Global Aluminum Mining and Processing

Environmental and Social Impacts



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History of aluminum

- Compounds involving aluminum (Al) have been used by humans for thousands of years
- **But because of aluminum's affinity for oxygen[1], it was only isolated as an element in 1825**
- In 1886, the Hall-Héroult process was invented, allowing aluminum to be produced in commercial quantities[2]
- **Its general approach is still used today, although with improvements over time[3]**

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Elemental properties

- Unalloyed aluminum is soft and has limited strength. The addition of small quantities of alloying elements, such as copper, magnesium, manganese, nickel, silicon, and zinc, can increase the hardness, strength, and other properties of aluminum[4]
- Aluminum is also corrosion resistant, conductive, food safe
- **Aluminum is one of the most versatile metals**[5] and can be fabricated into desired forms and shapes by every major metalworking technique[4]
- In addition, aluminum weighs about one-third as much as steel or copper[6]
- However, aluminum does have a higher coefficient of thermal expansion compared to other metals, leading to repair and maintenance costs that are approximately twice as high compared to traditional steel in products, such as cars[7]

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Uses

- **Aluminum is used in virtually all segments of the economy**[4]
- The principal industrial applications for aluminum and its alloys are in[5,8]:
  - transportation, automotive industry (offering a higher fuel efficiency performance, due to its light weight), railroads (28%)
  - construction and building materials (32%)
  - consumer durables (refrigerators, air conditioners, cooking utensils),
  - electrical conductors (electric transmission lines)
  - chemical and food-processing equipment.
- Aluminum is also an important material for the energy transition due to its use in the battery package and as a cathode in Lithium Nickel Cobalt Aluminum Oxide (NCA) batteries

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Uses (cont.)

- In part because of its use in long-life applications like buildings, **approximately 75% of all aluminum produced is still in use today**[9]
- Aluminum alloys come in two types: wrought (5% alloying elements), and cast (6-27% alloying elements)[10]

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Ores and co-present materials

- With a share of 8%, **aluminum is the third most abundant element in the earth's crust**. This makes the availability of ore supplies for Al production almost unlimited[2]
- **Bauxite ore is the primary source of aluminum[5], comprising 99% of the ore used to produce aluminum**[11]
- Bauxite also happens to be the primary source of gallium (as a by-product of aluminum production)[12]
- Many minerals including feldspars contains aluminum, but extraction from these is expensive and requires high energy compared to bauxite[13]
- Bauxite ore contains high concentrations of aluminum hydroxide minerals, plus iron, silicon and titanium oxides as the main impurities[2]
- **The aluminum content in bauxite ranges from 16% to 27%**[12]

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Mining locations

- **90% of the world's known bauxite resources are located in the tropics**[7]
- **The world's largest bauxite reserves are located in Guinea (24%) and Australia (20%)**[7], and they are the largest bauxite mining countries[5]
- Other countries with significant bauxite reserves are Vietnam (12%), Brazil (9%) and Jamaica (7%)[12]

