A Sustainability Framework for the Beneficial Reuse of Alumina Refinery Residue

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***Abstract*—When bauxite is processed to manufacture alumina, a solid waste by-product is created. For every one tonne of bauxite digested by the refining process about 400 kg of alumina and 600 kg of waste residue are produced. As a consequence, each year up to 120 million tonnes of solid waste residue are generated by about 100 alumina refineries in Australia, China, Brazil, India and elsewhere, and in excess of three billion tonnes of waste residue are reportedly stockpiled in impoundments throughout the world, making alumina refinery residue the world's single largest industrial waste product by volume.**

The physical and chemical properties of alumina refinery residue have long been the subject of scientific investigation because the residue contains iron, aluminium, silica, titanium, sodium and other elements and compounds of potential value. In the last ten years, this investigation has centred on not only the recovery of valuable components of the waste but also on the various beneficial reuse possibilities associated with this type of residue, both as a way of reducing the amount of waste being stockpiled as well harnessing the inherent valuable components in it. The alumina industry has therefore developed a series of "technology roadmaps" to address the growing inventories of alumina refinery waste, including how to better dewater and store it safely. However, while commendable, these roadmaps have mostly focused on process improvement and productivity dividends and failed to address certain fundamental truths related to sustainable and beneficial reuse, including lifecycle analyses, how the residue can be incorporated into wider regional plans for sustainable development, and the inescapable fact that alumina refinery residue is a classified hazardous waste in most jurisdictions with potentially detrimental human and environmental health effects when applied incorrectly or inappropriately.

By considering not only the obvious industrial, commercial and chemical imperatives which drive residue reuse and inform current technology roadmaps, but also by including the regulatory, environmental, investment, research and social licensing dimensions (among other factors) of a complete and holistic future, this paper presents a new framework for the beneficial reuse of alumina refinery residue. The paper argues that only through a comprehensive understanding and consideration of all aspects of alumina refinery residue beneficial reuse and a meaningful engagement with the broadest possible range of stakeholders can a truly sustainable future for this type of waste be realized by society and industry.

Keywords—sustainability, bauxite, alumina refinery residue, beneficial reuse

I. INTRODUCTION

Alumina (Al_2O_3) is produced by refining bauxite ore, which is stripped from large open-cut mines; aluminium, one of the world's most important lightweight metals for packaging, transportation and construction, is in turn produced by smelting alumina.

About 260 million tonnes (mt) of bauxite is mined annually throughout the world from a global reserve of between 55 and 75 billion tonnes, with 30% of bauxite mined in Australia (77 mt), 18% in China (47 mt), 13% in Brazil (34 mt), 12% in Indonesia (30 mt), 7% in India (19 mt), 6% in Guinea (17 mt), and 3% in Jamaica (9 mt), with the remainder mined in countries such as Russia, Guyana and Suriname [1].

Bauxite is either consumed by local refineries or exported to the more than 100 refineries throughout the world, with the number of alumina refineries in China alone increasing from seven in 2001 to 49 in 2011 [2]. This number is set to increase even further, with bauxite demands from China expected to reach 240 mt by 2030, with the total global bauxite demand for alumina and aluminium projected to reach 350 mt by 2018 [3].

The most common method of digesting alumina from bauxite is the Bayer process, developed by the Austrian chemist and industrialist Karl Bayer in the late nineteenth century (for a complete history of the Bayer process, see [4]). In this process, insoluble alumina is generated when bauxite is digested using sodium hydroxide (i.e., caustic soda, NaOH) at a temperature between 100-240° C and pressure between 1-6 atm. The waste by-product generated by the Bayer process is known colloquially as "red mud", but in the industry is referred to as "bauxite residue" or "alumina refinery residue" [5].

For every one tonne of bauxite processed using the Bayer process, between 300 and 500 kg of alumina and 500 and 700 kg of alumina refinery residue (ARR) are generated, with alumina going to a smelter for manufacture into aluminium and ARR discharged into long-term, on-site impoundments as a slurry (or sometimes disposed to the sea or ocean as submarine tailings [2]). The footprint of these impoundments can be significant, at 200 ha in area and up to 40 m deep, and hence land tenure can be a concern to parts of the industry. When discharged from the refinery, ARR is highly alkaline and sodic (typically around 5,000 mg/kg of total alkalinity, but sometimes as high as 30,000 mg/kg or 3%, which is comparable to salinity levels in seawater), with a pH greater than 12.0.

ARR is often classified as a “hazardous” (but not “toxic” [6]) industrial waste under many national and international jurisdictions and conventions, such as the Basel Convention (i.e., classification #B2110), due to its highly caustic nature; ARR can burn skin on contact, and is an irritant to eyes, nose and throat, among other damaging characteristics.

The generation of large amounts of ARR presents a significant disposal and operational problem to the alumina industry. To put this statement into context, consider that at least 120 mt of ARR per year are generated by refineries in Australia, Brazil, China, France, India, Romania, Russia and elsewhere [7], with projections of 140 mt by 2018 [3]. As the world’s largest industrial waste by-product, with about three billion tonnes of ARR currently stockpiled in impoundments around the world [8] and up to four billion tonnes projected for stockpile by 2015-2018 [9], the issue of safely storing, monitoring and managing hazardous ARR and its potential environmental and social impacts is a non-trivial worldwide industrial and social challenge.

When factoring in the closure of another 30 disused refineries around the world [2], leaving legacy stockpiles of many hundreds of millions of tonnes of hazardous waste, often in a derelict condition, the need for a sustainable ARR future is unambiguously important. For this reason, Alcoa, historically one of the world’s largest generators of ARR, stated in 2005 that “finding practical uses for new and stockpiled refinery residue—which has ongoing environmental and land use impacts and significant storage costs—is arguably the biggest challenge facing the global alumina industry” [10], and seven regional governments, including Australia, India and China, which together account for 53% of the world’s aluminium production and form the Asia-Pacific Partnership for Clean Development and Climate, have made ARR a key policy area worthy of significant further investigation and investment [11, 12].

Among the principal challenges associated with the management of ARR are its physical and chemical properties. Untreated ARR is typically composed of iron (25-35%), aluminium (10-20%), sodium (3-10%), titanium (5-10%), silica (5-20%) and calcium (5-10%) in oxide, hydroxide and/or oxy-hydroxide states. None of these elements constitute a particular problem in themselves, but because of their combined highly caustic nature they do pose significant long-term environmental management and human health risks.

