Challenges for the Corrosion Science, Engineering, and Technology Community as a Consequence of Growing Demand and Consumption of Materials: A Sustainability Issue

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This perspective is intended to bring awareness to the corrosion community that the growing demand for engineering metallic materials required for our increasingly technological society is unsustainable. Current strategies important for materials science and especially the corrosion community are presented. First, the consumption of metals is reviewed, and the global supplies and demands of metals are discussed given different scenarios, including models of global societal development. It is pointed out that expected future consumption rates place pressure on the availability of specific elements used regularly throughout the world, with nearly every element in the periodic table now utilized in production of new technological devices. The consumption pushes the mining and production of metals to levels that should be counterbalanced with novel engineering and technological methods that incorporate strategies for metal sustainability. Standard approaches such as "make-use-dispose" must gradually be transformed into a circular economy paradigm embracing the "reduce-reuse-recycle" approach. Although recycling can bolster the engineered material supply, the growing demands require additional actions to significantly preserve natural resources and prolong metal sustainability. Our views on the abilities of the corrosion community to contribute to the concept of a circular sustainable economy are introduced. Maintenance strategies and corrosion management control may not be sufficient and need to be complemented with existing or emerging new technologies such as additive manufacturing, inverse engineering design, and solvometallurgy in combination with integrative design, modeling, and machine learning approaches. The corrosion community can impact the end-of-life of components and infrastructure at different levels, starting from mining through design, production, use, reuse, and recycling. Each process step is discussed, seeking possible solutions to preserve the metal resources by, for example, achieving more efficient and high-yield mining, designing and modeling new materials, increasing production efficiency, introducing light-weighting and smart materials, as well as developing more efficient recovery, recycling, and separation.

KEY WORDS: circular economy, metal recycling, solvometallurgy, sustainability

INTRODUCTION

Today, probably more than ever, we face a growing need for robust metal preservation (i.e., to make materials more durable so that their physical life matches their functional or practical lives). This is critical to establish both greater sustainability and to enable a circular materials economy. The growing CO_2 issue is one of the consequences and an integral part of the problem with materials that perish by corrosion and must be replaced. These concerns go hand in hand with material stewardship. Both durability and reuse are important. Recycling may increase the supply of a material and forestall energy-consuming, CO_2-producing primary material production needed for replacement of corroded materials. Recycling itself can be made more energy efficient, more environmentally friendly, and more selective through advancement of electrochemical separation and collection processes. These include approaches such as selective leaching, well known in the corrosion field as "dealloying." This, in turn, can result in the consumption of fewer mined resources and enhance the engineered material supply available beyond the current mining (mine), production (make), use, and dispose cycle. However, civilization will not be able to "recycle its way out" of our growing demand and consumption of materials. There are many other critical strategies and innovations that must be undertaken as well to turn the tide on the current mine-make-use-dispose cycle. The development and use of low-cost, light-weight materials with enhanced durability and of strategies for enhanced repair/reuse of existing material systems are just two examples of the broad approach that must be taken.

Several important multichapter reports[1] and manuscripts[2,3] already cover the benefits of better corrosion

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management. Some of these works point out circumstances where institutionalization of good corrosion practices might be possible (e.g., infrastructure).[1] These reports often are organized by traditional business sectors such as oil and gas, water management, and concrete, as well as new sectors such as preservation of solar panels and wind turbines.[1] The main goal of these publications is to report sector by sector what can be done to "hold the line" on preservation, possibly in the face of even more severe and harsh environments encountered in the future. There is also a focus of publications on corrosion management geared toward traditional "anticipate and manage strategies" requiring along the way perfection of life prediction.[1,4] Here, end-of-life and choice of when and where to intervene to postpone end-of-life can help to ensure that maintenance strategies are timely, inexpensive, and impactful. An added wrinkle is that new corrosion mitigation strategies must, in the future, often contend with more severe climates and material-centric difficulties (e.g., such as undesired impurities in 2nd or 3rd generation recycled alloys), which may offer new challenges facing corrosion control. Selected manuscripts offer a direct link between corrosive consumption of materials and the equivalent CO_2 emission generated during primary or secondary production to replace them.[2] These papers are valuable to show corrosion through the lens of kg CO_2 spent for kg of metal produced. One additional method for consideration is the notion of "embodied" carbon dioxide that has been "invested" at all stages of production and spent "as it were" to mine, make, transport, and install the component. This can be expressed as CO_2 kg/kg metal. When this component is corroded away in kg/m^2, an equivalent amount of CO_2 is wasted in kg/m^2.[5] Analysis can go beyond this. Consider a thermal barrier coating (TBC). It takes enormous CO_2 to fabricate and build a jet engine with a TBC, yet operation of the jet engine at higher temperatures and greater fuel efficiency may save CO_2 over the total life cycle. We can all agree that corrosion's role in sustainability is probably undervalued due to its pervasive presence. What else can the corrosion community do in order to create a sustainable material cycle?