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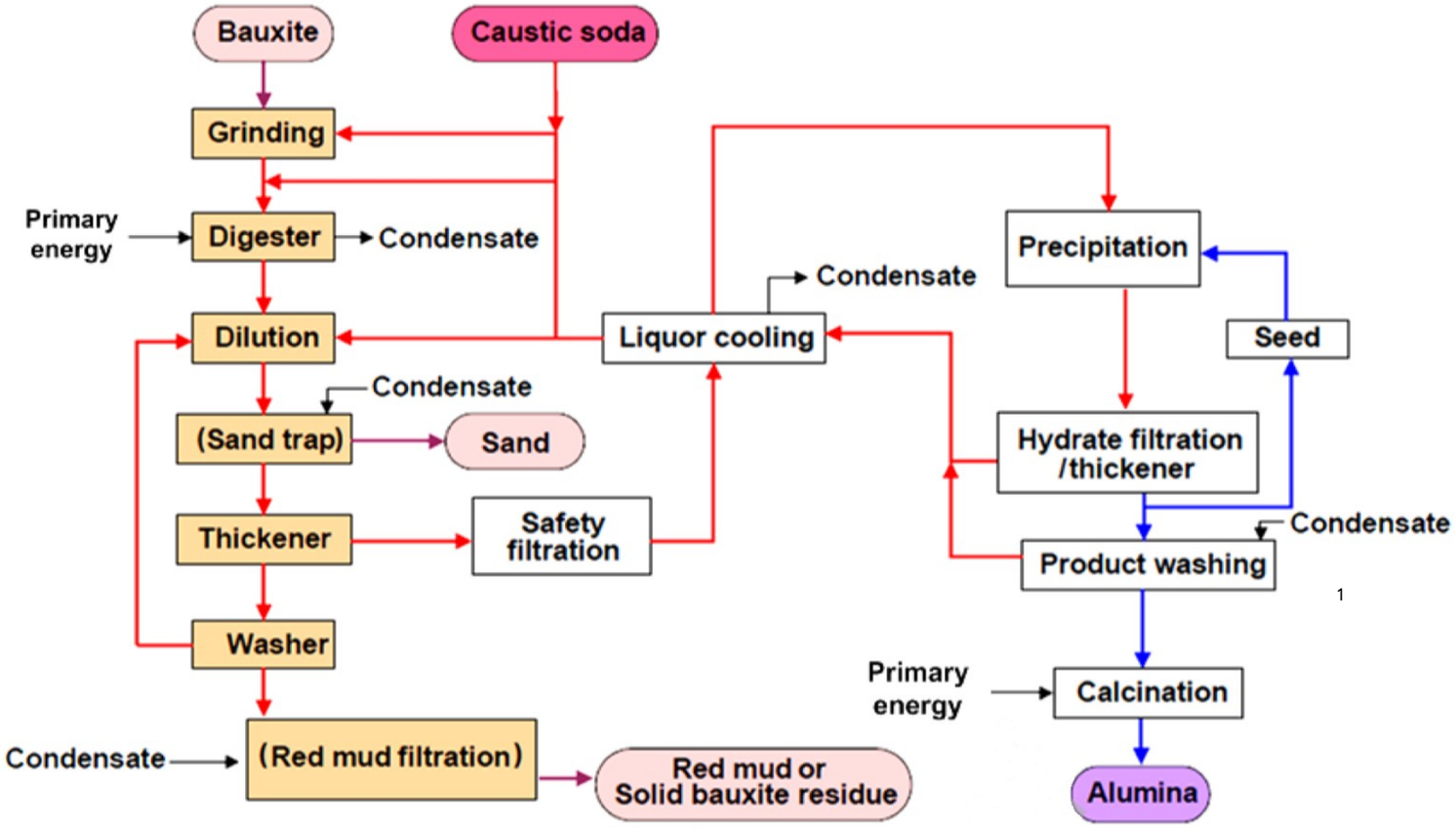
Mining process

- **Most bauxite is very near the surface and thus easily mined relative to other ores**[11]
- Bauxite is typically mined in open-pits (95%[12]) and is usually processed by a nearby refinery[14]
- **Unlike other base metal ores, bauxite is marketed without any significant processing at the mine site; it can even be directly shipped after mining**[12]

