seletiva e outras recolhas (ecopontos, porta-a-porta, circuitos especiais, ecocentros e grandes produtores de RU) 1 127,2 mil toneladas de RU (1 064,4 mil toneladas em 2018), um incremento de 62,8 mil toneladas.

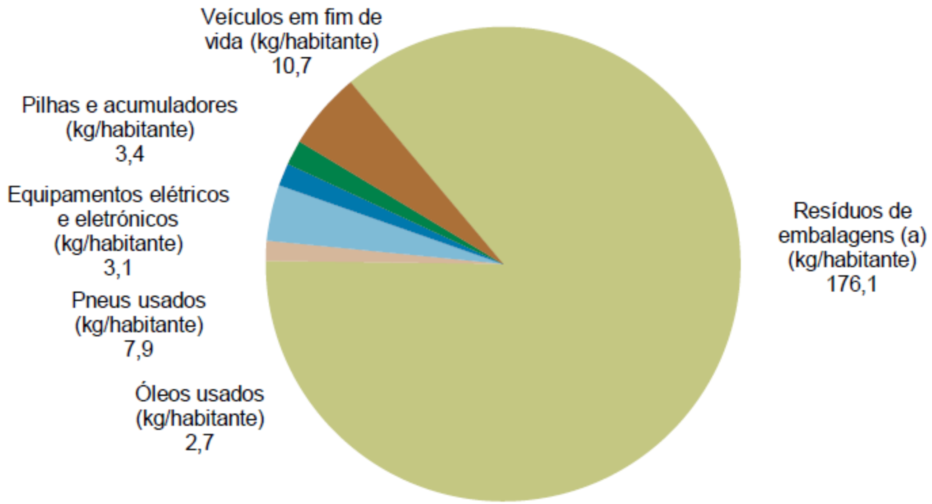
No período em análise constata-se que a importância relativa da recolha seletiva tem vindo a evoluir de forma positiva e consistente, fixando-se em 2019 em 21,3%, o que corresponde a um aumento de 0,9 p.p. face a 2018 e 5,8 p.p. quando comparado com 2015.

Fonte: Estatísticas do ambiente 2019, Edição 2020 (Instituto Nacional de Estatística)

A reciclagem

Contexto em Portugal

Figura 5.12 >> Quantidade de resíduos de fluxos específicos recolhidos por habitante (2019)



(a) Refere-se a estimativa de resíduos produzidos.
Fonte: APA, I. P.

Em 2019, as entidades gestoras de fluxos específicos registaram um acumulado de resíduos produzidos/recolhidos de 2 098 milhares de toneladas, dos quais 73,8% foram valorizados (1 548 milhares de toneladas).

O volume de resíduos de fluxos específicos produzidos/recolhidos em 2019 decresceu 7,8%, o que corresponde a -70,8 mil toneladas do que o total registado em 2018 (2 169 milhares de toneladas).

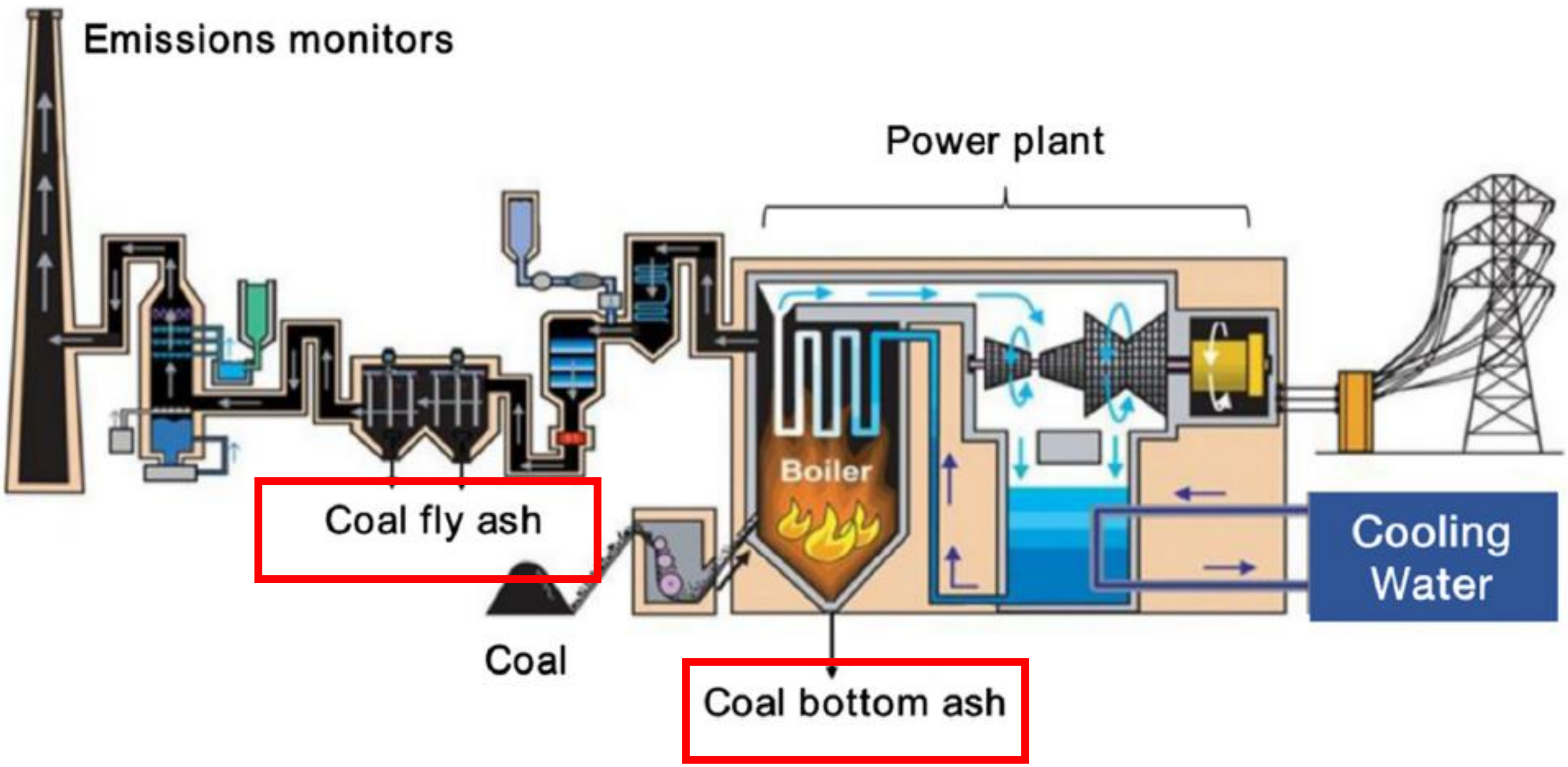
Em termos *per capita*, realça-se o significado dos resíduos de embalagens no conjunto dos resíduos de fluxos específicos, com uma estimativa de um rácio médio de 176,1 kg de resíduos de embalagens gerados por habitante.