For example, ARR is composed of a complex cocktail of metals and minerals, including hematite (Fe_2O_3), beohmite (γ-AlOOH), gibbsite ($Al[OH]_3$), sodalite ($Na_4Al_3Si_3O_{12}Cl$), anatase (TiO_2), aragonite ($CaCo_3$), brucite ($Mg[OH]_2$), diaspore (ß-$Al2O_3.H_2O$), ferrihydrite ($Fe_5O_7[OH].4H_2O$), gypsum ($CaSO_4.2H_2O$), hydrocalumite ($Ca_2Al[OH]_7.3H_2O$), hydrotalcite ($Mg_6Al_2CO_3[OH]_{16}.4H_2O$) and p-aluminohydrocalcite ($CaAl_2[CO_3]_2[OH]_4.3H_2O$), which contribute to its elevated causticity.

ARR may also contain heavy metals and metalloids, including arsenic (As), chromium (Cr), gallium (Ga), thorium (Th), uranium (U) and vanadium (V), although usually only in trace concentrations of between a few parts per million up to 200 mg/kg. While the presence of radionuclides, such as lead (Pb), Th and U, have raised concerns, these elements are almost always found in non-radioactive states [11].

FIGURE 1. PHOTOGRAPHIC EXAMPLES OF ALUMINA REFINERY RESIDUE IMPOUNDMENTS IN AUSTRALIA (TOP) AND ROMANIA (BOTTOM).

About 50% of ARR is amorphous, with its crystalline constituents composed mainly of goethite and hematite, quartz, and titanium species such as rutile, anatase and/or ilmenite; many minor remnant phases from the original bauxite ore (e.g., mica) and newly formed species created as a result of specific conditions in the Bayer process (e.g., natroalunite and noselite) may also be present. Upon contact with water, the solids in ARR (which are typically about 30-40% of the slurry waste stream) impart a pH of ±12.5, with elevated levels of electrical conductivity (EC) between 1.0 and 16 mS/cm and a high bulk density, with greater than 80% of ARR particles at <10 micron [13, 14]. However, the physical and chemical characteristics of any given ARR can vary widely, and are determined by the geological properties of bauxite ore and the industrial and process handling conditions of bauxite at the refinery from which it is generated.

For example, factors such as geographical origin and condition of bauxite, bauxite beneficiation practices at the refinery, volumes and quality of NaOH applied and consumed in the Bayer process, temperature and pressure settings, and other related industrial practices, such as thickening methods, can dramatically alter the final properties of ARR.

Due to these physical and chemical attributes, particularly its highly caustic nature, the ongoing storage and management of ARR can be problematic given it has been estimated the hundreds of impoundment facilities currently in production, on “care and maintenance”, or completely abandoned will have to be carefully monitored and managed for up to 500 years, with flood events being a particular concern [15].

Worries about human health, including the onset of cancer, at or near alumina refineries have also been highlighted, although Donoghue, an Alcoa medical officer, concluded that adverse risks such as acute and chronic health effects and incremental carcinogenic risk factors associated with exposure to ARR dust at or near Alcoa’s Wagerup and Pinjarra refineries in Western Australia, were negligible [16].

His study was commissioned because reports near the Wagerup refinery maintained “residents of the nearby south-west town of Yarloop say the emissions are making them sick, causing symptoms such as nose bleeds, sore eyes and skin ulcers…There is a very long list of known toxic or carcinogenic substances which are regularly emitted [from the refinery] and yet exactly what combination it is which is making people sick…hasn’t been clearly drawn out” [17]. Subsequent reports at both Wagerup and Pinjarra concluded the refineries, and ARR dust in particular, were not the source of these health concerns [18], although doubts linger [19].

Similarly, an independent government adviser in Australia identified four main categories of concern associated with emissions from alumina refineries: metals and metalloids; organic contaminants; organohalogens; and inorganic contaminants [20]. Many of the contaminants associated with alumina refining appear on Australia’s National Pollutants Inventory (NPI). For example, alumina refineries have determined that contaminants from emissions, including arsenic (As), chromium (Cr), lead (Pb), mercury (Hg), acetaldehyde, benzene, formaldehyde, polychlorinated biphenyls (PCBs), dioxin and dioxin-like compounds, polycyclic aromatic hydrocarbons (PAHs), toluene, xylenes, cyanide and fluoride compounds, sulfur dioxide, and thorium (Th) and uranium (U) are reportable and should be disclosed [20]. However, no empirical medical evidence has materialized linking alumina refinery operations, including the generation and storage of ARR, to adverse human health outcomes.

As a consequence of these findings and other improvements in operations, bauxite, alumina and aluminium industry ratings on a so-called “sustainability scorecard” have improved over the last ten years, with about 30 square kilometers of refinery land per year (equivalent to the annual area of new bauxite mining) being revegetated each year, electricity consumption down 6% since 1990 for smelters and 8% for refineries, and perfluorocarbon (PFC) and fluoride emissions from smelters down by 75% and 44% respectively since 1990, although reliable data on water consumption, which is a major input into alumina refining, are uncertain [21].

There is, however, another side to these salutary reports. Perhaps the starkest reminder of the hazardous properties of ARR and certainly one of the saddest events in the industry’s 120-year history was the burst embankment of a residue holding dam in Kolantár, Hungary in October 2010, which resulted in the deaths of ten people and injuries to 60 more when about one million tonnes of caustic ARR flooded seven townships and threatened to contaminate several rivers, including the Danube [22].

As a result of the spill, all biological life in the Marcal River was said to have been “extinguished”, with the event described by Hungary’s Prime Minister, Viktor Orban, as an “ecological tragedy” [23]. While the least parsimonious interpretation of this event suggested the victims “drowned” as a result of the spill, each was subjected to the highly caustic properties of ARR, with one man dying of his burns 30 days after the “flood” [23]. However, no adverse health findings associated with ARR dust generated by this industrial accident have so far been observed [24].

These and other findings are important when considering the possibility of reusing ARR in other industrial “waste-to-resource” initiatives or trans-locating it from impoundments to large-scale agricultural applications, as has been proposed [12]. For example, if ARR is reused, its hazardous properties need to be ameliorated in order for it to be handled and transported safely and for it to be re-applied in industrial or municipal settings or used in agriculture and the wider society. For this reason, many alumina refineries have sought ways to modify ARR by “neutralising” its total alkalinity (particularly its high Na concentrations) thereby reducing its pH and thus its causticity and sodicity.

A wide variety of different ARR modification methods have been identified and tested in the last 20 years, including carbonation, seawater neutralization, concentrated brine addition and nanofiltration, sulfur addition, and acid neutralization [13, 25, 26, 27, 28, 29, 30, 31]. Each method, to varying degrees, reduces alkalinity, lowers pH and electrical conductivity, and renders ARR "safe" (i.e., non-hazardous), and each method has advantages and disadvantages, although these are too numerous to catalogue here.