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Alumina production

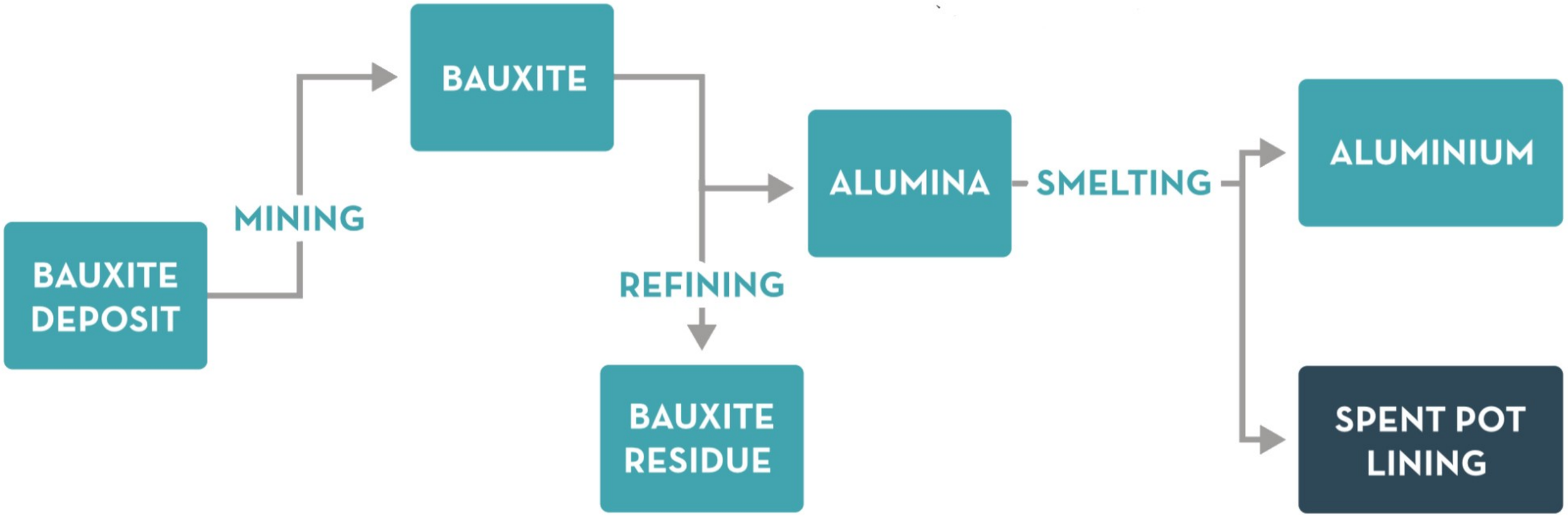
- **Bauxite is processed into pure aluminum oxide (Al_2O_3), so-called alumina, before it can be converted into primary aluminum by electrolysis[2]**
- The conversion of bauxite into alumina uses the Bayer process[8] 90-95% of the time[1]



1

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Wastes



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Red mud (bauxite residue)

- The Bayer process generates bauxite processing residue. Bauxite is digested in a hot NaOH solution that converts the alumina to dissolved aluminum hydroxide[16]
- The solid impurities that are filtered from the liquor are called red mud[16]
- Depending on the source of the bauxite, between 0.3 tons (for high grade bauxite) to 2.5 tons (for very low grade bauxite) of red mud are produced per ton of alumina[2]
- The red mud poses storage problems due to the large amounts of caustic solid waste[2]
- Globally, some 3 billion tons of red mud are now stored in massive waste ponds or dried mounds, making it **one of the most abundant industrial wastes on the planet**[17]

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What to do with red mud…

- Since 1964 researchers have patented some 700 uses for red mud, including tapping it to make decorative ceramics, dyes, and even fertilizer. Yet just 3% of red mud is currently recycled[17]
- "**The composition of [red mud] varies so much it means one [type of solution] will not work**," says Brajendra Mishra, a materials scientist at the Worcester Polytechnic Institute[17]
- No cost-effective integrated technologies exist so far for the complete recycling of bauxite reside on a large industrial scale[12]
- The iron industry has shied away from extracting the metal from it, for example, because the caustic waste destroys key components in their smelters[17]