Fonte: Estatísticas do ambiente 2019, Edição 2020 (Instituto Nacional de Estatística)

Wastes derived from thermal power stations

Coal-fired thermal power plant

Operation schematics



Schematic representation of the formation of the ashes

Source: Zhou *et al.*, Towards sustainable coal industry: Turning coal bottom ash into wealth, Science of the Total Environment 804 (2022) 149985

Coal-fired thermal power plant

Worldwide production

2019

American Coal Ash Association Phone: 720-870-7897
38800 Country Club Drive Fax: 720-870-7889
Farmington Hills, MI 48331 Internet: www.ACAA-USA.org
Email: info@acaa-usa.org

60% **32%**

2019 Coal Combustion Product (CCP) Production & Use Survey Report

Beneficial Utilization versus Production Totals (Short Tons)

2019 CCP Categories	Fly Ash	Bottom Ash	Boiler Slag	FGD Gypsum	FGD Material Wet Scrubbers	FGD Material Dry Scrubbers	FGD Other	FBC Ash	CCP Production / Utilization Totals
Total CCPs Produced by Category	29,319,239	9,150,680	965,138	22,975,581	6,217,129	3,707,974	18,428	6,293,721	78,647,890
Total CCPs Used by Category	17,768,235	2,923,586	697,001	13,285,876	359,529	90,346	0	5,882,468	41,007,041
1. Concrete/Concrete Products /Grout	12,604,878	332,036	0	95,090	0	10,300	0	0	13,042,304
2. Blended Cement/ Feed for Clinker	2,556,358	910,914	65,758	1,464,262	0	0	0	3,442	5,000,734
3. Flowable Fill	102,196	0	0	0	0	0	0	0	102,196
4. Structural Fills/Embankments	501,668	532,676	67,104	617,122	0	0	0	0	1,718,570
5. Road Base/Sub-base	154,822	105,869	0	0	0	0	0	0	260,690
6. Soil Modification/Stabilization	76,239	126,719	0	3,911	0	0	0	0	206,869
7. Mineral Filler in Asphalt	4,598	4,711	3,831	0	0	94	0	0	13,234
8. Snow and Ice Control	0	73,720	10,114	0	0	0	0	0	83,834
9. Blasting Grit/Roofing Granules	0	362,281	245,601	0	0	0	0	0	607,883
10. Mining Applications	17,282	0	0	0	0	0	0	5,831,652	5,848,935
11. Gypsum Panel Products (formerly Wallboard)	0	0	0	9,688,345	82,703	0	0	0	9,771,048
12. Waste Stabilization/Solidification	604,222	57,689	0	16,503	0	11,858	0	47,374	737,646
13. Agriculture	0	2,449	0	572,399	0	59,966	0	0	634,814
14. Aggregate	63,609	137	0	0	0	0	0	0	63,745
15. Oil/Gas Field Services	152,053	436	0	0	0	8,128	0	0	160,617
16. CCR Pond Closure Activities	720,411	357,558	304,592	713,573	276,826	0	0	0	2,372,960
17. Miscellaneous/Other	209,898	56,391	0	114,671	0	0	0	0	380,960

Summary Utilization to Production Rate

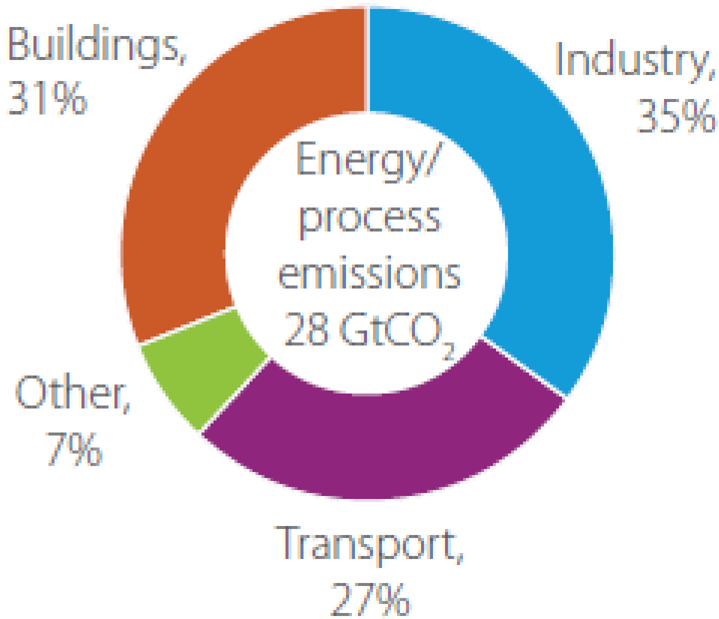
CCP Categories	Fly Ash	Bottom Ash	Boiler Slag	FGD Gypsum	FGD Material Wet Scrubbers	FGD Material Dry Scrubbers	FGD Other	FBC Ash	CCP Utilization Total
Totals by CCP Type/Application	17,768,235	2,923,586	697,001	13,285,876	359,529	90,346	0	5,882,468	41,007,041
Category Use to Production Rate (%)	60.60%	31.95%	72.22%	57.83%	5.78%	2.44%	0.00%	93.47%	52.14%
2019 Cenospheres Sold (Pounds)	943,603	Data in this survey represents 152 GW of Name Plate rating of the total industry wide approximate 236 GW capacity based on EIA's July 2019 Electric Power Monthly.							

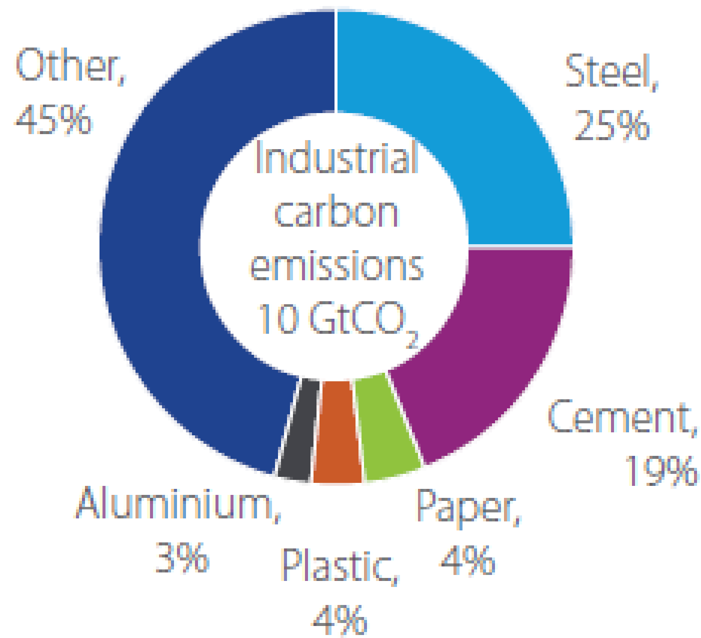
41 million tons of coal combustion products were beneficially used in 2019 out of 78.6 million tons that were produced.