The critical question in considering a method's viability is: will the ARR be stored in an impoundment after modification, or will it be reused? The answer to the former means that while the modified ARR can be stored safely without its inherent hazardous properties, there is no intention of reusing it in other applications and therefore the modification method need not factor in any specific chemical or physical features of the ARR once modified. The answer to the latter leads to specific decisions about the modification method employed, particularly if the reuse application requires ARR to neutralize acid or buffer acidity, sequester heavy metals, bind phosphate, add macro- and micro-nutrients to soil, synergistically interact with chemical and/or biological agents, or otherwise perform specific environmental, technological or industrial functions (these modification methods can loosely be referred to as ARR "beneficiation").

For example, when considering the properties of ARR in an impoundment, one modification method may lower its pH and render it chemically inert, thus reducing long-term leachate concerns [25], but the modified ARR may not retain its "useful" properties when considering its reuse in cementitious product manufacture or agriculture. Conversely, another modification method may enhance the acid neutralising capacity (ANC) of ARR, but this feature may not be warranted if the ARR is going to be stored passively in an impoundment.

In each case, therefore, it is fundamentally important to distinguish between: A) untreated and unmodified ARR, which is hazardous and not suited to beneficial reuse; B) treated and modified ARR, which is non-hazardous and therefore suited to safe long-term storage, but which may not be suited to beneficial reuse because some or many of its useful properties, which were present prior to modification, have been neutralised and not retained while undergoing caustic reduction; and C) modified ARR which is suitable for beneficial reuse.

For example, while their research into ARR and its potential reuse is comprehensive, this fundamental mistake of not differentiating between A), B) and C) can be observed in the work of Liu and Wu in China [32] and Traoré, *et al.* in Guinea [33]. For the purposes of developing this sustainability framework, the present paper only refers to C), i.e., modified ARR which is suitable for beneficial reuse, but for the purposes of brevity the paper does not distinguish between the different types of modified ARR which can be deployed.

Once modified, this type C) ARR has a number of important characteristics and functions, and these can be enhanced further by blending it with other chemical and biological additives [34, 35] or modified further for other applications through specialized industrial processes, such as pelletization [36]. Documented in more than 700 patents filed during the period 1964-2008 [12, 37], a summary of beneficial reuse applications for modified ARR is presented in Table 1.

TABLE I. SUMMARY OF DOCUMENTED BENEFICIAL REUSE APPLICATIONS FOR MODIFIED ALUMINA REFINERY RESIDUE, INCLUDING THE SCALE OF ANTICIPATED VOLUMES OF RESIDUE CONSUMED BY THE APPLICATION WITH PUBLISHED REFERENCES

Summary of Beneficial Reuse Applications of Modified Alumina Refinery Residue		
Application	**Scale**	**Reference**
Building and construction, including concrete, grouts, mortars and aggregates; road and dam construction	Large	37, 38, 39
Cementitious products, including brick, block, tile, furnace insulation and clinker manufacture	Large	40, 41, 42
Agriculture and horticulture, including compositing	Large	43, 44, 45
Mineral, metal and rare earth recovery, such as iron (Fe), titanium (Ti), gallium (Ga) and scandium (Sc)	Large	7, 46, 47, 48
Ceramics, plastics, catalysts, coatings, pigments and geopolymers	Large	49, 50, 51
Pig and cast iron smelting and steel manufacture, including dip coatings	Large	52, 53
Industrial waste treatment, including gaseous, liquid and solid waste treatment	Medium	13, 54
Mining waste treatment and mine site rehabilitation and revegetation	Medium	55, 56, 37
Contaminated soil treatment, including acid sulfate soils (ASS), and industrial site remediation	Medium	57, 5
Coal seam gas waste treatment	Medium	58
Flue gas desulfurization and other gaseous waste emissions treatment	Small	59
Drinking water treatment	Small	60
Municipal waste treatment, including gaseous, liquid and solid waste treatment	Small	61, 62, 63

From this overview it is evident that modified ARR has significant industrial, economic and environmental contributions to make to society, and for these reasons its sustainable reuse should be examined further.

II. EXISTING INDUSTRY ROADMAPS

Attempts have been made to create a framework for the sustainable reuse of alumina refinery residue at an industrial complex in the Middle East [64]. Similarly, a series of technology roadmaps have been developed by the bauxite, alumina and aluminium industries in the last 20 years; these roadmaps have guided the research, development and priority goals of these industries [e.g., 2, 65, 66, 67, 68, 69]. Together, the roadmaps represent how the alumina industry sees itself now and how it wants to be seen in the short- and long-term future.

Technology roadmaps for the alumina industry are generally of a high quality and identify the key policy areas of concern, with particular focus given to either industry goals, benchmarks and challenges or areas of research and development. The key industry goals, benchmarks and challenges, which have been identified by these roadmaps, include: 1) refineries should be self-sufficient in water; 2) refineries should minimize the discharge of dust, gaseous emissions, volatile organic compounds, alkali solutions, and other sources of real or perceived risks to the environment and human health; 3) refineries should reduce their energy consumption and seek alternate sources of energy; 4) refineries should reduce the impact of scale on operations, thereby reducing costs and improve equipment efficiencies; 5) refineries should improve liquor efficiencies; and 6) refineries should achieve greater flexibility in digesting a range of different bauxite ores, thereby improving alumina quality.

The key areas of further research and development, which have been identified by the roadmaps, include: 1) acceleration of alumina precipitation rates; 2) improved control strategies; 3) improved bauxite beneficiation methods; 4) improved removal of Bayer liquor impurities; 5) reductions in caustic consumption; and 6) improved heat recovery.

While the so-called “cost-effective inerting and alternative uses” of ARR have been considered in some roadmaps [e.g., 68], these are mostly in the context of converting residue into a safer material to handle when storing (i.e., ARR type B, described above) rather than exploring and implementing sustainable beneficial reuse options. This becomes particularly obvious when the industry advances the concept of “inerting” ARR (i.e., rendering it chemically inert or “neutral”) as a focus of the roadmap. In such cases, finding alternate uses for ARR is secondary in, or of token importance to, ARR modification because an “inert” residue has little or no environmental use. In fact, it is precisely because of the unique properties of ARR, including its ANC, and phosphate binding and heavy metal sequestering capacities, among other benefits, that make the beneficial reuse of ARR so appealing.

Nevertheless, the roadmaps do speak to the general goal of managing “bauxite residue in such a way as to promote/encourage use as a product and a resource for other industries and for all remaining residue to be stored in an environmentally friendly form” [68]. Where a specific industry-driven goal has been identified it has generally been framed within the context of overall sustainable development, a cornerstone of good planning and reporting [70].

However, it is reasonable to point out the roadmaps are not sustainable development models for beneficial reuse *per se* because they lack consideration of Leader-Member Exchange (LMX), Life Cycle Assessments (LCA) and Design for Environment (DfE) risk analyses and management, which are essential elements of any comprehensive sustainability framework.