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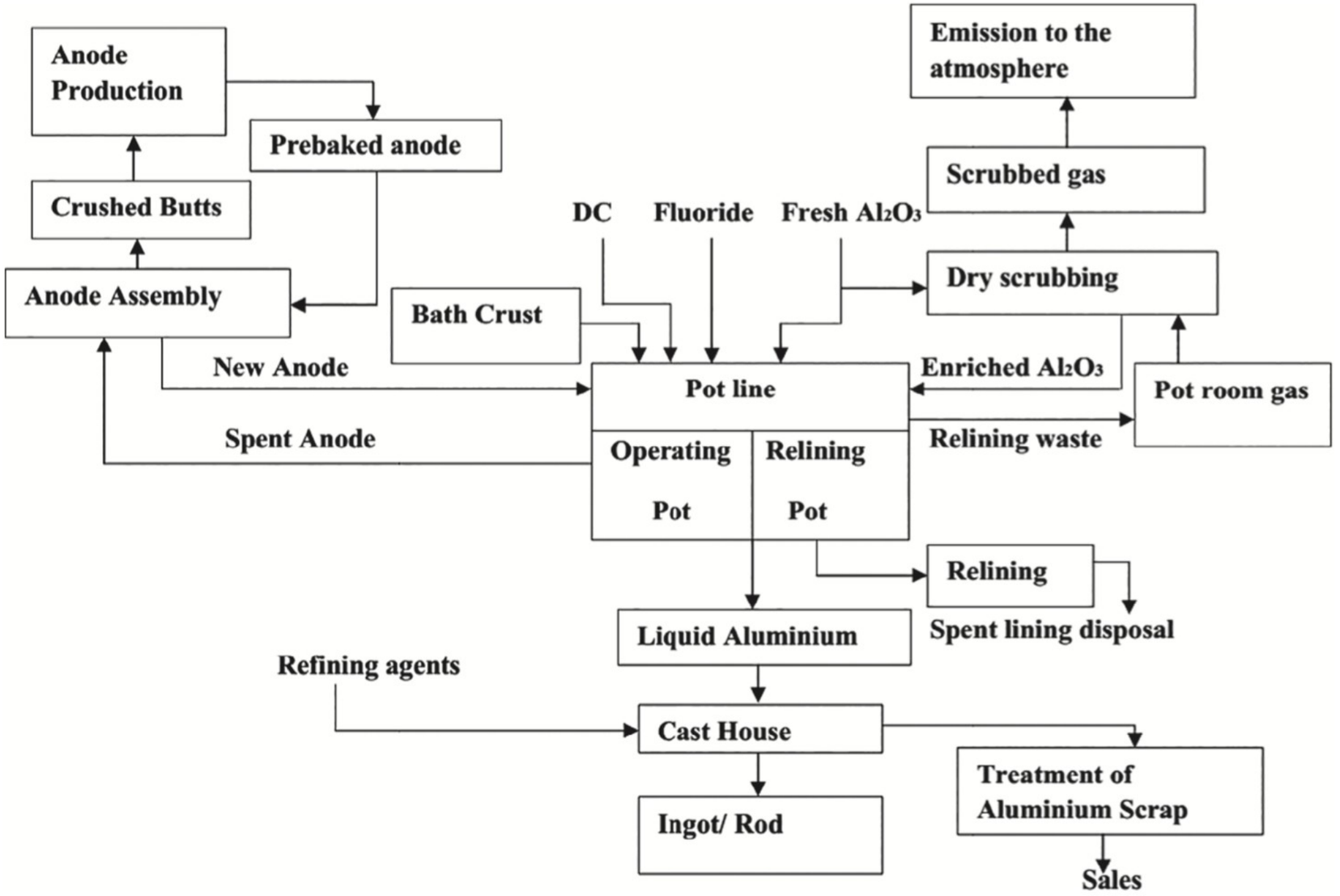
Red mud accidents and pollution examples

- **In 2010, an earthen dam at one waste pond in Hungary gave way, unleashing a 2-meter-high wall of red mud that buried the town of Ajka**, killing 10 people and giving 150 severe chemical burns[17]
- Even when red mud remains contained, its extreme alkalinity can leach out, poison groundwater, and contaminate nearby rivers and ecosystems[17]
- In Malaysia, images of rivers and coastal areas polluted with red sediment were a key factor in the government's decision to ban bauxite mining for environmental reasons in 2016 (which was ended in 2019)[19]



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Alumina production



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Alumina production (cont.)