This perspective seeks to build upon these existing publications in order to provide a more holistic view of the materials sustainability issue and a snapshot of the current status of the challenges and barriers that impede progress and of emerging concepts pertinent to the corrosion community, particularly, the *CORROSION* readership. Several new concepts perhaps "just over the horizon" are introduced. The perspective concludes with some ideas and possible ways that scientific advances may help the corrosion-metallurgy community succeed in the commonly expressed sustainability goals of dematerialization, durability, enhanced lifetimes by strategically well-timed maintenance, and diversion of waste from disposal by recycling. Amongst the exciting developments include improvements in (a) corrosion control, (b) electrochemical recycling such as the emerging field of solvometallurgy, (c) advanced materials design including additive manufacturing, (d) materials informatics to provide a "continuum material" approach, and (e) inverse methods of material design, which will open new degrees of freedom at conception that could enhance corrosion control measures without raising corrosion control costs and possibly reducing them.

MODERN SOCIETY AND THE CONSUMPTION OF METALS

The growing world population, given continual modernization, is boosting the consumption of various metals despite the need to transition to a low-carbon society. The seven major industrial metals required to satisfy the growing needs of society are iron, aluminum, copper, zinc, nickel, manganese, and lead.[6] Their use is broad and covers all aspects of modern society: iron (mainly in construction, machinery, and transportation applications), aluminum (mainly in transportation, building and construction, packaging, and electrical applications), copper (mainly in electrical, industrial, and transportation applications), zinc (mainly in galvanizing, die casting, and alloying), nickel (mainly in industrial machinery, household appliances and metal goods, building and construction, and transportation applications such as superalloys used in aerospace), manganese (mainly metallurgy), and lead (mainly in batteries).[7,8] Iron makes up roughly 94% of the metals mined (as iron ore), and aluminum (as bauxite) is the second-most mined metal, followed by manganese, copper, zinc, titanium, lead, and nickel.[9,10] The exploration of these seven major industrial metals accounts for more than 98% of all metal products used globally.[10]

Recent data for world production of metals estimate there to be roughly 2.8 billion metric tons in 2021 (Figure 1).[10-12] A vast majority is accounted for by iron (2.6 billion metric tons), followed by other industrial metals: aluminum (68 million metric tons), chromium (41 million metric tons), manganese (20 million metric tons), copper (21 million metric tons), and zinc (13 million metric tons). Mining of high-tech materials used in functional applications, such as solar panels and precious metals, accounts for roughly 1.5 million metric tons (Figure 1). Another source posits that we consume roughly 10 billion metric tons per year of engineered materials, or an average of 1.25 metric tons per person per year.[13]

The above scenario is further challenged by the ever growing highly technological nature of our civilization. Here is how. Until the most recent 300 to 400 years, only the seven to nine elements mentioned in Figure 1 had been discovered, let alone used. Natural products such as wood and leather were mainly utilized by civilizations hundreds of years ago. Metals were restricted to gold, native and smelted copper, silver, tin (used mainly for bronze), lead, and iron. Today, elements used expressed as a portion of the periodic table have advanced far beyond this. Advanced alloys and components have moved beyond using only two or three elements, such as in bronze (Cu-Sn) or brass (Cu-Zn). For example, aluminum aerospace alloys were originally only alloyed with zinc, magnesium, and copper.[13] Today, 13 other elements on average find use routinely as Al alloying elements. In our world of high-tech devices, materials developers now have access to all 92 stable elements of the periodic table and often utilize a good fraction of them in design of advanced systems such as light bulbs, smartphones, and jet engines.[13]

Such elements are sourced globally and the increasing demand far exceeds recycling. Given this scenario, there is concern regarding disruption of the metals supplied due to an inadequate "stock" of reusable materials. Various factors can limit the supply chain of certain elements on short notice and this situation creates risks to production efforts.[13] As results of this, 31 of these elements are identified on the U.S. Geological Survey (USGS) critical list.[14] This means that they are regularly utilized and critical to the health of the U.S. economy. However, sources may be limited and various risks to availability may be encountered. Light bulbs contained just one critical element in the past (i.e., tungsten) but today contain 27 elements, including 6 on the USGS critical element list. Rotary dailing telephones contained 12 elements yesterday but smartphones today deploy up to half the elements in the periodic table, including 21 USGS

