

A circular economy for metals is vital to achieving sustainability.

Sustainable Metal Production and Use in the Twenty-First Century: Challenges and a Path Forward

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In the context of materials and earth resources, sustainable development means meeting the needs of the present without compromising the needs of future generations. It is a fact that we entered the twentieth century with 1.6 billion people on our planet and exited that century and entered the twenty-first century with 6.1 billion people—a dramatic increase. And in 2024, our world population is a bit over 8.1 billion people. With such increases in human population comes increased usage of products that are made from mate-

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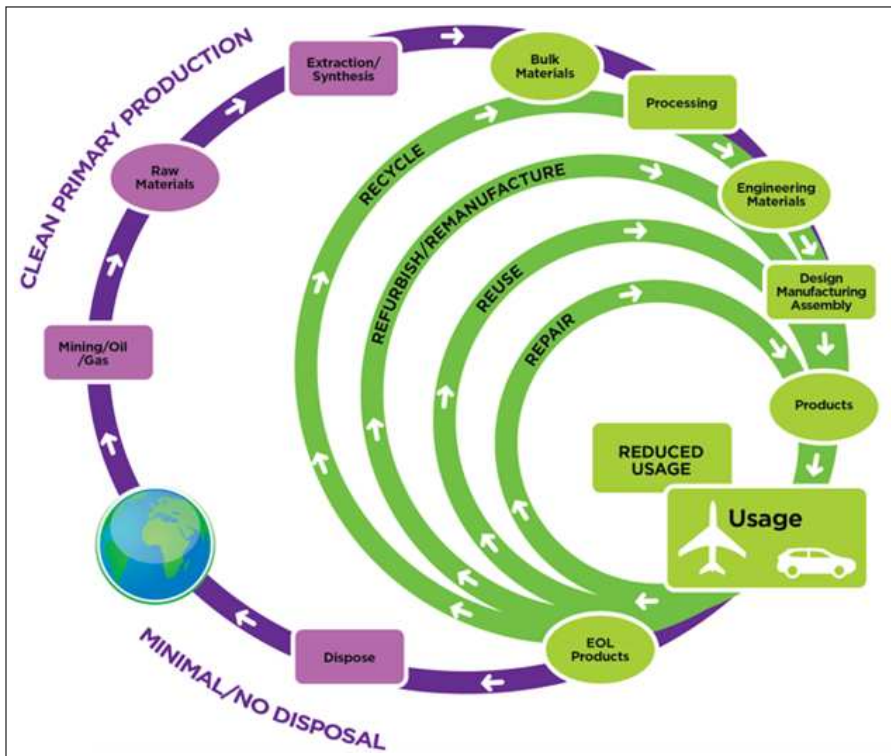


FIGURE 1 The circular economy as a new paradigm to sustain material usage in the twenty-first century (modified, based on BCAST [2023]).

rials.¹ The elements of the periodic table, with the exception of gases and inert metals, are found in the earth as ores (compounds like oxides, sulfides, etc.) that are mined and subsequently processed through various extractive operations, such as pyrometallurgy, electrometallurgy, or hydrometallurgy. However, there is substantial production waste and energy consumption, as well as a large carbon footprint associated with these extractive operations. A significant amount of energy needs to be utilized to break up the oxide bonds and produce elemental metal. Almost 50% of the global CO₂ emissions from industry are due to the production of three materials alone: steel, cement, and aluminum (Doerr 2021).

Inefficiencies exist not only at the production level but also at end of life, further countering the vision of a circular economy. A large portion of the manufactured goods in the twenty-first century are not repaired, recovered and reused, or fully recycled. Interestingly, in the 1920s, when the earth's population was less than two billion people, and there was an abundance of minerals and rich ores in the earth, manufactured goods were repaired, and

there was significant effort in the recovery and reuse of materials. It was an era when neighborhood cobblers existed and were thriving, and landfills were not urban mines. It was also an era when only a few of the elements of the periodic table were used. In the last five decades we have witnessed increasing complexity of our manufactured goods in that many of the elements of the periodic table are being utilized. As one example, in the 1980s the computer chip contained eleven elements of the periodic table, in the 1990s it contained fifteen elements, and today the modern computer chip contains over fifty elements of the periodic table (Greenfield and Graedel 2013). Such complexities in our manufactured goods are also the source of the challenges we face in recovery and reuse and recycling.