Source: American Coal Ash Association (https://acaa-usa.org/wp-content/uploads/coal-combustion-products-use/2019-Survey-Results.pdf)

Aluminium

Sources of global CO_2 emissions





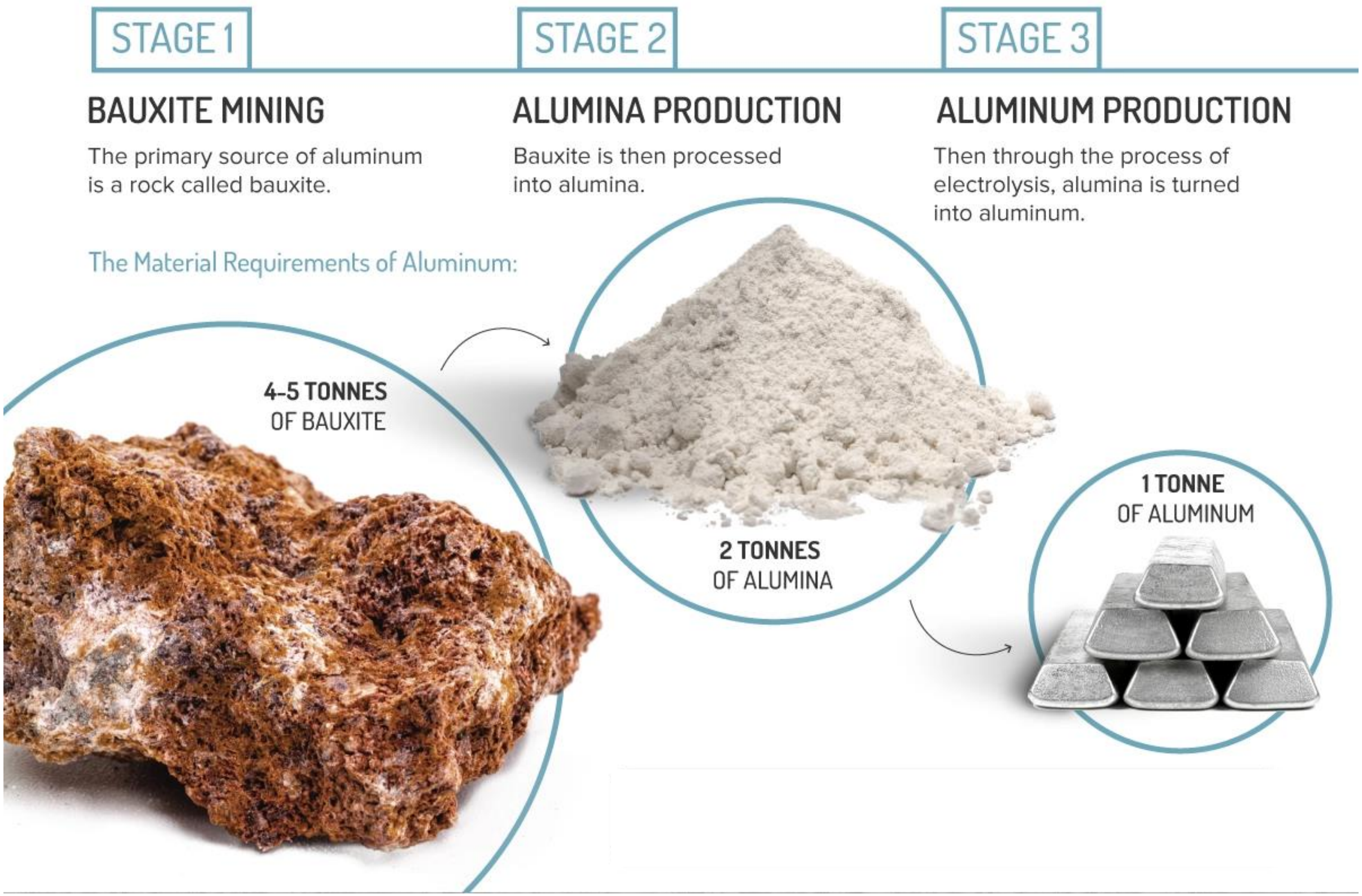
Source: "Sustainable Materials – with both eyes open", Julian M. Allwood, Jonathan M. Culle, UIT Cambridge Ltd. (2012).

"Aluminium is both an important input to a number of technologies critical to the energy transition, and a significant source of CO_2, responsible for about 3% of the world's 9.4 Gt of direct industrial CO_2 emissions in 2021"

Source: International Energy Agency (IEA) (https://www.iea.org/reports/aluminium)

Aluminium

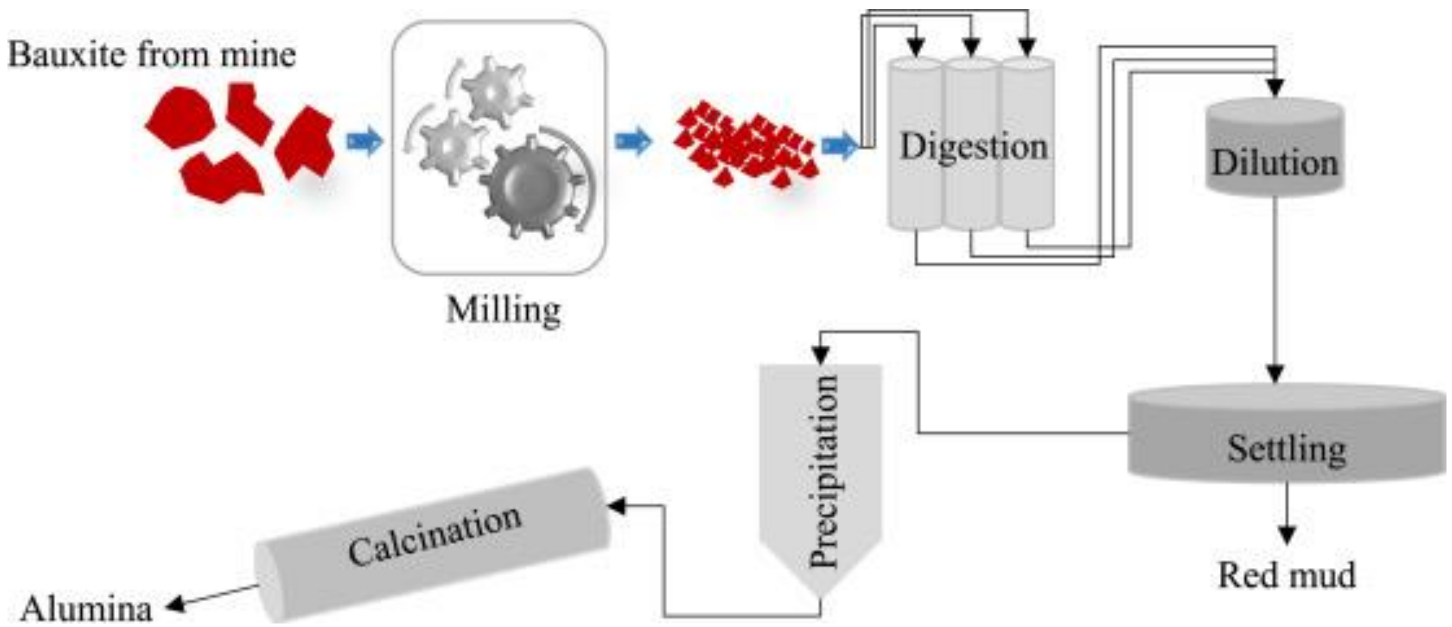
Where does aluminium come from?