For example, Fein and Tziner explain that true sustainability modeling includes connecting virtue-based leadership with moderated mediation in building a sustainable business, and this methodology helps build a “win-win” culture of linking individual responsibility to corporate and organizational responsibility and linking corporate and organizational responsibility to social sustainability [71]. This limitation in the current technology roadmaps is partly due to the fact they were developed in the early part of the century and approaches to designing and implementing sustainability programs, such as the one under consideration in this paper, were still emerging [72], but is also due to an “industrio-centric” view of ARR in which the interests of the refinery outweigh the interests of everyone and everything else.

The roadmaps make attempts at inclusivity in that they do refer to the involvement of industry, academics and industry associations in the management of ARR, and alumina refineries acknowledge the growing impact of environmental and social issues on their industry. However, their primary focus is on alumina as a commodity not on ARR as a potential beneficial reuse raw material, and as a consequence they tend to miss out on the richness of a complete and comprehensive framework for developing a sustainable future for the industry.

This shortcoming becomes obvious when, in parallel to advancing ARR reuse initiatives, some high-profile applications of ARR have gone spectacularly wrong, particularly when large-scale applications utilise unmodified ARR and when local community, media and other stakeholders have not been fully appraised of the planning, implementation and monitoring of such applications.

III. A NEW SUSTAINABILITY FRAMEWORK

The sustainability framework proposed in this paper has been conceived as a comprehensive and inclusive approach to conceptualizing a future for ARR; it assumes that all stakeholders can and should play a role in a transparent and open conversation, with broad understanding and agreement on matters related to the beneficial reuse of ARR.

The framework also considers as a fundamental principle that every stakeholder should contribute to, as well as receive benefits from, ARR reuse. For these reasons, communication, education and inclusion are seen as critical elements if the ramework is to work effectively and thus lead to long-term sustainability outcomes.In this sense, the new framework is fundamentally different from past roadmaps, which have a certain obscurity and lack of communication about them when implemented. For example, when Alcoa and the Department of

Agriculture of the government of Western Australia decided to apply unmodified ARR to farmland in the late 1990s, apparently not all stakeholders were consulted and community education and communication may have been lacking.

When newspaper reporters become aware of the large-scale reuse program and noted the presence of uranium in ARR, they assumed and publicized to the wider Australian public that receiving farmland had become radioactive (this application became known as the "great red mud experiment that went radioactive" [73]. Their conclusion was wrong but the damage had been done, and Alcoa and the Western Australian government have never fully recovered from this experience, with all other applications of ARR in that state having since been suspended.

Despite their best effort to explore the real-world reuse of ARR, the community backlash and poor publicity effectively destroyed any further attempts at ARR reuse in Western Australia. The extremely damning international publicity surrounding the aforementioned ARR spill in Hungary has similarly done little to advance the sustainability effort of this program.

Any effective sustainability framework for ARR must therefore achieve three basic objectives: 1) apply only modified, non-hazardous ARR in reuse projects; 2) be presented as a "whole-of-system" approach, not as an industry-driven "waste-to-resource" initiative (i.e., seen not merely as a way for industry to rid itself of a waste it does not want by packaging the initiative as "sustainable development"; the community will mistakenly see this as an attempt to "dump" industrial waste on an unsuspecting and naïve public); and 3) be implemented in a transparent, open and inclusive manner, involving all stakeholders in the process.

For this reason, the sustainability approach proposed in this paper is proactive and pre-emptive rather than reactive; it is designed to inform and educate stakeholders—a process seen as paramount to any sustainable future for ARR. If there are concerns, these need to be addressed "up front" not after a series of complaints or claims have been made, usually to a regulator or the media and often founded on biased or skewed information.

Such a fate is currently befalling the coal seam gas (CSG) industry in Australia, in which the community's perception of the dangers posed by hydraulic fracturing chemicals and drilling processes has at least partially been caused by the industry's own obfuscation; the fact that the CSG industry is reluctant or refuses to disclose the chemical properties of its "fracking" fluids (many of which contain known mutagens and carcinogens [74], but many of which are also never used) only adds to a society's disquiet and opposition.

In the face of obscurantism and lack of knowledge, fear and hostile resistance to change are inevitable, often at the expense of potential social advancement.

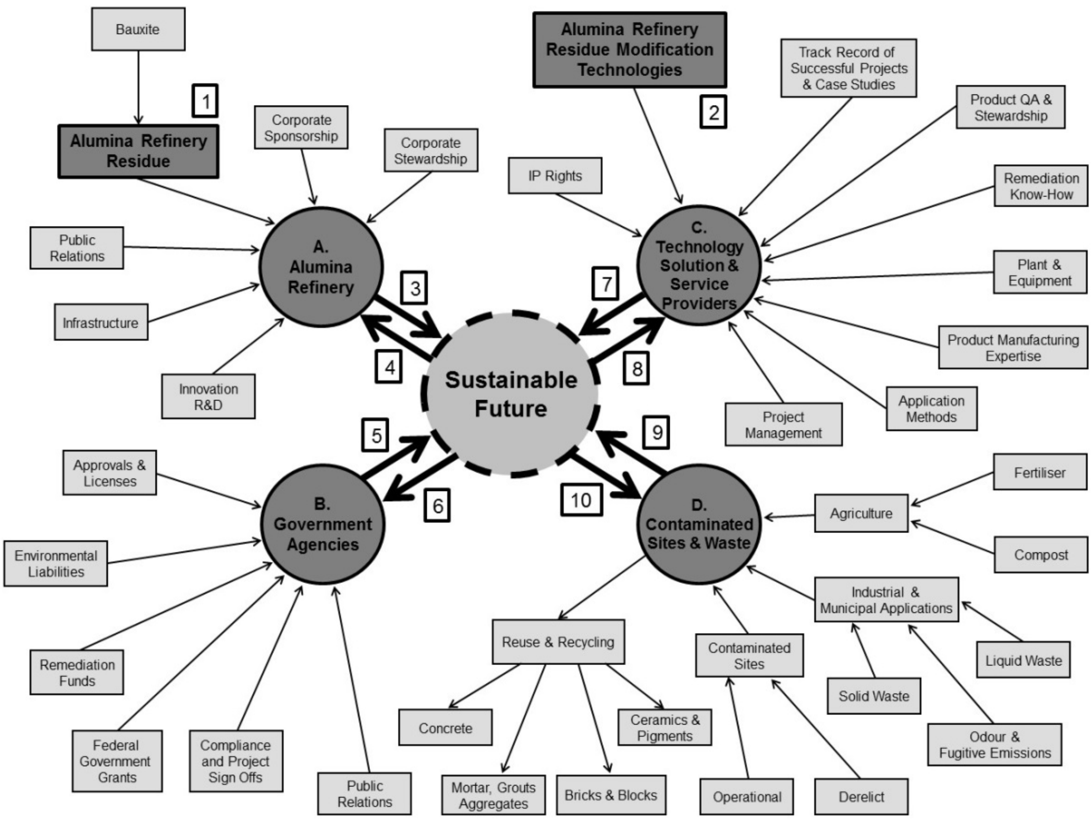

FIGURE 2. SUSTAINABILITY FRAMEWORK (PART A), IDENTIFYING KEY STAKEHOLDERS (WITH A FOCUS ON A-D) AND THEIR CONTRIBUTIONS TO AND BENEFITS FROM A SUSTAINABLE FUTURE.