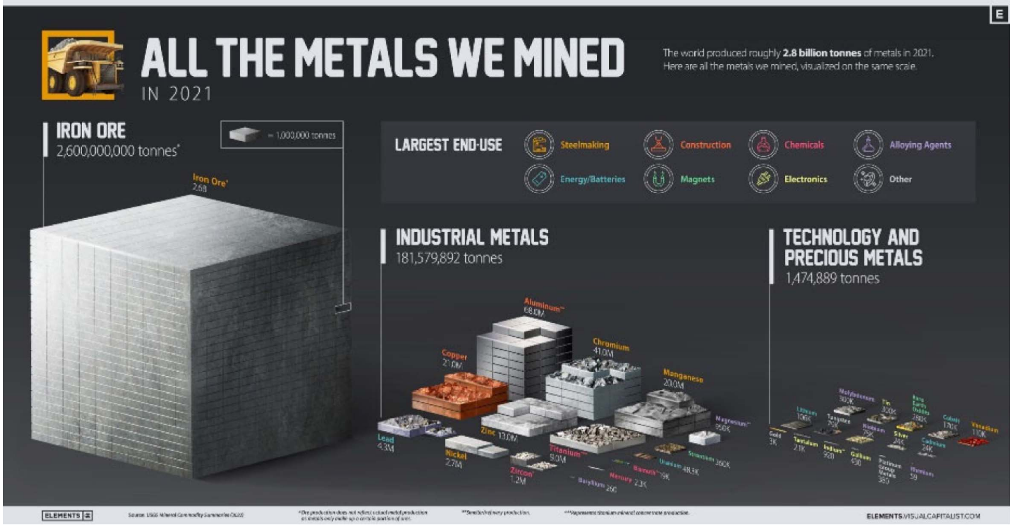

FIGURE 1. *Summary of materials mined in 2021. Reprinted from https://elements.visualcapitalist.com/all-the-metals-mined-in-2021/.*[11] *© 2022, Visual Capitalist.*

critical elements. As one last example, jet aircraft engines now utilize up to 24 elements, with 9 on the critical list.[13] Such material utilization has direct connection to energy consumption and CO_2 emission. Figure 2 gives the global CO_2 emission by material type and elements. Iron and steel are at the top of the list due to the shear tonnage used, closely followed by concrete.[15] It is also informative to consider embodied energy, as shown in Figure 3, where kg CO_2 produced per kg of metal produced are reported.[15] Here it is evident that Mg, Ti, and Ag generate the most CO_2 in their production. These issues illuminate some of the challenges to materials' sustainability.

Building the facilities of renewable energies such as wind turbines, solar power systems, geothermal systems, and others such as nuclear power all have day-to-day operational emissions that are CO_2 free. However, the infrastructure for clean energy will require large quantities of metals and other materials such as cement, steel, and glass.[16] According to the World Wide Fund for Nature, about 3,200 million metric tons of steel, 310 million metric tons of aluminum, and 40 million metric tons of copper will be required to build wind and solar facilities by 2050.[17] In addition, electric vehicles and their batteries, buildings, as well as infrastructure demand enormous amounts of the major industrial materials and may use many of the 92 stable elements from the periodic table.

Moreover, increased consumption of short-lived devices such as smartphones, which are rapidly upgraded from the standpoint of both the hardware and software, exacerbates the situation. In some cases, material durability can exceed functional lifetimes, recycling is limited at present, and consumer access to repair options in order to extend life is lacking. The short lifetime prior to obsolescence of such electronic devices coupled with the lack of repair options and limited recycling has contributed to the increase in electronic waste (e-waste) to over 50 million metric tons in 2021, up 21% in just 5 years. E-waste is projected to reach 74 million metric tons by 2030.[18,19] This is fueled by the expansion of elements used in components described above such as smartphones, rapid device functional obsolescence, and limited repairability.

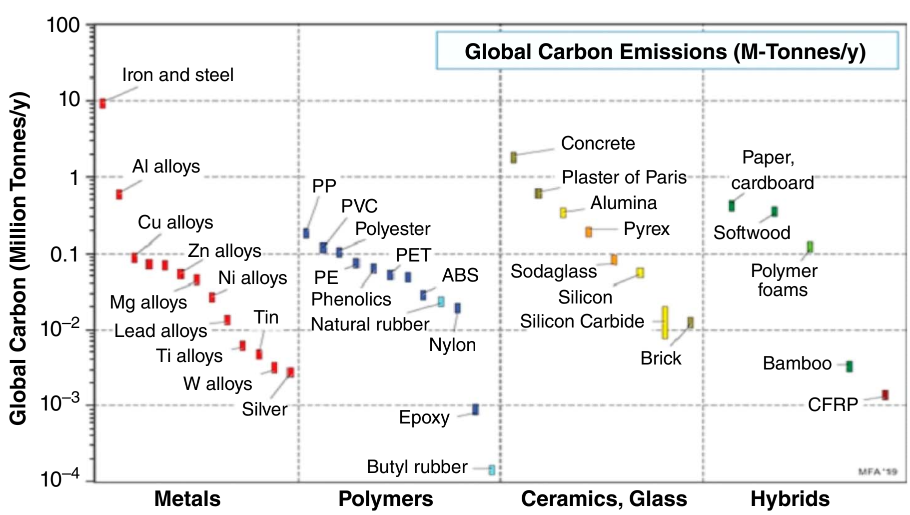

FIGURE 2. *Global CO_2 generated in metric tons per year as a result of production of various engineered materials. Data are given for metals, polymers, ceramics, and glasses, as well as hybrid materials. Reprinted with permission from Ashby.*[15] *© 2021, Elsevier.*