To ensure that our earth's resources are also available to future generations, one of the grandest challenges of the twenty-first century is the sustainable management of those resources. A serious effort to implement the core principles of the circular economy is needed to sustain the earth's resources, reduce energy usage for the production of metals and materials, reduce our carbon footprint, and reduce waste, as well as to create value from end-of-life (EOL) consumer waste. Figure 1 illustrates the components of the circular economy, a new paradigm that has emerged over the past decade. This approach focuses on avoiding the loss of resources at EOL through repair, reuse, refurbishing and remanufacturing, and recycling (highlighted in green). To make this paradigm a reality and execute it globally will require massive efforts in three sectors: (i) education; (ii) policy; and (iii) engineering solutions and technological innovations (Apelian 2012). *Education* is needed to ensure that an informed global citizenry emerges. Issues related to earth's resources do not have any national or territorial boundaries, but rather they are global issues affecting all nations and the planet as a whole. *Governmental policies* and laws are pivotal in establishing a collective and shared

¹ The human population figures in this paragraph are from www.worldometers.info/world-population/.

responsibility to ensure the sustainable use of resources in the twenty-first century. Designing manufactured goods for recovery and reuse will only be a reality if there is a level playing field. That requires massive political will and the voice of the consumer, which can be heightened through education. *Engineering solutions and innovations* are key to reuse and recovery and to metal/material sustainability, but by themselves they are not sufficient. All three sectors—education, policy, and engineering solutions—are needed to execute the new paradigm, as visually described in figure 1.

In this article, we set the context for how a circular economy for metals might be implemented by focusing on one metal, aluminum. We could have just as easily selected metals that are utilized in applications such as magnets, lithium-ion batteries, smart phones, etc. However, a metal like aluminum is ideal for discussing life cycle issues and how to execute the new paradigm that is needed to attain sustainability.

The Case for Aluminum: An Exemplar

Aluminum is the third most abundant element (8%) after oxygen and silicon and more abundant than iron (5%) in the earth’s crust, yet it is a comparatively new industrial metal that has been produced in commercial quantities for just over 100 years (see figure 2). Measured either in quantity or value, aluminum’s use exceeds that

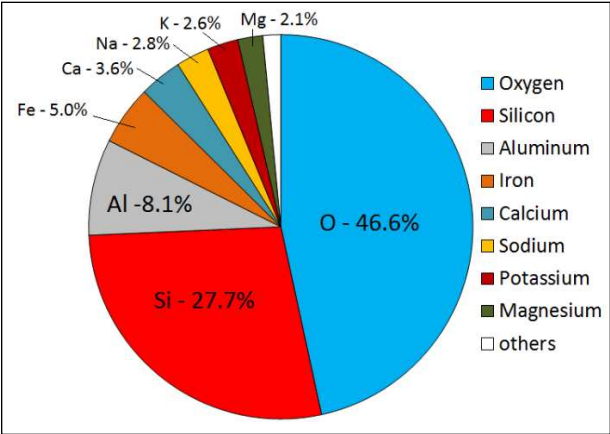


FIGURE 2 Major elements in earth’s crust. Source: Earle 2019.

of any other metal except iron, and it is important in virtually all segments of the world’s economy. Annual global aluminum production in 2023 was 70 million metric tons and is expected to grow by 80% by 2050 (IAI 2021; Merrill 2024). About 75% of current aluminum production is fueled by coal and natural gas, as shown in figure 3. This highly recyclable metal plays a critical role in enhancing the sustainability of a variety of industries through lightweighting and electrification. In the United States, transportation and packaging represented the two largest sectors for aluminum use, accounting for 35% and