Aluminium production - Wastes

Red mud

The bauxite residue (BR) is the most significant waste by volume associated with aluminium production. Its management is one of the most sensitive topics for the green credentials of the aluminium industry.



Source: Mahinroosta *et al.*, "Recycling of Red Mud for Value-Added Applications: A Comprehensive Review", Encyclopedia of Renewable and Sustainable Materials, Volume 2, 2020.

Aluminium production - Wastes

bauxite residue derived from the alumina production

High pH (> 10.6), high sodium content & contains HMs

Global RM reserves have exceeded 4 billion tons[1]!

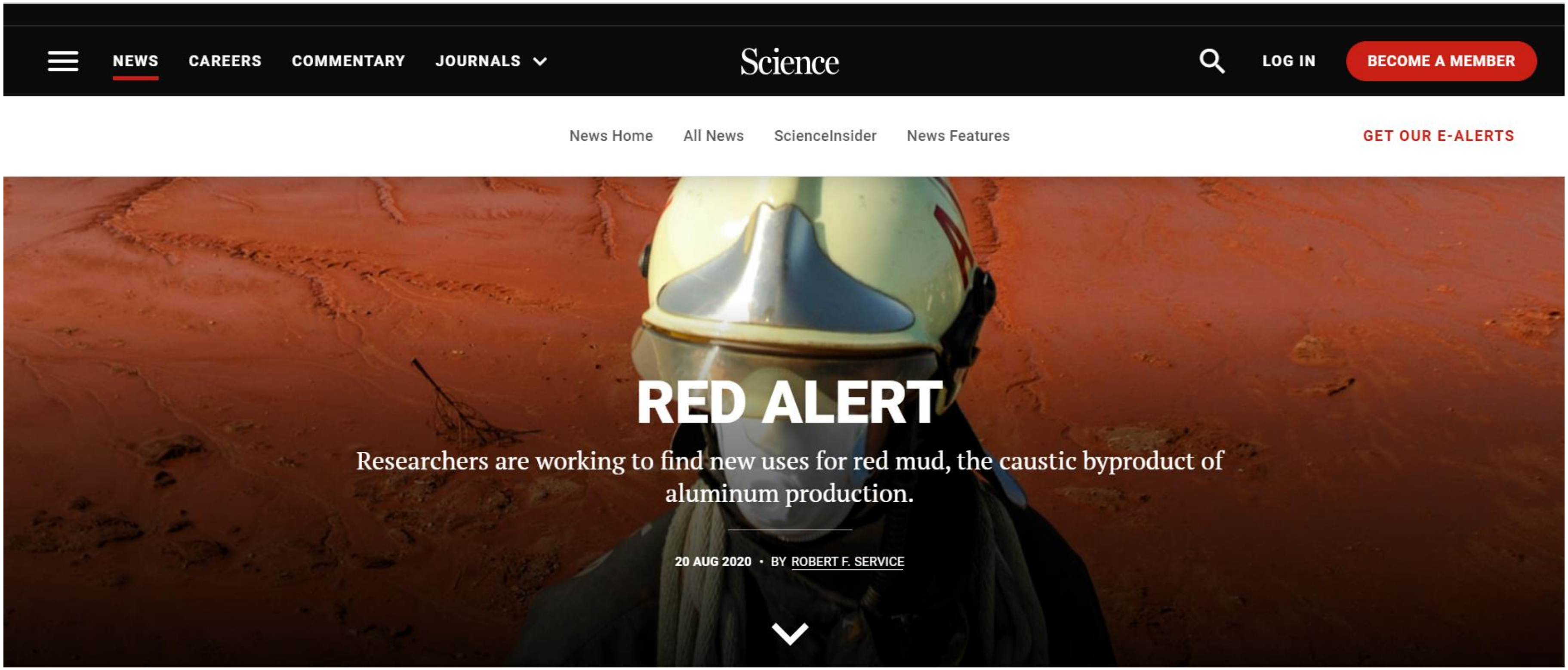
This distressing scenario is attributed to the wastes' strong alkalinity, particle fineness, and toxicity, which hinders recycling. In fact, less than 2.7% of the annual red mud production (150 million tonnes) is reused, while most of it is disposed of in large lagoons or tailing dams.

Source: Novais *et al.*, "Red mud-based inorganic polymer spheres bulk-type adsorbents and pH regulators", Materials Today, Volume 23, March 2019.

[1] **Zeng *et al.*,** *Minerals 10 (9), 773* (2020).

Aluminium production - Wastes

Red mud



Source: https://www.science.org/content/article/red-mud-piling-can-scientists-figure-out-what-do-it

Aluminium production - Wastes

Challenges in red mud (bauxite residue) management

Disposed in large lagoons

(in slurry form)

https://en.wikipedia.org/wiki/Red_mud#/media/File:B%C3%BCtzfletherm oor_Rotschlammdeponie_Luftaufnahmen_2012-05-by-RaBoe-478-1.jpg