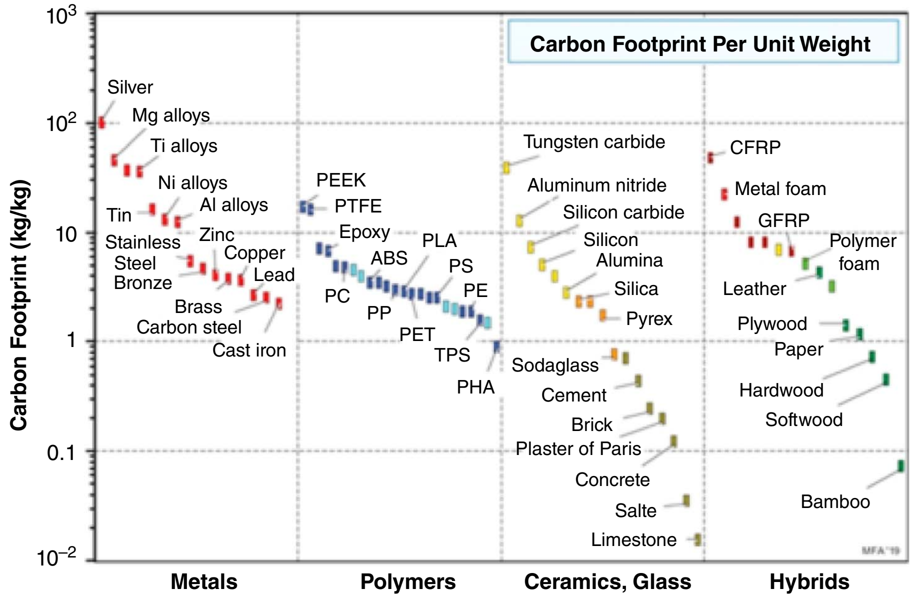

FIGURE 3. *The ratio of carbon content to energy consumed in material production. The curve provides data for metals, polymers, ceramic, glasses, and hybrids. Reprinted with permission from Ashby.*[15] *© 2021, Elsevier.*

Currently, nearly half of e-waste is metallic and only about one-fifth of e-waste produced is recycled.[18,19] Moreover, such devices contain gold, silver, copper, platinum, and other high-valued materials in small quantities albeit with high economic value. One belief is that there is more gold in 1 metric ton of retired computers than 17 metric tons of gold ore.[20]

Most e-waste is currently dumped or burned in third world countries, which creates additional hazards.[18,19] Similar circumstance applies to solar panels (photovoltaic or PV). PV retirement after 20 to 30 years of usage is an opportunity for significant recycling. The International Renewable Energy Agency and International Energy Agency estimated that $450 million (in 2016 terms) of raw materials could be recoverable from PV panels globally by 2030, which is comparable to the cost of raw materials to produce 60 million new panels, or 18 gigawatts of power-generation capacity.[21,22] The recoverable value could exceed $15 billion by 2050.[21,22]

RESOURCES OF METALS

A recent report by the United Nations, "Making Peace with Nature," poses the question of whether the current development model degrades the Earth's finite capacity to sustain human well-being.[23] It states, "[o]ver the last 50 years, the global economy has grown nearly fivefold, due largely to a tripling in the extraction of natural resources as described above and energy production that has fueled growth in the mining of materials and consumption covered above."

Regarding the future global supply and demands of metals, there are generally two opposing views. One considers that the resources are limited and humankind will eventually run out of mineral resources; the other one is that we will cope with the shortage by discovering new resources, developing new technological solutions, and increasing recycling (so-called fixed stock and opportunity cost paradigm).[24]

Several scenarios have been described to predict the demands and supply of metal resources to account for trends in the coming decades. This is not an easy task, and there are no globally accepted criteria. A recent critical review by Watari, et al., discussed the long-term projection of anticipated demands and supply of the major industrial metals through the 21st century.[6] Models were based on analyzing many publications dealing with the future status of metals and compiling a data set containing predicted global demand and supply data gathered from various articles to provide a comprehensive review. The demand for major industrial metals will increase two to six fold by 2100. By the year 2050, the most significant growth will be seen in aluminum (215%), followed by copper (140%), nickel (140%), iron (76%), zinc (81%), and lead (46%).[6] The projected demands depend on many factors, e.g., methodology choices, socio-economic variables, gross domestic product (GDP), population growth, etc. Basic models can be divided into those driven by socio-economic parameters and stock dynamics. Consequently, estimations may vary. Elshkaki, et al., calculated resource demand scenarios for the major industrial metals.[8] As the starting point, the global production of seven metals in 2010 was taken, and metal demands evolved based on adopted annual growth percentages.[8] The calculations accounted for four scenarios postulated by United Nations Environment Program and Global Scenario Group on how the global societal/material evolution might occur:[25] Market First, Policy First, Security First, and Equitability First.[(1)]

Several important conclusions emerged, among which we highlight three:

(1) The calculated demand for each of the seven metals doubles or triples relative to 2010 levels by mid-century.