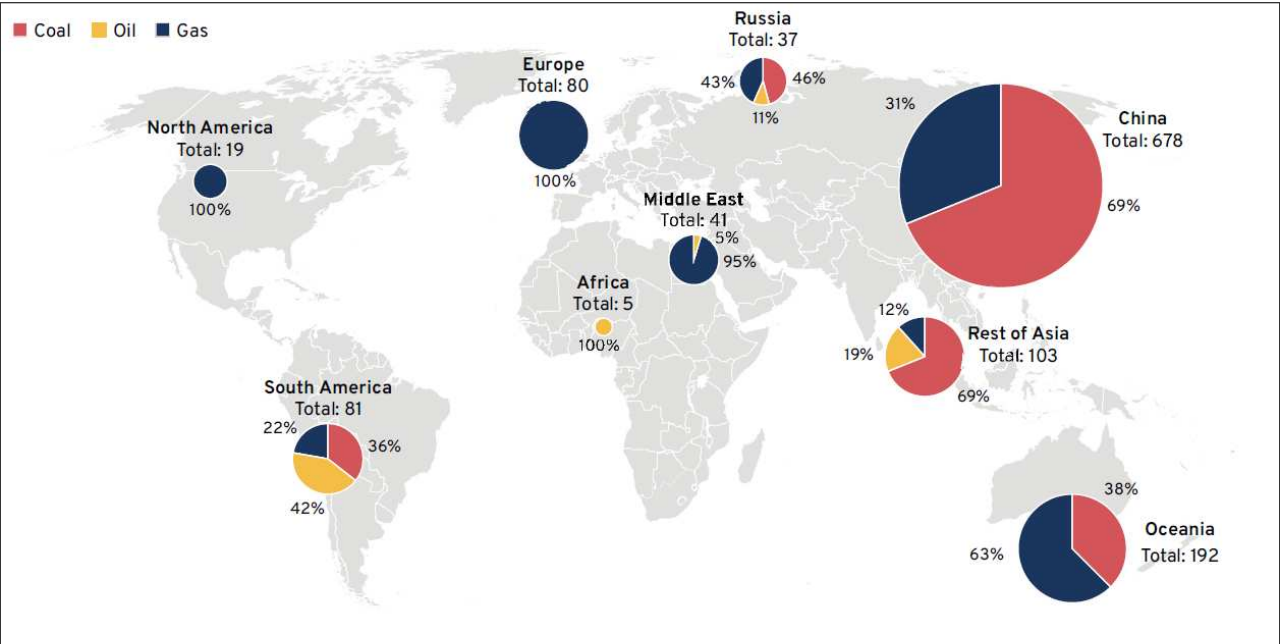


FIGURE 3 Map of 2020 energy consumption for alumina refining by region, total (in petajoules) and percentage. Source: Mission Possible Partnership and IAI 2022.

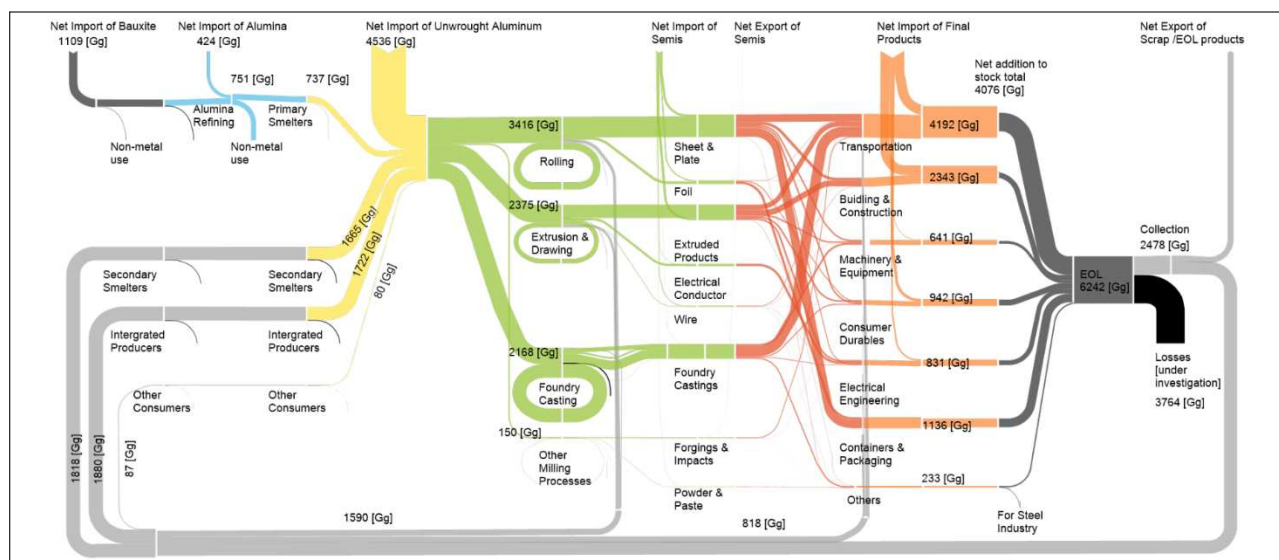


FIGURE 4 Sankey diagram showing the US aluminum cycle in 2017 from production to end-of-life management. Source: Althaf and Reck 2024. Note: About two-thirds of the “losses under investigation” were recycled.

23% of all domestic consumption, respectively (Merrill 2024).