Figures 2 and 3 present an overview of the new framework, with nine key stakeholders contributing to and benefiting from a sustainable future for ARR; these stakeholders are labeled A-I (with a focus on stakeholders A-D in Figure 2 and E-I in Figure 3). Stakeholders in this context are defined as individuals (or groups of individuals) and entities who can reasonably be expected to contribute to, and who would be impacted by, the implementation of ARR beneficial reuse.

The nine key stakeholders are: in Figure 2, Stakeholder A. the alumina refinery, which plays a central role as the supplier of ARR; Stakeholder B. government agencies; Stakeholder C. technology solution and service providers; Stakeholder D. owners and/or managers of contaminated sites, waste producers, and operators of companies which can benefit from the reuse of ARR; and in Figure 3, Stakeholder E. socially responsible investors; Stakeholder F. the media, including print, digital and broadcast media, and marketing and public relations companies; Stakeholder G. the scientific research community, including Cooperative Research Centers (CRCs) and independent researchers; Stakeholder H. consultants, contractors and industry associations, including civil engineers, environmental consultants and auditors, transportation companies and analytical laboratories; and Stakeholder I. the general public.

It should be noted that because existing roadmaps place emphasis on issues such as human resource management (HRM), workplace health and safety (such as lost time injury rate [LTIR] and total recordable injury rate [TRIR]), and industrial relations, the current framework is set against the backdrop of contemporary occupational health and safety workplace standards and therefore does not address these issues directly.

The model also assumes that parties contributing to a sustainable future for ARR are workplace safe and all parties are responsible corporate citizens. Similarly, the framework has not highlighted the significance of, and need for, risk assessments by relevant stakeholders.

Chileshe, *et al.* have outlined the critical strategic risk pathways for pursuing a sustainable business in the construction industry [75]. These pathways are predicated on the assumption that an industry, such as alumina refining, "hold[s] the future of the planet in [its] hands" and "fundamental notions about commerce and its role in shaping our future are transforming, and far-sighted companies are seizing the opportunity to not only survive but to prosper" [75]. In this context, risk assessments are not only desirable, according to Chileshe, but necessary; a conclusion made more relevant by the fact that ARR poses a long-term liability and risk for both industry and society.

Therefore, the present framework assumes that risk assessments, along with other aspects of building a sustainable future, such as crisis management, environmental reporting, sustainable procurement practices, ethical behaviour, education and training, and human rights and gender equality, will play an integral part in the planning and implementation of ARR beneficial reuse. Moreover, the framework has not highlighted the need for stakeholder documentation and reporting, but assumes such basic sustainability practices would be in place and carried out by the relevant party.

In this framework, no single stakeholder benefits from the process to the detriment of any other stakeholder, and the framework has been modelled along the lines of "everbody and everything wins" [76]. While the outcome may conceptually represent a zero-sum game (i.e., benefits are offset equally by contributions), the framework is non-zero sum because the result of applying the model is not economically or environmentally zero. If anything, the result of implementing such a model should be a non-zero sum in favour of benefits over contributions.

For example, some alumina refineries believe their "gain" when reducing ARR (i.e., by transfering their liability by giving away or selling hazardous ARR) is greater than their "contribution" (i.e., to downstream beneficial reuse applications). They also mistakenly believe that by abrogating their responsibility and reducing their long-term liability (i.e., by altering the hazard equation in their favour as a result of ARR leaving their site) they should have little or no concern for what happens to ARR beyond their boundary gate. However, this one-sided industrio-centric approach is unsustainable; it assumes: "we win, and we don't really care about the rest".

Moreover, some refineries have adopted the attitude "we don't want to participate or be involved in downstream applications because we are not in the reuse business", although this attitude is changing. Notable examples include RUSAL, one of the world largest alumina producers with the support of the Russian Ministry of Science, who is currently testing large-scale ARR metal and rare earth recovery programs, and steel and concrete manufacturing [77], and the entire Indian alumina industry which is exploring ways to produce pig and cast iron and alumina-rich slag by plasma smelting from ARR [52].

In other words, it is not enough to say "we will work toward creating a sustainable future for ARR" (when in fact we only wish to rid ourselves of industrial waste); true sustainability and corporate responsibility require a far more active engagement in the wider sustainability landscape, with accountability and trust being the cornerstones of any such engagement.

Alumina refinery residue (1), derived from bauxite, is the first major input into this sustainability framework; everything in the model is predicated on ARR being supplied by an alumina refinery (A). The model also assumes the second main contributors to the process are innumerable modification technologies (2), which convert ARR into a benign, safe, useable but not inert raw material (the model assumes such methods and resultant ARR have been approved by relevant authorities for reuse in environmental, municipal and industrial applications).

These (sometimes patented) specialist processes often reside with technology solution and service providers (C).

Contributions to a sustainable future by an alumina refinery (3) include: ARR feedstocks; expertise in handling and transporting ARR; industry know-how and credibility; public relations capabilities; sponsorship and corporate philanthropy; corporate stewardship (as the generator and owner of ARR); infrastructure; and research and development capabilities. Such contributions fit squarely into the categories of corporate ethics, public responsibility and corporate social responsibility (CRS) and responsiveness, all of which are cornerstones of contemporary business sustainability practices and reporting [70]. The benefits to an alumina refinery from these contributions (4) include: reduced long-term ARR management and monitoring liability; reduced costs associated with maintaining and managing this liability, and therefore an improved balance sheet; remediation of their own contaminated site(s), including revegetation of ARR impoundments; increased kudos within industry, government and society; and goodwill.

Contributions to a sustainable future from government agencies (5) include: licensing and approval of environmental projects; funding for projects through government grants and remediation funds; public relations capabilities and inputs; data and statistics; compliance monitoring; and project sign-offs.

Governments also have an extensive inventory of abandoned and derelict ARR impoundment facilities, as well as abandoned and derelict environmental sites (particularly mine sites as a result of lapsed leases or defaults) which have reverted to government control and monitoring and for which governments are responsible.