[(1)] Market First: the private sector, with active government support, pursues maximum economic growth as the best path to improve the environment and human well-being for all. Policy First: the government sector, with active private- and civic-sector support, implements strong policies intended to improve the environment and human well-being, while still emphasizing economic development. Security First: the government sector and the private sector vie for control in efforts to improve, or at least maintain, human well-being for mainly the rich and powerful in society. Sustainability (Equitability) First: the civic, government, and private sectors work collaboratively to improve the environment and human well-being for all, with a strong emphasis on equity.

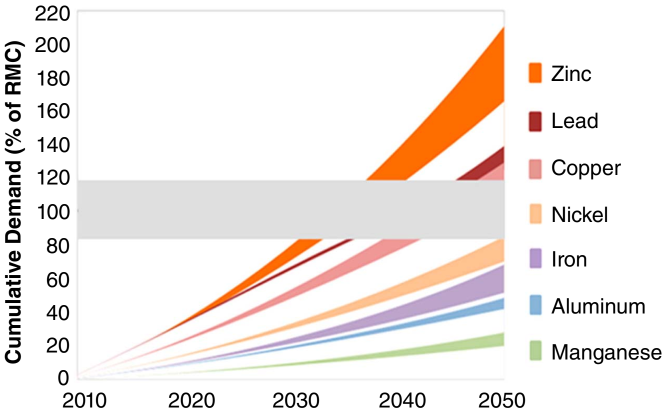

FIGURE 4. *The cumulative demand (2010–2050) calculated for each of the seven metals over the four developmental scenarios (expressed by colored bands[(3)]), whereas a gray area represents the estimated resources to Mid-Century RCM value.[8] Reprinted with permission from Elshkaki, et al., Environ. Sci. Technol. 52 (2018): p. 2491-2497. © 2018, American Chemical Society.*

(2) In the case of copper, zinc, and perhaps lead, supply may be unlikely to meet demand by about mid-century assuming the current use patterns for these respective metals. The calculations were made as a cumulative demand compared to the Resources to Mid-Century (RMC) value.[(2)]
Figure 4 illustrates the cumulative demand (2010–2050) calculated for each of the seven metals over the four developmental scenarios (expressed by colored range[(3)]), whereas the gray horizontal bar represents the RCM value.[8] Ni, Fe, Al, and Mn are not expected to exceed their RCM value by 2050, imposing no immediate concern. However, Zn, Pb, and Cu may exceed their RCM earlier than mid-century. A more detailed study confirmed these concerns for Cu.[26,27] The demand for copper is expected to increase between 275% and 350% by 2050, depending on the scenario (the highest being for the Equitability scenario).[26] Possible policy responses include improving the efficiency of the copper cycle, developing copper-free energy distribution, and improving the copper recycling rate.[26]

(3) Increased demand rates for metals imply substantial new energy allocations for mining, leading to increases in overall global energy demand of 21% to 37%. These results imply that extensively modified or new technological approaches are required along with new governmental policies to meet rising demands for metal supply.

Moreover, Li ion batteries are forecasted to create a 300% increase in demand for Li, as well as Co and Ni, over the next decade.[28] Now consider Co in particular. Co is used in batteries and as an alloying element in Ni-based superalloys.[13] Demand for Co is expected to increase from 235 to 430 thousand metric tons by 2030 and require 280% of the entire production capacity available in 2016.[28] Co is mainly used as an alloying element in gas turbines, Ni superalloys, batteries, and magnets, and Co oxides are used as catalysts.[29] Cobalt is a relatively rare element and is found as a trace element in nickel, copper, silver, iron, and uranium. Co supply will have to diversify and will require hydrometallurgical approaches to obtain small amounts of Co from other metals. Pyrometallurgical approaches releasing toxic gases as well as hydrometallurgical approaches are used today. Acid leaching or solvent extraction, electrochemical electrolysis, and selective chemical precipitation are all used. There is limited reliable data on Co recycling. Recycling does not in general match demand.[29]

ENGINEERING CHALLENGES TOWARD THE ESTABLISHMENT OF A SUSTAINABLE METALS-BASED SOCIETY

According to the Brundtland Report,[30,31] "sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Therefore, it is a more holistic approach that considers various dimensions of our society, including ecological, social, and economic, aiming together to achieve the best for society as a whole. Economic dimension (or approach) is hence one part of sustainability. Society today is well aware that the classical linear economy approach, "mine-make-use-dispose," is not sustainable (Figure 5).