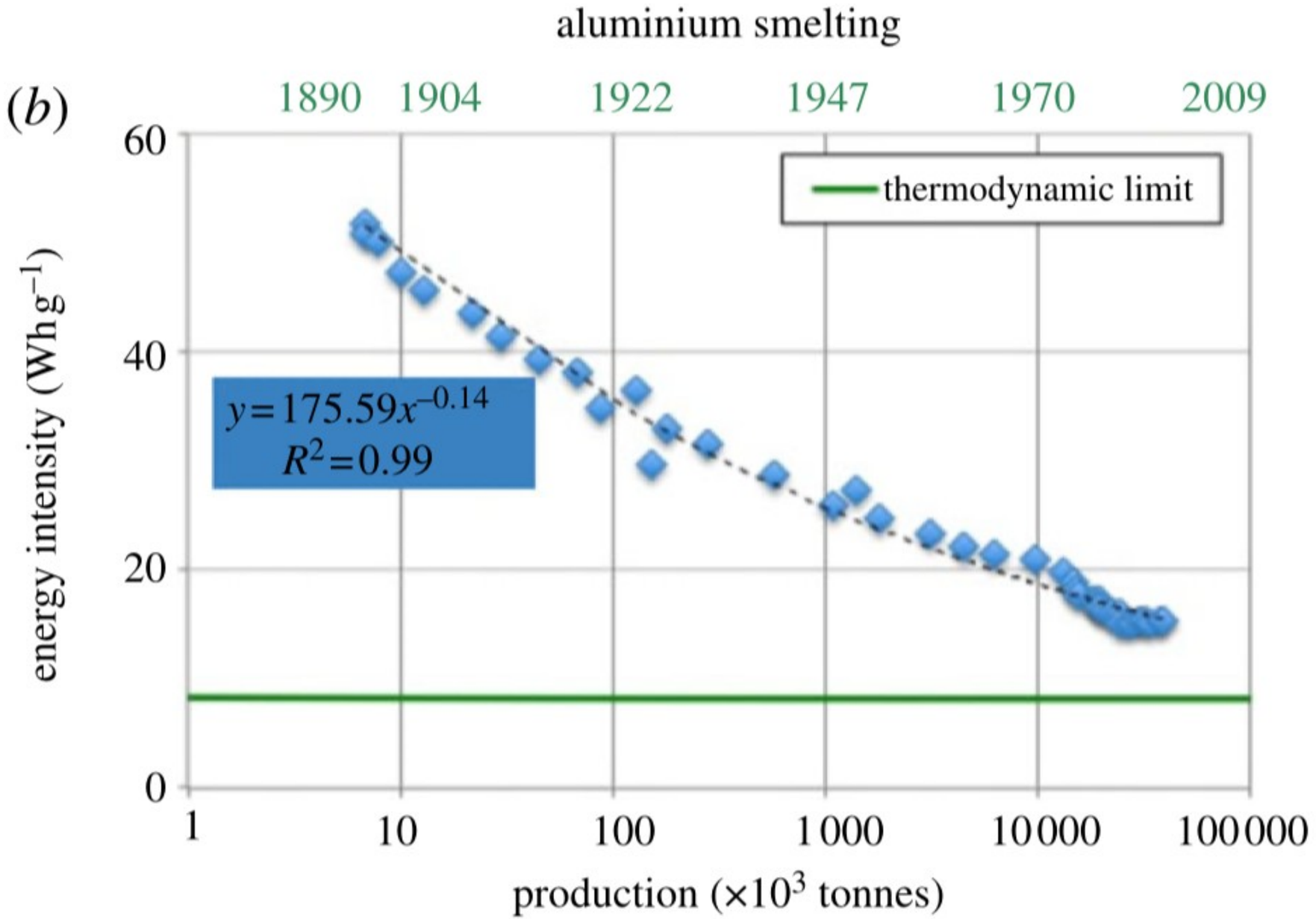
- 90-95% of refined aluminum oxide produced by the Bayer process is sent to primary aluminum smelters through the Hall-Héroult electrolysis process[1]
- China is by far the largest producer of aluminum[5]
- **Depending on the ore grade, it takes 4-6 tonnes of bauxite to refine approximately 2 tonnes of alumina, which in turn are smelted to make 1 tonne of primary aluminum metal**[12]
- In China the environmental effects of bauxite, aluminum oxide, and electrolytic aluminum are respectively 1.4%, 8%, and 90.6% of the environmental burden[21]
- Overall, **Al is one of the most carbon-intensive industrial metals to produce**[12]
- For example, theoretically, 31.1 GJ/ton aluminum is necessary to reduce aluminum from alumina, compared to the 6.8 GJ/ton iron theoretically required to reduce iron from iron oxide[2]

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A little about thermodynamics

- So what is it about removing the oxygen from aluminum that is so energy intensive?
- Thermodynamics can give us some insight
- If we look at the pure ores used to make metals (in the case of aluminum, Al3O2), we can determine the theoretical minimum amount of energy required to separate the molecules (the green line in the graph)[22]
- The blue dots represent the average energy intensity involved in aluminum smelting (the process to separate the aluminum atoms from the oxygen atoms) over time.