Many of these sites (for example, the 1,322 Superfund sites in the United States [78] and the more than 50,000 orphaned, abandoned and derelict mine sites throughout Australia currently under government control [79]) are contaminated and need to be remediated. In many instances, modified ARR is well-suited to this task. Benefits to government agencies (6) from contributing to a sustainable future therefore include: reduced long-term liability; reduced costs associated with the long-term management and monitoring of derelict ARR impoundments and other contaminated sites; potentially reusable and valuable public land; better public relations and perception of government by society; and increased kudos and goodwill.

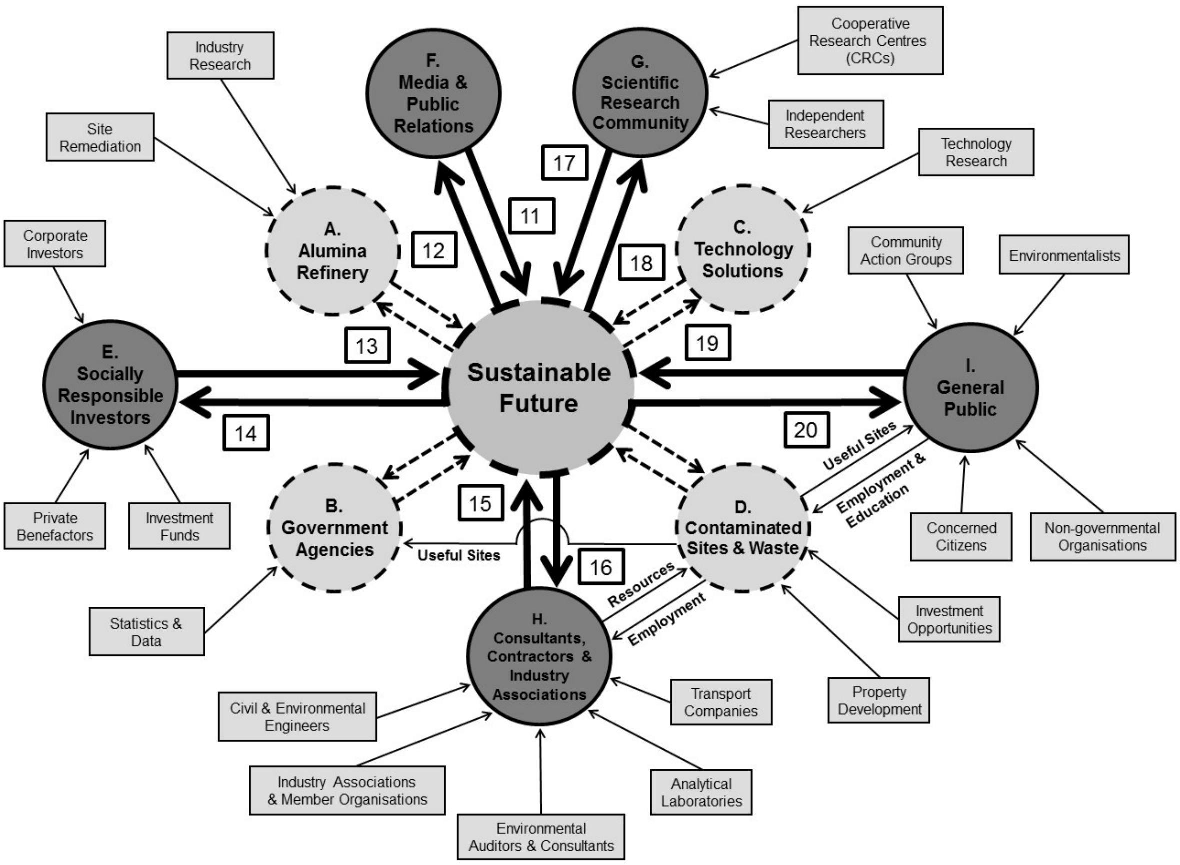

FIGURE 3. SUSTAINABILITY FRAMEWORK (PART B), IDENTIFYING KEY STAKEHOLDERS (WITH A FOCUS ON E-I) AND THEIR CONTRIBUTIONS TO AND BENEFITS FROM A SUSTAINABLE FUTURE.

Contributions to a sustainable future from technology solution and service providers (7) include: technological know-how, particularly in relation to economical and effective methods for modifying ARR in preparation for reuse applications; manufacturing and product expertise related to ARR product development, quality control and quality assurance, as well as knowledge about chemical blending and product packaging and delivery; a track record of success in marketing and applying modified ARR and a client base through which ARR can be applied; research capabilities and access to market data; case studies and other technical documentation, including materials safety data sheets (MSDS); plant and equipment suited to delivering ARR in a variety of forms, including as a slurry, a powder, or a pellet; application expertise, such as systems and process designs and controls for direct addition and filtration; and project management and implementation expertise.

Examples of technology solution and service providers working in metal recovery from ARR, environmental remediation and waste treatment utilizing ARR include Orbite Aluminae in Canada (www.orbitealuminae.com) and Virotec in Australia (www.virotec.com), with whom this author is affiliated [13, 80]. Benefits to technology solution and service providers from contributing to a sustainable ARR future (8) include: increased commercial opportunities and growth of business; access to grants and tenders; access to a wider range of environmental projects; project documentation and expanded technical capabilities; an expanded client base and commercial feedback; increased market capitalization; kudos within industry, government and society; and goodwill.

Contributions to a sustainable future from owners and/or managers of contaminated sites and waste producers, in addition to companies which may benefit from the reuse of ARR in cementitious product manufacture or other value-added applications (9), include: the effective treatment of a variety of gaseous, liquid and solid waste streams which are amendable to ARR recycling and/or reuse; reduced short- and long-term liability; reduced risk of non-compliance and fines from environmental agencies; and potential for waste “cost centers” to become “profit centers”. Owners and managers of contaminated sites and waste producers, as well as property developers, also provide investment opportunities to socially responsible investors and other companies particularly when, for example, they have a contaminated site whose ownership cannot be transferred until it has been remediated and signed off by government prior to resale.

Benefits to these types of companies (10) include: reduced (hazardous) waste; best industry practices for managing and treating waste and remediating contaminated sites; a raw material resource stream as a feedstock into other industrial products, such as concrete manufacture, bricks and blocks, ceramics, geopolymers, and mortars, grouts and aggregates; goodwill and kudos; reduced fines and other infringements; and government sign-offs and permanent site closures.

In Figure 3, the media (11), including online, print and broadcast media, both in the general communications space as well as via specific industry media channels, have an important role to play in contributing to and creating a sustainable future for ARR beneficial reuse. This role is becoming increasingly recognised as a key element in sustainability assessments of corporate responsibility, such as in the Dow Jones Sustainability Indices [81]. Contributions by the media include: factual and informative communication with the general public, government and industry on ARR reuse projects and other industrial waste reuse initiatives; factual and informative communication on sustainable development; as well as exchanges of information and opinion via online discussion forums and blogs. The media can benefit from a sustainable future (12) by receiving information on sustainable development initiatives and environmental projects from industry, government and the general public, thereby enhancing their intellectual capital and credibility in society, leading to greater goodwill toward the media.