In contrast to the linear approach, the circular economy approach was postulated to meet the need for sustainable development (Figure 5). We are currently in the reuse economy phase, a mixture of the two models. Resource input and waste, emissions, and energy leakage in a circular system are minimized by slowing, closing, and narrowing energy and material loops; this can be achieved through different approaches, the most known being the so-called "3Rs" (reduce-reuse-recycle), implying the use of fewer resources, use of materials more than once, and conversion of waste into new products. A broader concept of materials stewardship was recently introduced as a concept of improved materials conservation through a 4D strategy: dematerialization, durability, design for multiple life cycles, and diversion of waste streams through industrial symbiosis.[1,32] Individual strategies must be evaluated in concert because efficiencies in one dimension may be correlated with increases elsewhere.[33]

To expand on this point, the principles espoused by Ashby are worth considering. Chiefly, if design improvements occur, materials efficiency is increased. Ashby defines "materials efficiency" broadly as providing for materials needs with less reliance on primary production.[13,15] He reminds us that an "active stock" of recycled materials decreases reliance on production and requires less energy. Accordingly, "materials efficiency" is not just more recycling. There are four broad strategies to consider. These are (a) "better stuff" or improved materials technology, (b) better design and longer product life, (c) better business models to track materials cradle to grave and repurposed materials as long as they are not perishable (i.e., by corrosion and other forms of degradation), and (d) better human behavior, which can be taken to include more

[(2)] A McKelvey diagram distinguishes between Reserve and Resources: Reserve is that part of a resource which might be economically extracted or produced at the time of determination, whereas Resource is a concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible. The McKelvey diagram is used to estimate the uncertainty and risk associated with availability of a natural resource. Resources to Mid-Century (RMC) value is the roughly estimated global resource production potential to 2050.

[(3)] The colored range is limited by the upper and lower lines denoting the calculated region depending on the scenario taken. The four scenarios gave different results, e.g., "Market First" scenario requires fewer resources than "Equitability First " scenario but is less sustainable.

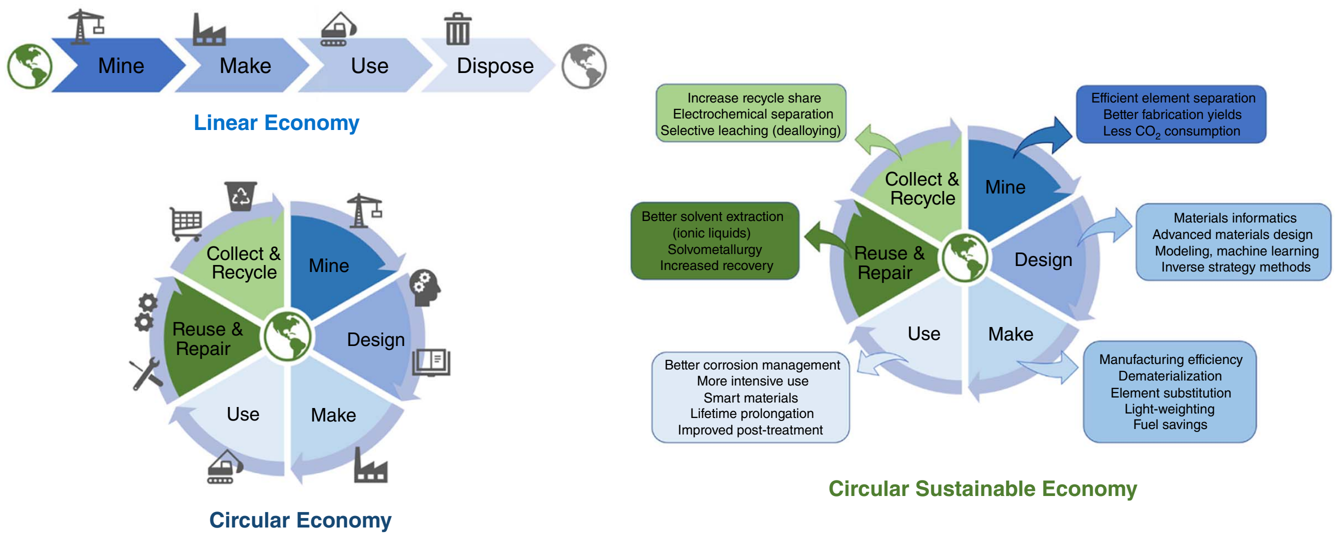

FIGURE 5. *Two classical models of a materials economy are linear economy, with a "mine-make-use-dispose" approach focusing mainly on profit without concern for ecological footprint, and circular economy, with a "make-use-recycle" approach comprising renewable resources and targeting sustainability. The next step is the advanced approach of a circular sustainable economy, where each process step can be further improved by materials science and engineering and corrosion science.*

preservation. Better design can take on lots of possibilities as described below.

Figure 5 presents a sustainable circular economy as the next advanced approach for our society to follow, considering the latest scientific and engineering achievements in materials and corrosion science. This section describes several novel strategies and approaches to contribute to a higher level of sustainable development. Today, materials technology can be improved through ICME (integrated computational materials engineering) and relies less on lessons learned and serendipity to advance materials performance.[13] Technical societies such as Association for Materials Protection and Performance (AMPP) can play a major role here. Corrosion must "be considered in design at the ground floor level" and not just as an afterthought or, worse, during deployment when service exposures reveal flaws or the perils of missing corrosion control. However, that does not mean that we should "gold plate" everything as a blanket measure in design. Durability is complex because there is no need for life extension beyond function or after obsolesce and corrosion resistance is needed in specific components and geographic locations but not others—the challenge becomes knowing where and when. Moreover, new products that cost less and/or are more energy efficient might emerge during operation and may hasten the retirement of current components even though they are perfectly good. Better design is not as straightforward as it may seem; it is not just to strive for long life without constraint, it involves consideration of the practical life, whether it be physical, functional, or something else. The corrosion community can advance corrosion-limited life prediction, calling it CLP 3.0, over its old routine methods by turning life to functional life and applying corrosion measures strategically and tactically.