Aluminum Production and Recycling

Primary, or virgin, aluminum currently meets roughly 70% of global demand and is produced from bauxite ore through a series of energy-intensive processes (IAI 2021). Aluminum accounts for approximately 3% of human-generated emissions, with 90% of those emissions associated with primary production (IAI 2021; USGS 2022). Additionally, the aluminum industry produces 3-4 tons of bauxite residue (red mud) per ton of aluminum, which is a serious environmental challenge. Although actively pursued, the current utilization of bauxite residues is less than 4%. Globally, some 3 billion tons of bauxite residue are now stored in massive waste ponds or dried mounds, making it one of the most abundant industrial wastes on the planet. Additionally, alumina refining plants generate over 150 million tons of red mud each year.

Secondary, or recycled, aluminum is produced from two main sources of scrap: “new” scrap, which is generated during manufacturing, and “old” or “post-consumer” scrap, which originates from manufactured goods that have reached the end of their useful life. Recycling is critical to meeting demand at a fraction of the footprint, generating roughly 80% less emissions compared to the primary production of aluminum. Current production from recycling avoids the generation of roughly 300 million tons of CO₂e, which is equivalent to taking half of all US cars off the road

for a year. The US recovered 3.34 million tons of aluminum from scrap in 2022, with old scrap recycling meeting approximately 30% of consumption (IAI 2021).

Aluminum Material Flows

Material flow analysis is a powerful tool to illustrate how and at what efficiencies materials move through the economy, from production to end-of-life (EOL) management. Figure 4 shows a Sankey diagram for the US aluminum cycle in 2017 (Althaf and Reck 2022) that used the same methodologies, data sources (Aluminum Association, U.S. Geological Survey), and data frameworks as an earlier study by Chen and Graedel (2012) that characterized US aluminum stocks and flows for the period 1900-2009. The EOL collection rate for aluminum is similar to the 60% rate for steel (Reck et al. 2024), and the average recycled content in aluminum production was 40%. The use of “new scrap” from foundry alloys (castings) is significantly higher than that of wrought products (sheet and extruded).

The recycling industry plays an essential role in stabilizing supply chains, minimizing loss to landfills, and sustainably meeting demand for metals, such as aluminum. In the US post-consumer scrap has the potential to address upwards of ~45% of apparent consumption, but current misalignment between the quality of scrap material and manufacturing requirements results in the export of 2 million tons of this valuable resource (USGS 2022). There are opportunities to address this

gap and “leak” points, where material falls out of circulation and is not properly recovered. Along the global recycling value chain, approximately 7 million tons of aluminum is lost each year. If these leaks are not plugged, and business as usual (BAU) continues, a projected 17 million tons will be lost annually by 2050 (IAI 2022). According to the International Aluminum Institute, “a fully circular system without any (collection, process and melt) losses and no generation of new and internal scrap would deliver a 20% reduction on BAU sector emissions.”

There is no one-size-fits-all solution to achieving a fully circular system, as each industry sector has its distinct set of challenges, exemplified by the challenges and opportunities facing used beverage cans (UBC) and automotive recycling. However, the one constant in all potential solutions is the need for circularity of the material chain and creating value from waste.

UBC Recycling

As reported by the Aluminum Association, about 3 billion pounds (1.5 million tons) of cans was shipped, while only 1.3 billion pounds (650,000 tons) of cans was recycled by US consumers in 2020 (Wang 2022). That calculates the unrecycled cans at 850,000 tons, with around \$840 million worth of aluminum ending up in landfills. Landfill mining involves excavating landfills, and the buried resources are processed for environmental, economic, or social benefits. The vast quantities of metal buried in landfills can be suitable for use as potential secondary resources. Nonferrous metals, especially aluminum, have the maximum potential to be used as a secondary raw material after recovering from landfills and to contribute to adding value to waste materials.

That volume of aluminum cans lost to landfills could have otherwise been responsibly recycled, made into new cans, and added to the revenue stream. It will be worth more than \$1 billion with the present scrap-per-ton value of UBC (about \$1300/mt). The recycling rate of the aluminum can in the US stands at roughly 45%. This falls significantly short of European rates, which can be



FIGURE 5 The four pillars of action needed to hit target recycling rates. Source: Ally and Breen 2023.

as high as 73%, or that of US transportation and construction aluminum, which is over 90% (Ally and Breen 2023). Causes of this recovery rate disparity span from collection to processing to remelting, calling for sweeping solutions across the recycling chain. If a 70% recycling rate had been achieved in 2020, 25.6 billion more cans would have been recycled. This would have generated \$400 million in additional revenue for recyclers, a critical figure when considering that UBC recovery is the foundation for the profitability of most recycling facilities of municipal solid waste. A 70% recycling rate would have conserved enough energy to power more than 1 million US homes for a year (Recycling Today 2022). With these economic and environmental benefits in mind, the Can Manufacturers Institute has set a target of a 70% recycling rate for UBCs by 2030 and 90% by 2050 (Ally and Breen 2023). To achieve this goal, four pillars of action have been defined (see figure 5).