Contributions to a sustainable future by socially responsible investors (13) include the opportunity to invest and participate in bankable, high-return environmentally and socially responsible investments in projects and companies which make a difference to the welfare of society; investments may be made by socially responsible investment funds, corporate and private investors, or private benefactors. Socially responsible investors benefit from a sustainable future (14) by securing a return on investment, enhancing their kudos and intellectual capital, and by participating in more socially and environmentally responsible investment opportunities.

Contributions to a sustainable future from environmental consultants and engineers, industry associations and independent third parties, such as civil contractors (15) include: participation in projects by engineering and environmental experts; significantly expanded client and colleague networks; analytical capabilities from certified laboratories; and transportation of products by transport companies. Benefits to environmental consultants and engineers, contractors, industry associations and independent third parties (16) include: greater industry expertise; increased employment and business opportunities; increased know-how and exposure to more projects; increased access to client and colleague networks through business synergies; increased business opportunities and an expanded client base; an increased member base for industry organizations; research and consulting opportunities; an opportunity to interact and work with other industry experts; kudos; and goodwill.

Contributions to a sustainable future from the scientific research community (17) include:

participation of independent researchers who can examine the merits and outcomes of sustainable development in ARR; participation of Cooperative Research Centers (CRCs), who have both extensive research skills and resources as well as significant ties to industry and government; access to international, peer-reviewed journals; and exposure to scientific and community projects and initiatives. Benefits to the scientific research community (18) include: access to a wide variety of environmental projects at the leading edge of science and technology; data on the environment and sustainable development; research expertise and capabilities; and increased knowledge capital.

Contributions to a sustainable future from the general public (19) include: participation of non-government organizations (NGOs), environmentalists, concerned citizens and community action groups; and clarification of the “public will” through community forums, workshops and town hall meetings. Benefits to the general public (20) include: increased access to useful public sites which had previously been of no value or a liability to society; reduced long-term environmental liability; reduced government liability; greater employment opportunities; and improved educational opportunities and increased knowledge of the environment.

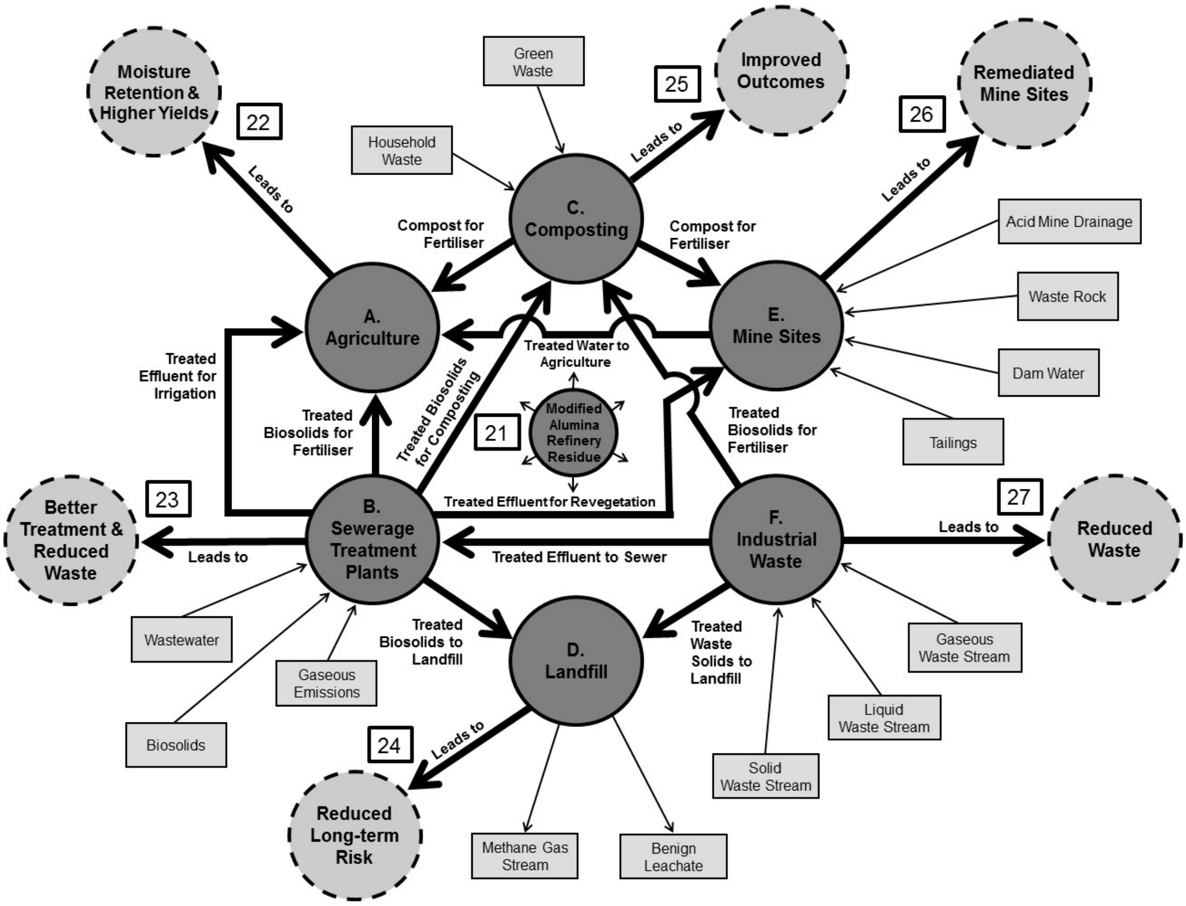

FIGURE 4. SUSTAINABILITY FRAMEWORK (PART C); BENEFICIAL REUSE POTENTIALS ACROSS SIX INDUSTRY EXAMPLES (A-F) WHEN CONSIDERING WASTE AFTER TREATMENT WITH MODIFIED ARR, HOW THE WASTE CAN BE REUSED BY ANOTHER INDUSTRY, AND WHAT SUSTAINABILITY OUTCOMES CAN BE EXPECTED FROM EACH INDUSTRY.

As noted above, there are a wide variety of industries and applications which can benefit from the reuse of modified ARR to treat waste and remediate sites and in some cases generate a reusable product from treated waste. These include: agriculture and horticulture; concrete manufacture and specialty cementitious product manufacture; sewerage treatment plants (STPs); composting facilities; landfill operations; mine sites and industries, such as lead and zinc smelters, gas works, timber preservation companies, quarries, manufacturing companies, and electroplating companies; dredging and land reclamation operations; coal seam gas operations and other oil and gas companies; bio-refineries; property developers; coal-fired power plants; steel plants; among others (12, 13, 80].