When considering the materials' life cycle of raw materials mining-production-use-recycling, the possible solutions require a comprehensive and integrative approach. Each step of the cycle is foreseen as a part of the final solution toward more sustainable development. Metal refining and manufacturing can be considered a high-pollutant activity, e.g., sparking of steel produces millions of metric tons of solid and gaseous residues.[34] More efficient technological solutions are thus required, such as improvements in fabrication yields, reduced losses in smelting, and more efficient element separation. In the production step, several advanced strategies are vital for further reduction in metal use. For example, additive manufacturing produces less metal waste, is material efficient, and can produce on-demand complex compositional, property, and geometric "shape" components according to the company's needs. It can also produce new materials with additional functional properties, opening possibilities for broader applications. Computer-aided-design (CAD) technologies are advised for more accurate planning with less waste. Another strategy[35] is to substitute heavier materials with lighter ones. This is particularly useful in the transportation industry to achieve better fuel efficiency and reduce CO_2 emissions by cars, as well as heavy-duty and other vehicles, without compromising functionality.

Other strategies include substitution (replacing a less sustainable material with a more sustainable choice), more intensive use, lifetime extension, reuse and remanufacture, and enhancing recycling. Watari, et al., suggested that a strong bias exists in the attention given to the end-of-life phase, with recycling being examined more than, for example, light-weighting or life-extension.[6,36] The recycling rate (percentage of remelted scrap for product manufacture as a fraction of total scrap) of the major industrial metals is relatively high, over 50%.[37] However, recycled contents (percentage or amount of scrap for product manufacture in the total amount of material—primary material and scrap) are lower, between 30% and 40%, except for aluminum cans (80%) and lead (66% due to recycling of batteries).[37]

One important goal should be to increase the percentage of recycling rates and contents. However, the metal recycling flows in many scenarios meet only a modest fraction of future metals demand for the next few decades.[8,37,38] Metal recovery requires leaching, extraction, and stripping. The environmental impact of metal production is expected to increase steeply.[39] The corrosion field can contribute to recycling by devising new, more efficient recycling strategies to help leaching and extraction, such as using electrolytes which enable more facile selective leaching or dealloying.[40] There is also a need for help toward stripping and electrodeposition in the broader field of electrochemistry.[41] Solvent extraction can consider using ionic liquids serving as both extractants and diluents.[(4)] Current recycling approaches rely on pyrometallurgy and hydrometallurgy, which consume large amounts of energy and resources, such as water. In hydrometallurgy, solid-liquid extraction (leaching of metals) is achieved by acids or bases and chelating agents. Such leaching is not very selective in the elements leached.

Given these challenges, ionic liquids provide a path forward.[42] There are over a million possible ionic liquids, which are sometimes referred to as the "designer solvent." Ionic liquids or nonpolar organic solvents may prove useful. Indeed, the emerging field of solvometallurgy or ionometallurgy involves precise tuning of non-aqueous electrolytes for optimal selective leaching. In contrast to hydrometallurgy and pyrometallurgy, which use aqueous solutions to recover metals from ores, concentrates, or recycled materials, solvometallurgy[(5)] implies non-aqueous solutions such as ionic liquids and deep eutectic solvents with no discrete water phase.[40] Due to changes in solvating properties, the extraction mechanism can be exploited by selective leaching of metals in organic solvents. The process, which proceeds at moderate temperatures in a non-aqueous environment, allows controlling of metal speciation and tolerates impurities. The RTILs (room-temperature ionic liquids) are typically low-water environments so that water resources are saved.

It seems, however, that regardless of the global scenario,[(1)] the most effective option to reduce environmental impact is to increase the share of secondary production, which uses significantly less energy than primary production.[39] Recycling enables significant savings in energy consumption compared to the high needs of primary production, but the energy savings depends on the metal.[43] For example, the energy for recycling aluminum is 8.9 MJ/kg and is only about 5% of the aluminum smelting step, which requires 180 MJ/kg. However, in contrast to aluminum, for steel, the energy for recycling (3.2 MJ/kg) accounts for 40% of primary production. Therefore, there is an optimum between the recycled rate, recycled content, and energy consumed for each metal concerned. The closer the scrap metal recovery approaches 100%, the greater the energy required for each additional increment of improvement in recovery.[37] For steel, the maximum is 91%; beyond, the energy consumed in recycling exceeds that consumed in primary steel production.[37] However, secondary production is not expected to contribute a large portion of the metal supply until 2050 due to the vast demand increase over that period outpacing recycling efforts.[39] It is pointed out that the circular economy agenda for metals is, therefore, a long-term agenda similar to climate change.[39]

The importance of corrosion protection and efficiency due to durability is recognized in all sectors, from the solar industry, to geothermal and nuclear sectors, to infrastructure.[3] Corrosion science, engineering, and technology are expected to play an important role from the metal life cycle perspective in the following decades.[44-47] Material and corrosion management, including proper selection of materials and designs, can greatly improve the starting point for long-term use.[34,48] Novel corrosion protection strategies using efficient corrosion inhibitors, protective treatments and coatings, self-healing, and response-to-damage materials offer versatile options for prolonging the life cycle of the materials. Less environmentally harmful treatments should replace toxic materials and chemicals used in corrosion protection. Our effort should also be directed toward advanced materials produced by additive manufacturing or other routes with attention toward improving their post-treatment and protection.