Disposed in tailings dams

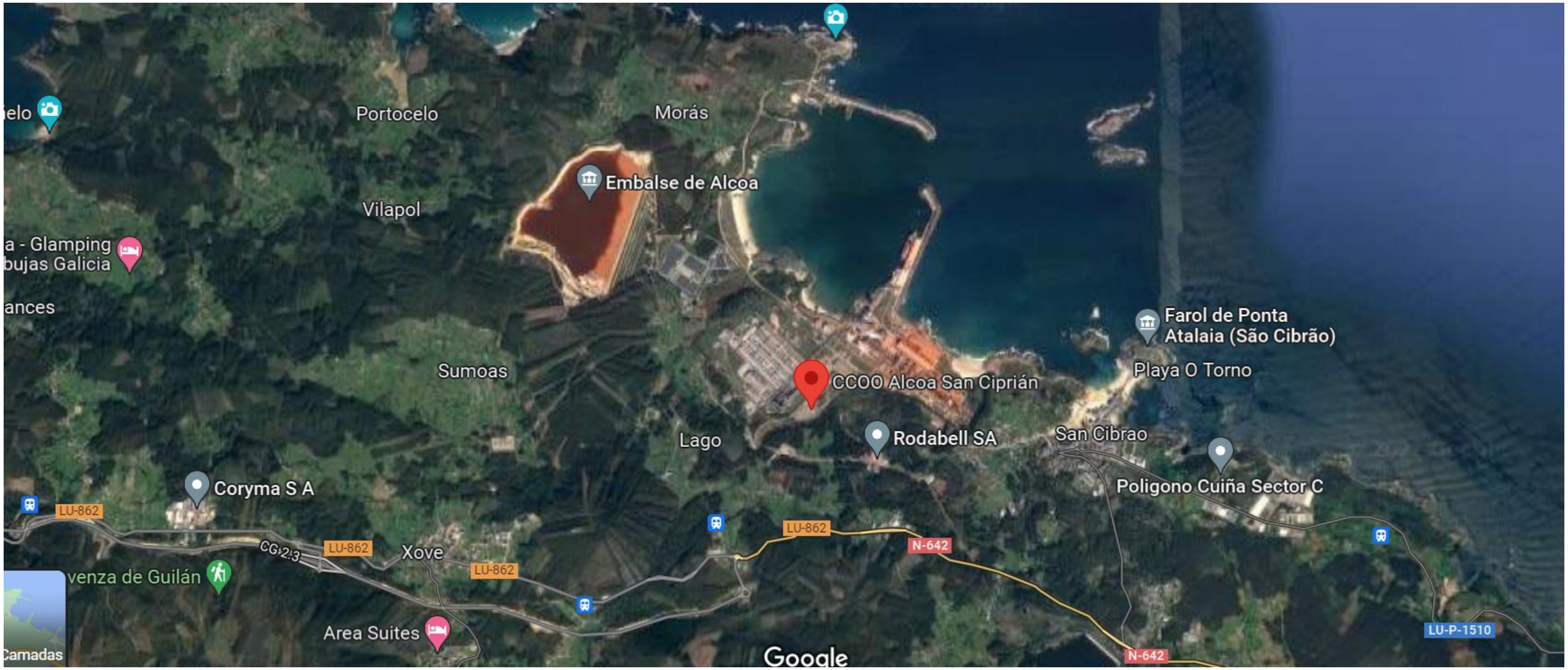
(as dried red mud)

https://www.linkedin.com/pulse/future-mining-tailings-managment-davide-cavalli

Deposition of red mud (bauxite residue)

Aerial view of S. Ciprian (Galiza), Alcoa dam for red mud

(Google Maps, 27.11.2022)



Deposition of red mud (bauxite residue)

S. Ciprian (Galiza), Alcoa dam for red mud

(images collected from Google)

Deposition of red mud (bauxite residue)

S. Ciprian (Galiza), Alcoa dam for red mud

(images collected from Google)

Aluminium production - Wastes

Deposition of red mud - Catastrophic red mud dam failure in Hungary (2010)

On 4 October 2010, the red mud reservoir (tailings dam) collapsed at the Hungarian alumina plant in AjKa run by MAL-Magyar Aluminium Ltd., and nearly one million cubic metres of highly alkaline, saline and metal(loid)-rich sludge was released. The red mud flooded several villages, killed ten people, injured almost 150, and polluted vast areas of land of about 1,000 ha in the surrounding environment, as well as surface waters (all life in a nearby river was eliminated). The Ajka red mud disaster (or the Kolontar/Devecser disaster) is considered to be Hungary's worst industrial catastrophe, one of the greatest ecological disasters in Europe, and the most severe accidental load of red mud slurry ever experienced

Source: Georgitzikis *et al.*, **"**Sustainability aspects of Bauxite and Aluminium", Technical report, European Commission.

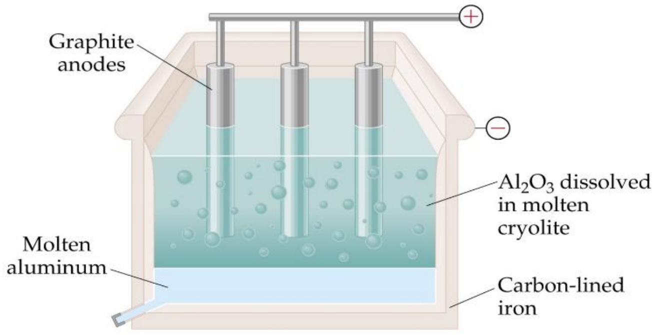
Electrometallurgy of Al – Hall-Héroult cell

This stage comprises the electrolytic reduction of aluminium oxide to aluminium.

Problem: Al_2O_3 melts only at 2000°C

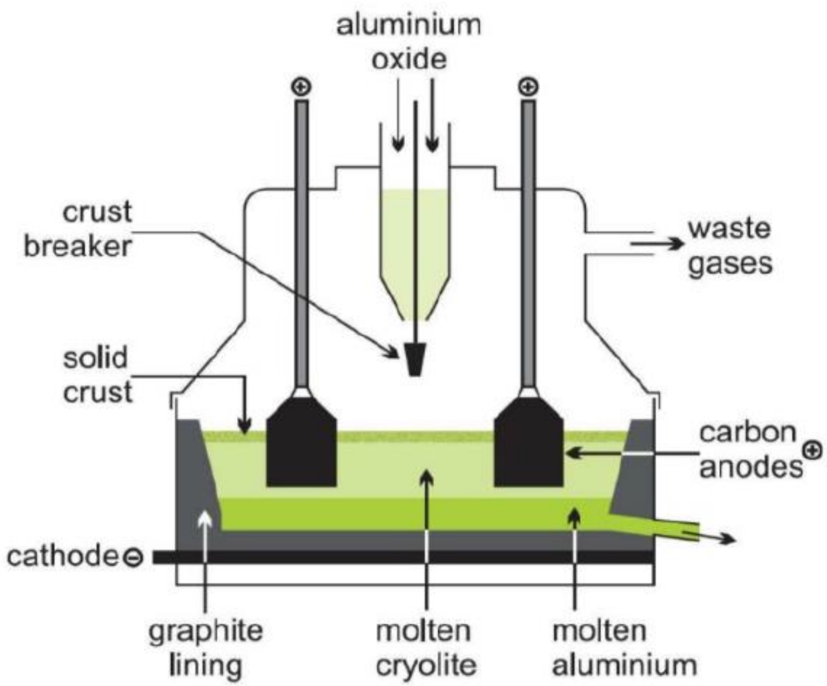
Hall used Al_2O_3 in melted cryolite (Na_3AlF_6, melting T = 1012°C).

The electrolytic process, known as the Hall-Héroult process, is carried out in smelting plants. This is the most energy-intensive stage in the aluminium production chain requiring massive amounts of electricity.



The Hall-Héroult process is a fused-salt electrolysis that comprises aluminium oxide's breakdown into aluminium and oxygen using direct current.