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A little about thermodynamics

- This graph shows us that we are nearing close to the theoretical minimum. Scientists estimate that perhaps 80% efficiency is the best we can hope for overall[22] given that these molecules are in reality are part of a physical system subject to energy dissipation, etc.
- **It also shows us is that there are unavoidable energy inputs needed to separate out pure metal atoms from their ore molecules, which, for older refining processes are getting fairly close to their theoretical minimum**
- Having said that, keep in mind this isn't the whole story. Accessing and mining the raw ore, getting the pure ore molecules separated out from contaminants (here, the Bayer process) create another set of energy needs. And, when choosing metals, use-phase energy impacts matter (e.g. aluminum being lighter than steel especially matters in transportation[23])

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Aluminum dross

- During the process of melting and alloying, molten aluminum meets the oxidizing atmosphere; therefore, a surface oxidation takes place, leading to the formation of a **semisolid skin over the molten metal, called aluminum dross**[24]
- Dross forms in both primary and secondary (recycling) aluminum processes[24]
- **Secondary aluminum dross is regarded as a hazardous waste in many countries**[18]
- More than a million tons of aluminum black dross (from recycling) are reported worldwide each year, and around 95% of this material is landfilled[24]

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Spent pot linings

- **Spent pot lining (SPL) is an unavoidable by-product of aluminum smelting**[15], and is the second largest solid waste stream generated from the primary aluminum production process after bauxite residue[25]
- Primary aluminium is produced in steel pots which are lined. Over a period of typically between 4–7 years, the pot lining wears down[15]
- SPL is classified as a hazardous waste or is subject to strict regulations in most jurisdictions due to its fluoride and cyanide content. It also has the potential for volatile reactions with water to produce explosive gases[25]
- Almost half (40-50%) of SPL generated is recycled and used in other industrial processes, such as: cement, steel, and mineral production[15]
- However, some of these secondary uses are only one-time, as cement, for example, has no effective recycling processes[22]

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Environmental impacts

Table 1. Environmental Hazard Potential related to bauxite's geological features and mining practices (1)

Indicator	Assessment of environmental hazard potential	Explanation	Data quality
Environmental hazard potential related to geological features			
Preconditions for acid mine drainage (AMD)	Low	According to the Goldschmidt geochemical classification, aluminium is a lithophile element readily combined with oxygen. Bauxite is an oxidic ore consisting mostly of the aluminium minerals gibbsite ($Al(OH)_3$), boehmite (γ-AlO(OH)) and diaspore (α-AlO(OH)), mixed with iron oxides. Therefore, geochemical preconditions for Acid Mine Drainage (AMD) do not exist in bauxite mining	High
Paragenesis with heavy metals	Medium	The main constituents of bauxite are Al hydroxides and Fe oxides (not heavy metals). However, bauxite deposits may contain slightly elevated concentrations of heavy metals.	Medium
Paragenesis with radioactive substances	Medium	Average data on Chinese bauxite deposits (about 21 % of world production in 2018) suggest that in many cases aluminium is associated with slightly elevated concentrations of uranium and/or thorium	Medium
Environmental hazard potential related to mining practices			
Mine type	High	Bauxite is a bulk commodity extracted mainly from weathered, near-surface horizons in tropical regions; therefore, mining frequently requires access to large land zones.	High
Use of auxiliary substances	Low (2)	No toxic auxiliary substances are used for bauxite mineral processing.	High

(1) Annex 2 presents the evaluation method for the Environmental Hazard Potential
(2) UBA's study assesses the use of auxiliary substances as 'Medium' as the use of caustic soda for the further processing of bauxite into alumina (Bayer process) is taken into account

Source: Adapted from (Dehoust et al., 2020).

Land use

- Bauxite extraction is considered to have a large mining footprint as bauxite mines are mostly opencast, and bauxite deposits often cover a large area[12]
- **Since major deposits are commonly found in tropical and sub-tropical areas, they often overlap or are adjacent to areas of high conservation value**[12]
- A recent World Bank's study on the impacts of large-scale mining on forests suggests that bauxite mines represent 5% of the world's large-scale mines in a forested area[12]
- In addition, **aluminum smelting consumes large amounts of electricity and helps drive dam-building worldwide**[26]

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Water

- Additional environmental challenges can derive from bauxite mines' location in water-scarce areas or nature protected areas[12]
- **84% of the capacity of operating bauxite mines in the EU sourcing countries is located in places with water stress ranging from high to extremely high**[12]