Valuable aluminum UBCs, whether from a container deposit collection or single stream material recovery facility, are comingled with materials such as paper, plastic, and steel that, when not sorted effectively, can result in the contamination of aluminum products or the loss of UBCs within other material streams. In 2022, more than 25% of UBCs were missorted at recovery facilities (Recycling Today 2022). Advanced separation capabilities such as eddy currents and optical and robotic sorting systems can minimize leakage or the loss of UBCs. The Can

Manufacturers Institute estimates that proper sortation has the potential to increase the recycling rate by 3%, which is equivalent to 3.5 billion additional cans, resulting in the avoidance of approximately 650,000 tons of CO₂e and an increase in recovery rates at material recovery facilities by more than 50% (Ally and Breen 2023).

Automotive Recycling

When one's vehicle, or even an old washer and dryer, reaches the end of its life and has been fully picked for usable parts, it will be sent to a processing facility. There it is run through a massive hammermill shredder, where in a matter of moments it is converted to a pile of fist-sized pieces of mixed material known as automotive shred, or auto-shred. A series of separation methods, including magnets, eddy currents, and density separators, remove the ferrous (steel), nonmetallic (foam and plastic), and heavy nonferrous (copper and zinc alloys, predominantly) content. What remains is the aluminum fraction of auto-shred, referred to in the industry as "twitch," which contains a variety of cast and wrought alloys of aluminum.

Unlike UBCs, automotive aluminum in the United States has a very high collection and recycling rate, in excess of 90% (Kelly 2018). However, this does not indicate a circular process; post-consumer material from a car door, or other quality stringent components, does not get converted back into a car door. Historically, twitch has been used to produce 380 and 319 aluminum cast alloys, which are lower-value cast alloys, for power train components. These alloys have a higher tolerance for compositional uncertainty and contamination associated with a mixed scrap feedstock. In this case, higher-value alloys, such as 6000 and 5000 series aluminum alloys, are downgraded, or downcycled, into lower-value materials; current practices result in the downcycling of 60-80% of the high-value wrought and cast alloys (Kelly 2018). The shift to electric vehicles has led to a weakening demand for power train components, such as the internal combustion engine, and a rising need for quality extruded, sheet, and structural cast aluminum. Downcycling perpetuates a dependence on primary aluminum that is unsustainable and uneconomical, both for the scrap processors that sell the scrap material and for the melt facilities that consume it. The combined value of twitch's constituents can be 25-120% higher than that of twitch and approximately 10% to as much as 30% lower than that of primary aluminum, meaning increased profits for both stakeholders.

To create economic benefit and reduce primary alu-

minum consumption, advanced technologies for the handling of automotive scrap must be implemented. Rapidly growing in adoption are advanced sortation systems that leverage compositional sensors and artificial intelligence to distinguish between and sort out alloy types. The most predominant sortation method for aluminum alloys utilizes laser-induced breakdown spectroscopy (LIBS), which has the ability to measure levels of light elements, such as silicon and magnesium, in addition to heavier elements, such as copper and iron, to create clean scrap packages down to the individual alloy. The granularity of the sort must be balanced with the throughput of the overall system. Once sorted, these scrap products are blended to deliver the desired composition and material properties. Today this is a large manual process requiring the physical sampling of both solid-state input material and the melt to create and modify melt recipes. Across the recycling value chain there are a number of opportunities to leverage availability data and Industry 4.0 capabilities, which includes advanced sensing, automation and artificial intelligence, to reduce manual processing and enhance material recovery.

New aluminum alloys are being developed to tolerate more impurities, such as iron in aluminum scrap, and to provide equivalent mechanical and corrosion properties of primary aluminum alloys for structural application. Figure 6 shows the effects of microalloying with manganese and the cooling rate on the formation of iron-containing intermetallic phases in secondary aluminum-silicon-based alloys based on computational thermodynamics and experimental validation (Cinkilic et al. 2019). Based on this study, a new recycled alloy with high iron content (about 0.5wt.%) showed comparable mechanical properties to a typical primary die cast alloy (≤ 0.2 wt.%) with similar composition (Cinkilic et al. 2022).