Electrometallurgy of Al – Hall-Héroult cell



- Hall used Al_2O_3 in melted cryolite (Na_3AlF_6, melting T = 1012°C).

  anode: $C(s) + 2O^{2-}(l) \rightarrow CO_2(g) + 4e^-$

  cathode: $3e^- + Al^{3+}(l) \rightarrow Al(l)$
- Graphite is consumed in the reaction.

Source: Georgitzikis *et al.*, "Sustainability aspects of Bauxite and Aluminium", Technical report, European Commission.

Secondary Aluminium production

Aluminium properties do not change during use; therefore, it can be recycled multiple times without losing its original properties. Aluminium has no dissipative uses and it is infinitely recyclable.

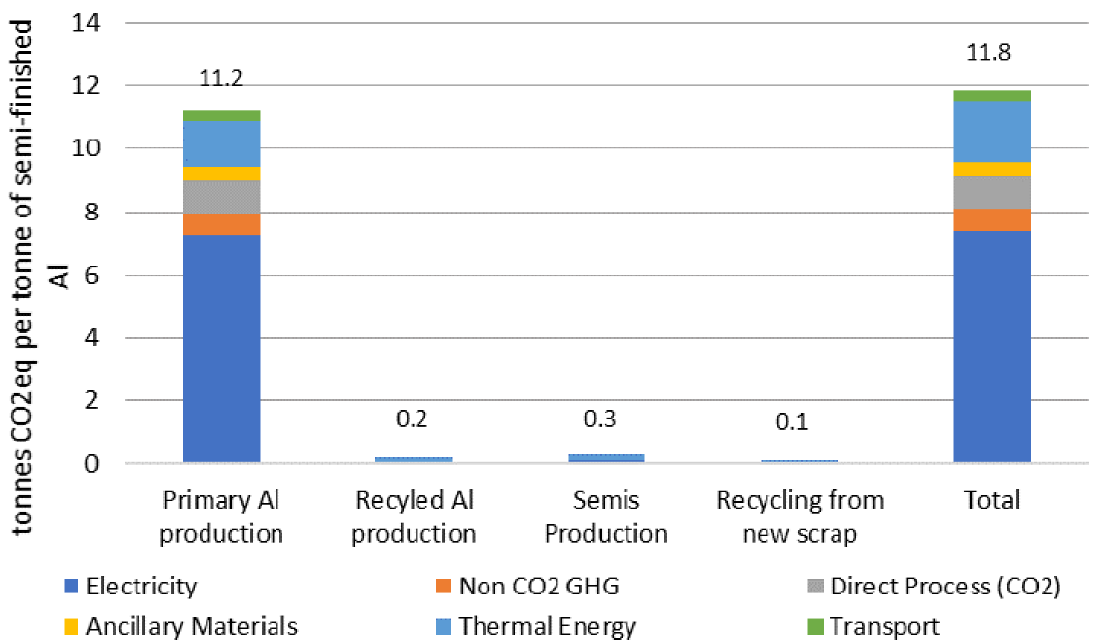
As current estimates suggest, the result of aluminium products' recyclability and long lifespan in many applications is that today around three-quarters of all aluminium ever produced (1.5 billion tonnes) is still in use, some having been through countless loops of its lifecycle. In 2019, around 36% of the stock was located in buildings, 25% in electrical cables and machinery and 30% within transport applications

However, wastes are generated in the process!!

Secondary Aluminium production

The production of secondary aluminium is much less demanding in terms of energy, accounting for a consumption per kg of about 5% of the energy needed to produce primary aluminium.

Figure 16. Greenhouse gas (GHG) emissions (as CO_2 equivalent per tonne of semi-finished production) in the aluminium sector worldwide per industrial segment, in 2018 ([25])



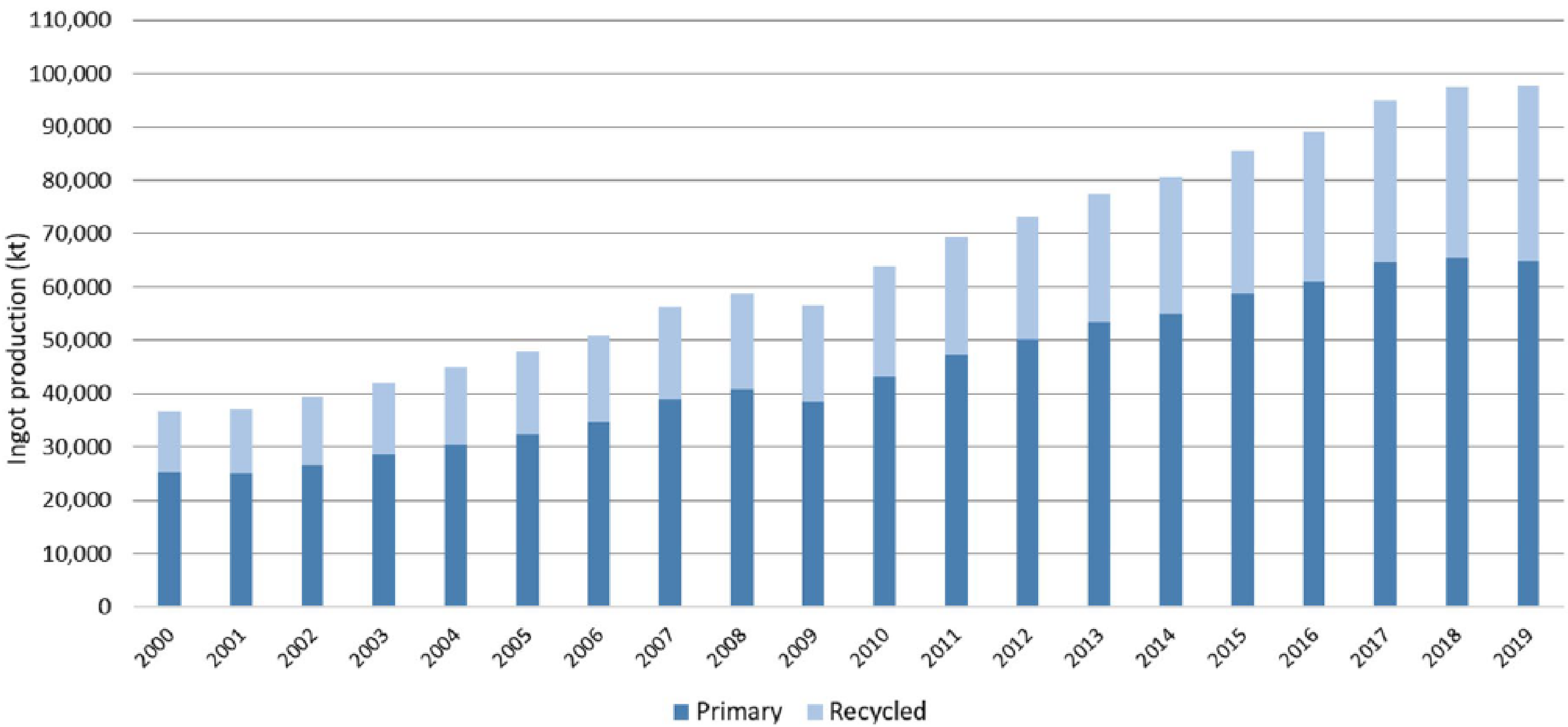
Source: (IAI, 2020c).