Figure 4 presents an example model of six industries (A-F) which can benefit from the application of modified ARR and/or products derived from it, and shows the potential interactions between them. Specifically Figure 4 suggests how a waste stream treated by ARR in one industry can be reused as an input for beneficial reuse by another industry. Figure 4 also summarizes the sustainable outcome for each industry as it relates to waste that has been treated with ARR. Figure 4 is predicated on the input of modified and/or neutralised ARR (21) into all six application areas, which are: Application A. agriculture; Application B. sewerage treatment plants; Application C. composting; Application D. landfills; Application E. mine sites; and Application F. industrial waste.

For example, when applied to agriculture (A), ARR has been shown to help soil retain moisture, help soil retain phosphate in a bioavailable form, promote plant growth through the addition of macro- and micro-nutrients, help soil sequester heavy metals which may be damaging to plants and trees, leading to improved crop yields as a result of greater moisture retention and healthier crops (22) [82]. Similarly, when applied to the treatment of sewage at STPs (B), ARR-derived products have been shown to reduce phosphate, nitrogen, biological oxygen demand (BOD), chemical oxygen demand (COD), heavy metals and *E.Coli* in municipal wastewater, as well as reduce the volume of biosolids and reduce the need for other chemicals, such as flocculants and polymers, when treating biosolids, leading to better treatment outcomes and reduced volumes of waste (23) [83, 84].

When ARR is applied to STPs, treated biosolids have reuse value as a fertilizer in agriculture and horticulture and at mine sites; treated biosolids can also be used in composting facilities and treated biosolids can be discharged to landfill without the long-term negative impacts at landfill sites associated with untreated biosolids. Moreover, treated municipal wastewater has potential value as recycled water for use in agriculture and composting facilities and at mine sites, although worrying research indicates that treated effluent and biosolids may not be as benign as first thought [e.g., 85].

When ARR is added to green and household waste used in composting (C), this application results in higher composting temperatures, more rapid degradation of compost, and a better quality compost (25) [86]. Treated compost can be used as a fertilizer in both agriculture and in mine site revegetation. When solid landfill waste (D), such as building and demolition waste, acid sulphate soils, contaminated soils and other solid waste streams like biosolids, are treated prior to disposal to landfill, these solids can either be reclassified (i.e., from “hazardous” to “low-level contaminated” or “low-level contaminated” to “clean material”, thereby reducing the cost of disposal) or can reduce the likelihood of long-term contamination, including the generation of contaminated leachate; under either condition, landfill waste can generate methane for reuse or resale (24) [87].

There are a wide variety of gaseous, liquid and solid waste streams generated at mine sites (E), including waste rock, tailings, wastewater, and fugitive emissions. When gaseous emissions are treated with modified ARR, for example, they do not result in the generation of greenhouse gases or pollution of the atmosphere. Depending on the type of waste, treated mine site wastewater can similarly be discharged to the local receiving environment, and sites can be remediated using ARR. Such rehabilitation programs also promote grass and tree growth, including revegetation of derelict mine sites, resulting in remediated mine sites and a cleaner, more sustainable society and environment (26) [88].

There are also a wide variety of gaseous, liquid and solid waste streams generated from most industries (F), many of which are amendable to treatment by modified ARR. For example, treated gaseous emissions do not result in greenhouse gas generation or pollution of the atmosphere [59]; depending on the type of waste, treated industrial wastewater can also be discharged to the sewer as “trade waste”, and some treated solids can be used in composting or go to landfill in a reclassified form, thereby reducing the cost of solid waste disposal. The result of this initiative for industrial waste is a general reduction in waste and a cleaner, more sustainable society and environment (27) [12, 37].

IV. CONCLUSION

Alumina refinery residue is a large-volume hazardous waste, which when modified can have beneficial physical and chemical properties. A number of important research studies have shown that ARR has significant reuse value [32, 33], including applications in wastewater and solids treatment, cementitious product manufacture, metal recovery, ceramics and contaminated site remediation. The alumina industry has gone some of the way to realizing this future by developing technology roadmaps which have begun to address the question of ARR, but further work is required. This conclusion becomes particularly true when considering that most roadmaps do not consider converting the chemical properties of ARR, thereby reclassifying it from a “hazardous” waste to a benign raw material, and only then reusing it in other industrial or environmental applications. The wisdom of not advocating the modification of ARR, while simultaneously proposing to reapply it, should be questioned by a concerned society.

Moreover, current industrio-centric roadmaps fail to engage all relevant stakeholders in, or fully consider the wider implications of, developing a sustainable future for ARR. Such a position results in less than credible conclusions and outcomes, and as a consequence the accountability, liability and trust of the industry have been called into question. While these conclusions and outcomes are unwarranted in most cases due to the noble efforts of the alumina industry, more can be done to build a consensus around issues related to the sustainable future of alumina refinery residue.

For these reasons, the present paper advances a framework which aims to embrace more sophisticated approaches to building a sustainable future for the beneficial reuse of ARR, including foundations in transparency, communication, education, and building stakeholder trust. While not highlighted specifically, the model assumes international standards, empirical research, and sustainability reporting [70] will together underpin the foundation of a sustainable future for alumina refinery residue reuse.

The model recognizes that stakeholder expectations and motivations will differ, but also recognizes that these differences should be acknowledged and clarified not shied away from; attempts to engage and understand differences should be encouraged, and attempts to comprehend the wider social and industrial landscape in which the program is designed are deemed critical for the success of reusing ARR in commercial and environmental applications. In effect, the framework is founded on building a network of concerned, educated and committed process owners, and is predicated on the assertion that commercial, regulatory and social alliances and synergies are best examined and exploited, rather than simply be driven by a roadmap from the alumina industry's point-of-view.

From an anthropological perspective, the new framework advocates more of an ethnographic path to modeling ARR reuse, encompassing both emic (i.e., an examination and implementation of ARR priorities and initiatives from within the group) and etic (i.e., an appraisal and acceptance of these priorities and initiatives from outside the group) approaches to building consensus and achieving the sustainability goals identified by the alumina industry, government and broader society.

In this sense, the current framework is designed to result in on-going learning and education by every stakeholder, with core supporters, drivers and process owners taking personal responsibility for leadership and key decisions and project implementation. We have seen this ideal adopted in the leadership shown by Alcoa in Australia and other refineries throughout the world, including RUSAL in Russia and Chinalco in China, where stakeholders actively seek to reuse alumina refinery residue more broadly throughout industry and society. It is in the interests of the entire international community and the long-term sustainability of the planet that efforts such as the Asia-Pacific Partnership for Clean Development and Climate and other like-minded initiatives, which explore and exploit beneficial reuse opportunities for alumina refinery residue, continue and flourish.

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