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Forced and child labor

- Last year, **reporting on the links between aluminum smelters and forced labor in China's Northwest region of Xinjiang led to the United States targeting aluminum in a ban on imports linked to forced labor**[27]
- Guinea and Sierra Leone have the lowest values for the Human Development Index and Fragile State Index, which measures socio-economic vulnerability and risk and state capacity to respond to pressures. According to ILO estimates, child labour is also spread in these countries, with 25% (Guinea) and 37% (Sierra Leone) of children between 5 and 14 years old in employment[12]

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Conflicts

- Considering conflicts classified by the EJ Atlas as high or medium intensity and started in between 2010-2020, in order to focus on the most recent, eight cases were reported related to bauxite/aluminum projects[12]
- In addition, one severe accident was reported by another source with a deemed 'high to medium' intensity[12]
- These conflicts took place in Guinea, Brazil, Venezuela, Mozambique, Tajikistan, India, China (2), and Malawi[12]
- **Land use for bauxite exploration and new mine development was the most frequent cause of conflicts**[12]

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Recycling rates and sources

- The 2018 global Recycling Input Rate (RIR) of aluminum was 32%. The RIR is an indicator of the proportion of recycled from new (pre-consumer) and old (post-consumer) scrap contained in the metal produced in a given region[28]
- **The post-consumer recycling rates for aluminum are generally rather high, but they differ substantially by product, alloy and region**, ranging from as low as 20% to as high as 80% for some packaging products[23]
- For example, about half of all used aluminum beverage cans in the US were recycled in 2020, whereas in Germany the rate was 99%[29]
- The transportation sector was the most important source of aluminum from end-of-life products, **as scrap aluminum from buildings only became available in the 2000s**[23]
- Approximately 75% of all aluminum produced is still in use today[9]

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Recycling benefits

- Compared to other high-volume materials, such as copper (Cu), zinc (Zn), magnesium (Mg), and steel, **Al production has one of the widest energy differences between the primary and secondary (recycling) production**[30]
- It is estimated that only about 5 to 8 percent of the energy required to produce primary aluminum ingot is needed to produce recycled aluminum ingot[4]
- In addition, to achieve a given output of ingot, recycled aluminum requires only about 10 percent of the capital equipment compared with primary aluminum[4]
- **Overall, primary aluminum production has higher impacts than secondary aluminum production for all impact categories**[12]
- **Recycling 1 kg of aluminum can save about 8 kg of bauxite, 4 kg of chemical products and 14 kW h of electricity**[2]

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Recycling challenges

- **The reactive chemical nature of aluminum makes it almost impossible to remove alloying elements from remelted aluminum scrap**[10]
- While some processes have been invented to do this, the mechanical or thermal treatment required is currently uneconomical[23]
- Unfortunately, **aluminum alloys have small tolerances for "tramp elements," which quickly lead to undesired properties like brittleness and corrosion**[23]
- An accumulation of alloying elements is inevitable with successive rounds of recycling, which means that much recycled aluminum does not meet the strict component specifications required for wrought alloys[10]

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Recycling challenges (cont.)

- Cast alloy production receives most of its scrap from end-of-life products because it can tolerate a high concentration of foreign elements[31]
- This down-cycling works well as long as the demand for cast alloy is sufficiently greater than the quantity of scrap generated[31]
- However; recycled cast alloys serve a limited number of applications, and are mostly only used in vehicles engines. **Scientists have indicated that the continuous down-cycling (accumulation of alloying elements), along with the introduction of electrical vehicles, will result in a significant unrecyclable scrap surplus in the coming decades**[32]

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Summary

- Because of aluminum's affinity for oxygen, it was only isolated as an element in 1825
- Aluminum is a highly versatile material used in virtually all segments of the economy
- Bauxite ore is the primary source of aluminum and is very near the surface and thus easily mined relative to other ores
- But red mud, a caustic output from initial processing of bauxite into alumna, is one of the most abundant industrial wastes on the planet
- Aluminum dross and spent pot linings are other wastes produced by the alumnium production process
- In addition, aluminum is one of the most carbon-intensive industrial metals to produce
- While aluminum has high recycling rates, over time the recycling tends to be downcycling, because of trace elements that cannot be cost/energy-effectively removed
- Having said that, recycling aluminum represents one of the highest energy savings for any metal (some estimates are as low as 5% of the initial energy requirements)

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Thank you

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