Source: Georgitzikis *et al.*, **"**Sustainability aspects of Bauxite and Aluminium", Technical report, European Commission.

Secondary Aluminium production

Evolution of production for unwrought aluminium ingots globally

Figure 11. Evolution of production for unwrought aluminium ingots globally (22)



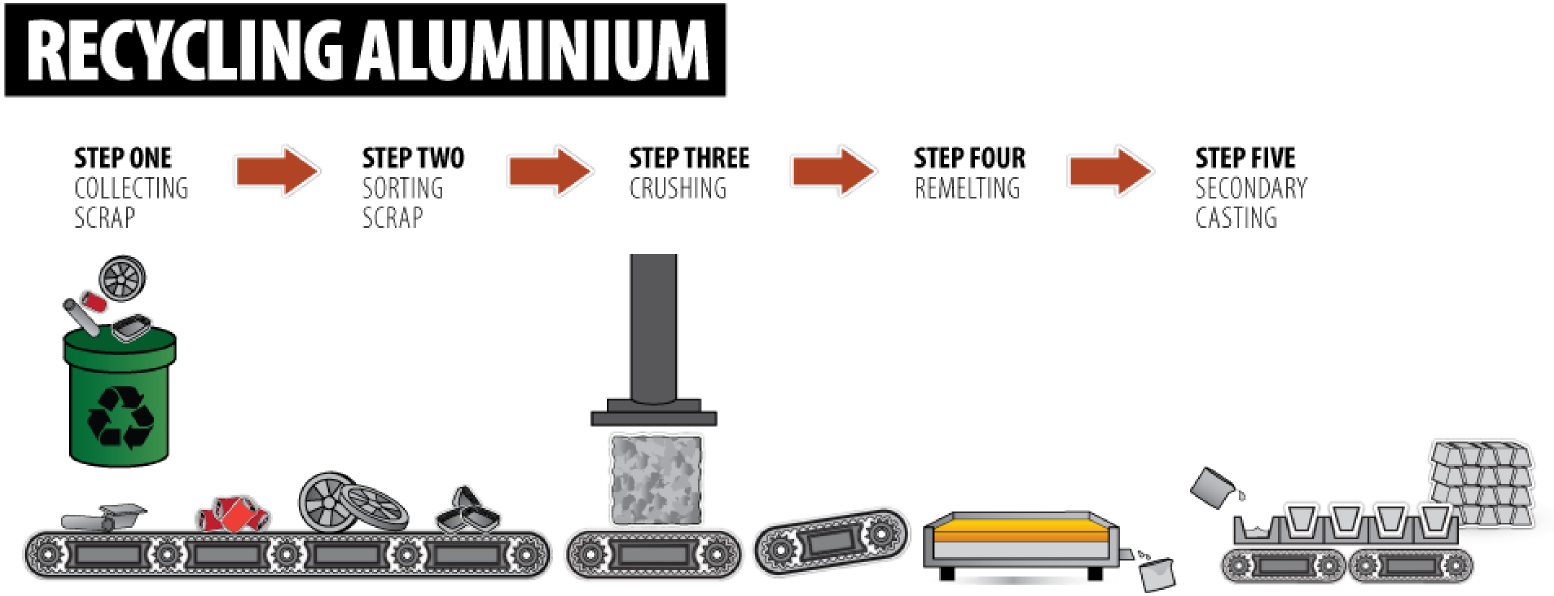
Source: Background data from (IAI, 2020d).

Source: Georgitzikis *et al.*, "Sustainability aspects of Bauxite and Aluminium", Technical report, European Commission.

Secondary Aluminium production

Recycling of aluminium scrap involves the collection, sorting, pre-treatment, melting and ingot casting. Secondary aluminium production is characterized by the diversity of old scrap types available, i.e. a high variety of alloys, size, type and degree of contamination by paints, ink or plastics, which correspondingly determines the necessary pre-treatment technique (e.g. mechanical separation) and the melting process to be applied (e.g., rotary furnace with salt flux)

Source: Georgitzikis *et al.*, **"**Sustainability aspects of Bauxite and Aluminium", Technical report, European Commission.



Source: https://www.bespokeguttering.co.uk/aluminium-recycling/

Secondary Aluminium production

Recycled (or secondary) aluminium is produced by melting old and new aluminium-bearing scrap:

- **New or process scrap:** generated from the fabrication of semi-finished aluminium and the manufacturing of finished products, such as extrusion discards, sheet edge trimmings, turnings, millings etc.

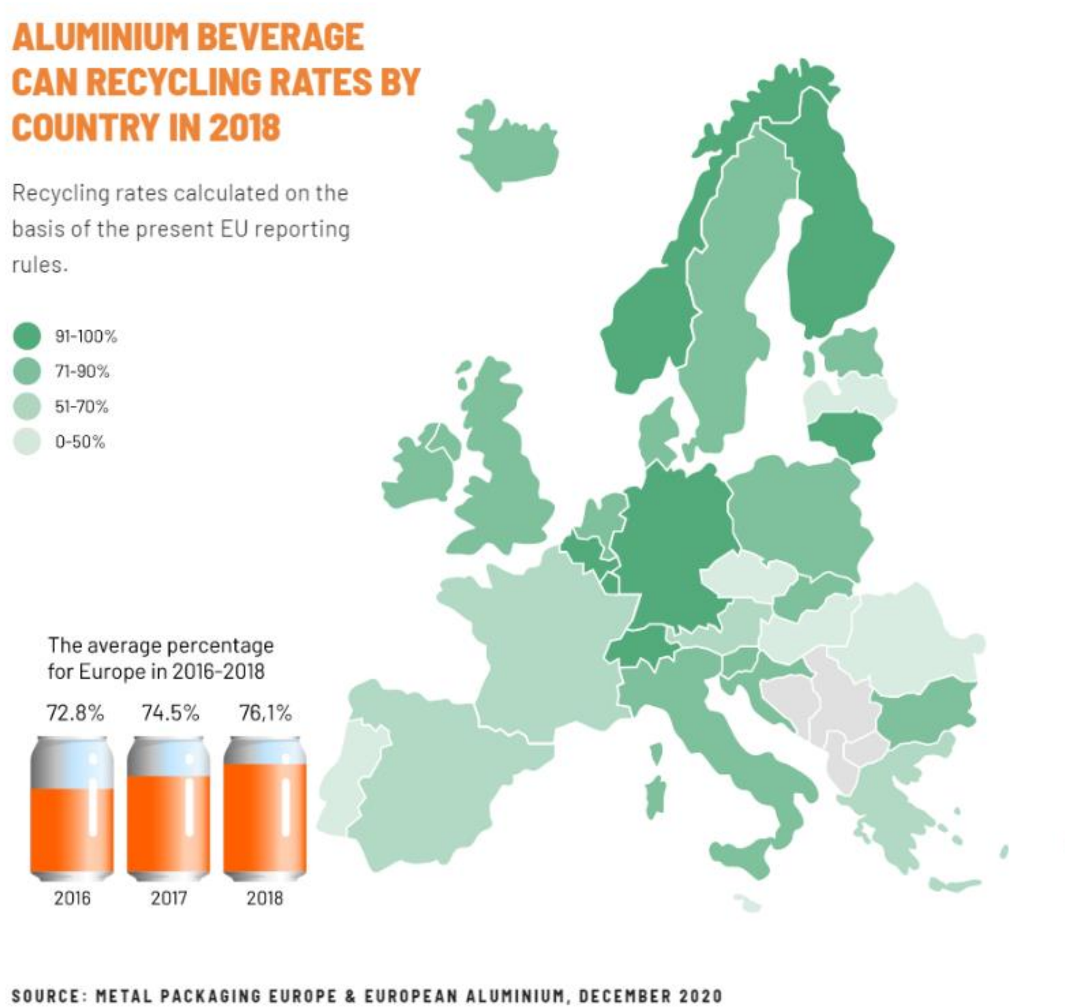
- Old or post-consumer scrap: post-consumer scrap recovered from end-of-life sources, such as used beverage cans, engine blocks, aluminium window systems, electrical conductor cables, etc.