Alloy design, including ICME principles, CALPHAD[(6)] approaches,[49] and DFT (density functional theory) sprinkled with a healthy dose of expert intuition, is well underway.[50] Alloy design in the age of additive manufacturing means the merger of materials performance with component design (blurring the separation and distinction between adaptation of the material with the component design, treated traditionally as two separate phases). In additive manufacturing, the door is opened toward creating location-dependent properties to combat corrosion where needed. In this paradigm, materials are used where they are needed, while being spared or substituted by more affordable materials where they are not needed. This new paradigm breaks the legacy design practice of "individual materials selected for each individual component." Up until now, the material has been considered a fixed entity with a given set of properties that are static fixed inputs to the design. The situation may be even worse, as corrosion may or may not be considered upfront and could be an afterthought to the design. Don't like it? Choose another material with another set of static properties. Additive manufacturing or, more broadly, 3D printing offers an alternative.[(7)] Directed energy deposition additive manufacturing (and other deposition methods) enables x, y, or z location-specific materials choices on a component. Today this is a reality more than a dream. Materials can be chosen selectively now and varied with x, y, or z to produce specialized composition, processing, and microstructures to create specific properties and functionalities.[51] Moreover, the era of inverse methods for materials designs is upon us.[52] Traditional "forward" approaches investigate the material "bottom-up," e.g., how morphology or fabrication conditions impact a macroscopic property set for a specific application. In contrast, "inverse" approaches start "top-to-bottom" and set the macroscopic properties required for an application and then search for suitable structure, morphology, and fabrication method to produce an optimal set of properties.[52] Some argue that even using machine learning and large data sets in a forward-looking mode may face challenges, making it difficult to arrive at the desired properties because there are so many descriptors[52] in materials science necessary to arrive at certain properties.[53] Inverse methods for materials design have promise as a way to optimize properties by defining them first and then exploring ways to get close to them by looking back at the design and build steps. This is a broad area with many possibilities in which the corrosion community should participate. Tunable corrosion properties can be mastered to "design in" high corrosion resistance at the location in the x,y,z space where needed and/or to face harsh environments only where the component is exposed and needs protection. Arrays of wave breakers can also thwart morphogenic corrosion propagation, an emerging area of corrosion.

(4) An ionic liquid typically contains inorganic anion and organic cation.
(5) Solvo meaning in Latin: loosen, untie, release, free.
(6) Calculation of Phase Diagrams (CALPHAD) is a phenomenological approach for calculating/predicting thermodynamic, kinetic, and other properties of multicomponent materials systems.
(7) It should be noted that there are many deposition methods available today to deposit metals layer by layer and also with lateral changes besides additive manufacturing in the form of 3D printing. The purpose of this perspective is not to provide comprehensive coverage.

Alloy design could not only consider the desirable alloying elements needed to achieve various properties but be tolerant of recycled alloying elements perhaps utilized at lower purity. Ideally, repurposing and recycling materials may involve a greater tolerance for low levels of impurities and trace elements normally not intended in order to increase the level of "in stock" materials that can reduce production.[13]

Moreover, the design of new materials could consider using certain "recycle-friendly" alloying elements from genesis, given the opportunity. Ideally, these elements would not compromise corrosion or other properties.[54] Of course, there may be trade-offs. Here "recycle-friendly" elements might have a dual purpose and contribute to corrosion resistance in the intended service environments. Imagine if at end-of-life, the same elements could be "turned on" toward rapid dissolution in the recycling leach and extract stage? For instance, certain elements could be selectively leached using exposure to a specific designer solvent (i.e., ionic liquid) tuned for recycling. The recycling environment would utilize designer solvents tuned to solubilize only the desired metallic cations without solubilization of other cations. The corrosion research community must help improve the understanding of these phenomena as dissolution and passivity in ionic liquids are currently not well understood.[55] The profound knowledge would enable better selective solubilization utilized in solvometallurgy.

Furthermore, the integrative approaches of experiments, modeling, and machine learning procedures are expected to become increasingly important because they significantly lessen the number of experiments required for corrosion management. Presented options show that current and future activities of corrosion scientists and engineers should be directed toward refining the approaches to prolong the life cycle of the materials by developing new technological and engineering solutions as suggested herein and beyond. There is great promise and possibilities given these ideas. The corrosion community has a broad skillset drawing upon its many researchers and would be well positioned to contribute to this effort.

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