Going forward, next-generation integrated computational materials engineering (Luo et al. 2022) and Industry 4.0 capabilities have the potential to make automotive aluminum truly circular, where the alloys of cars manufactured ten to twenty years ago are not just recovered but converted into alloys used in manufacturing today. This requires alloys and processes that maximize material quality and value across every step in the production and recycling chain.

Environmental and Policy Considerations

In addition to technology innovations, material sustainability, specifically in the case of aluminum, requires both environmental and policy considerations in primary

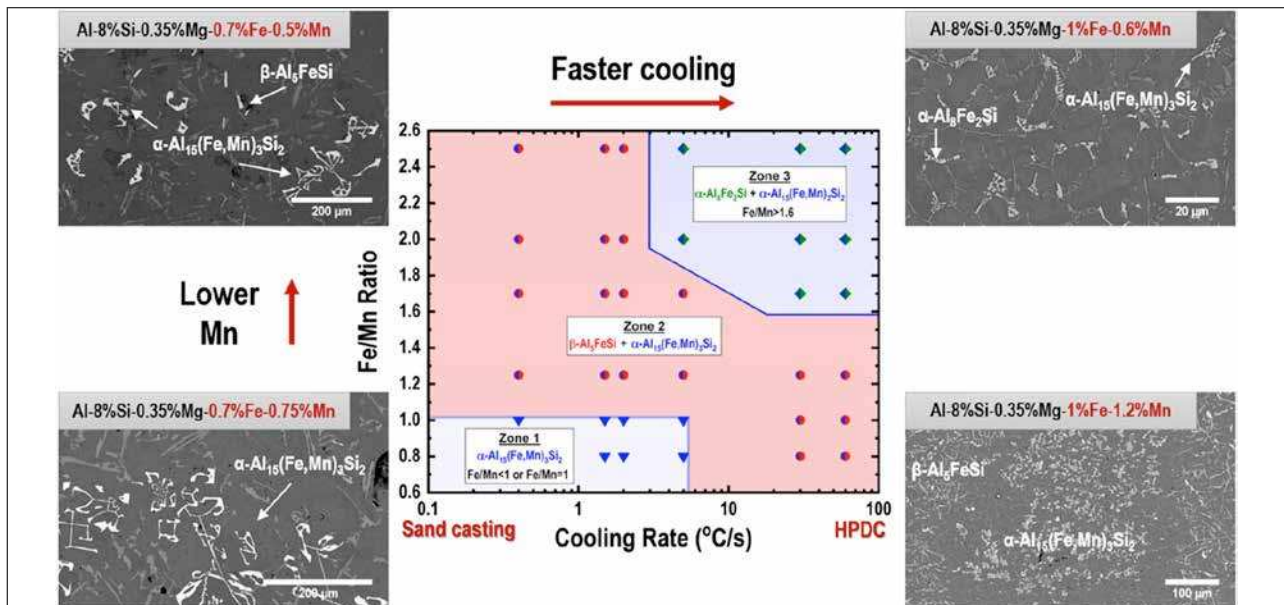


FIGURE 6 A formation map of iron-containing intermetallic phases: effects of cooling rate and iron/manganese ratio on intermetallic phase formation in aluminum-silicon-magnesium alloys with high iron contents. Source: Cinkilic et al. 2019.

production, recycling, and supply chain closure. Those environmental and policy considerations include:

- Incentivizing the use of clean electricity (hydro and other renewable energy vs. coal and natural gas) in primary aluminum production around the world via carbon calculations and economic/legislative policies.
- Rewarding beverage can recycling via nationwide legislative measures, such as return deposits.
- Promoting sustainable practices, such as bauxite residue reuse and aluminum recycling, and minimizing landfilling by offering carbon credits and tax benefits.
- Encouraging and incentivizing landfill mining projects to optimize resource utilization and further sustainability goals.
- Incentivizing manufacturers to design for recovery and reuse at EOL and have manufactured goods made in such a way that they can be disassembled for recycling.
- Adopting a circular economy model for major manufactured components, such as automobiles, wherein at EOL the manufacturer is responsible for the disassembly and reuse of the materials that were utilized in the product.
- Enhancing the role of education from kindergarten to corporate America to develop a culture of material circularity, as depicted in figure 1.

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