Source: Georgitzikis *et al.*, "Sustainability aspects of Bauxite and Aluminium", Technical report, European Commission.

Secondary Aluminium production

Recycling rates for aluminium-based products

Beverage cans



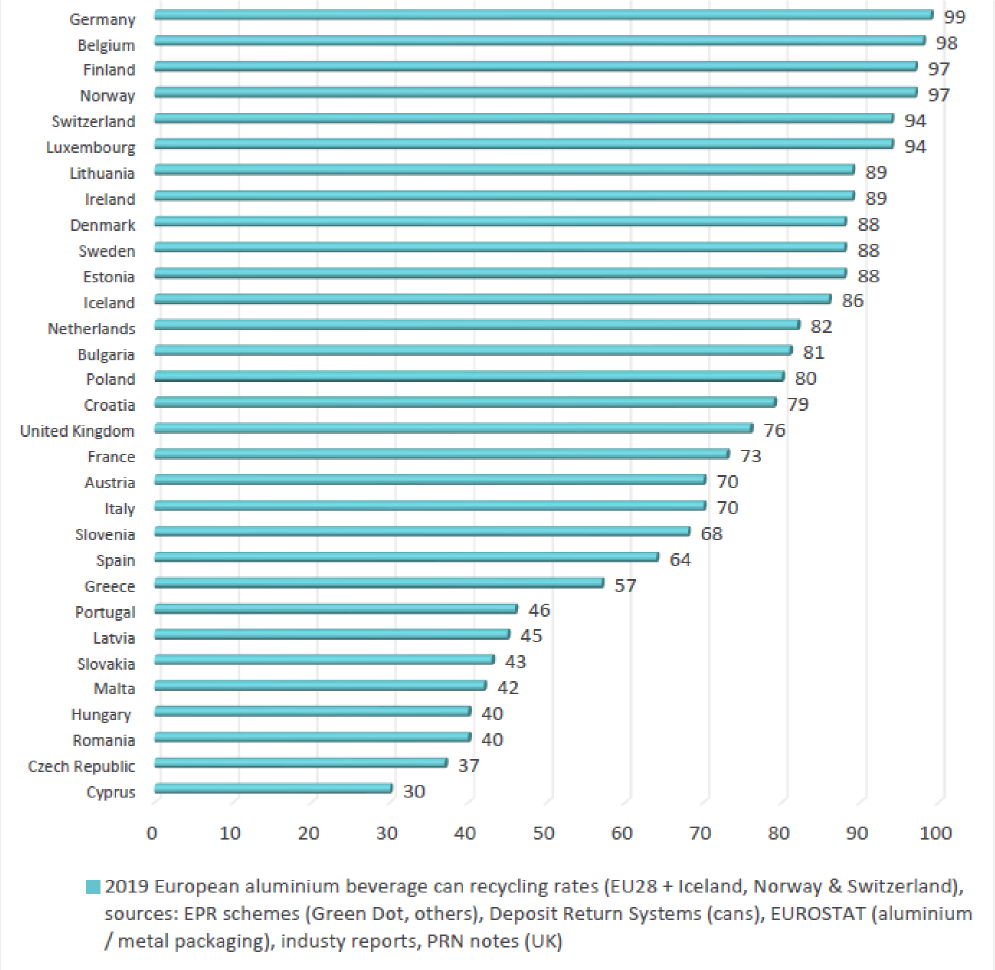
Source: REUTERS (https://www.reuters.com/article/uk-aluminium-recycling-ahome-idUSKBN2BI2EY)

Secondary Aluminium production

Recycling rates for aluminium-based products

Beverage cans

Recycling rates by country in 2019



Source: European Aluminium.

Aluminium salt slag

Formation:

In the rotary salt furnace process, an oil or gas fired furnace is charged with the scrap/dross and a salt flux (up to 50% of the feed) is added. The metal when comes in contact with air forms oxide of aluminium at the outer surface of the melt. The salt protects the metal from the reactive atmosphere and facilitates agglomeration and separation of the metal, thereby increasing metal recovery. It also enhances the heat transfer to the metal, it prevents the oxidation of the metal and takes up contaminants, such as oxides, nitrides, carbides and others contained in the scrap or produced by reactions during the melting process. After melting, aluminium metal and salt slag are tapped from the furnace. The nonmetallic components from raw mix are completely absorbed by the liquid flux and forms after tapping and cooling the so-called salt slag or salt cake.

Source: Tsakiridis *et al.*, **"**Aluminium salt slag characterization and utilization – A review", Journal of Hazardous Materials 217–218 (2012) 1– 10.

Aluminium salt slag

The non-metallic residues generated from scrap/dross smelting operations is often termed **“salt cake” or “salt slag”** and contains 5–7% residual metallic aluminium, 15–30% aluminium oxide, 30–55% sodium chloride, and 15–30% potassium chloride and, depending on the scrap type may contain, carbides, nitrides, sulphides and phosphides.

Aluminium salt slag

Depending on the raw mix the amount of salt slag produced per tonne of secondary aluminium ranges from 200 to 500 kg.

Toxic waste:

As salt slag has been classified as toxic and hazardous waste, it should be managed in compliance with the current legislation. Its **landfill disposal is forbidden** in most of the European countries, and it should be recycled and processed in a proper way by taking the environmental impact into consideration.