Travaux 46, Proceedings of 35th International ICSOBA Conference, Hamburg, Germany, 2 – 5 October, 2017.

Sustainability and Alumina Refinery Design

Peter-Hans ter Weer
Director
TWS Services and Advice, Bauxite and Alumina Consultancy, Huizen, The Netherlands
Corresponding author: twsservices@tiscali.nl

Abstract

Sustainability appears to be gaining more importance in the Bauxite and Alumina industry. Unfortunately, the relationship between sustainability criteria and their applicability to our industry may not always be obvious. In addition to some it may seem that implementing sustainability criteria would negatively affect economics. Sustainability in the Bauxite & Alumina industry in more general terms, including reporting guidelines, sustainable development goals, and corporate sustainability targets have been addressed in papers presented at the TMS Light Metals 2014 and 2015 conferences. This paper provides an overview of the subject and further explores the relationship between sustainability and some key design criteria for alumina refineries in the context of applicable Global Reporting Initiative (GRI) sustainability performance indicators.

Keywords: Alumina, alumina technology, sustainability, alumina refinery design.

1. Sustainability Reporting Guidelines – Mining & Metals Sector Supplement

Sustainability in the Bauxite & Alumina industry in more general terms, including reporting guidelines, sustainable development goals, and corporate sustainability targets have been addressed in papers presented at the TMS Light Metals 2014 and 2015 conferences [1, 2].

The GRI Reporting Guidelines are intended to serve as a generally accepted framework for reporting on an organization’s economic, environmental, and social performance [3]. They are used by many aluminium industry majors as standard for sustainability reporting although they are applicable to organizations of any size, type, sector, or geographic region.

Members of the International Council on Mining and Metals (ICMM)[1] are committed to reporting against the Mining and Metals Sector Supplement (MMSS). The mining and metals sector in this context includes exploration, mining, and primary metal processing (including refining, smelting, recycling and basic fabrication) and covers the project life cycle from development through operational lifetime to closure and post-closure.

The GRI Reporting Guidelines consist of Reporting Principles and Guidance, and Standard Disclosures (incl. Performance Indicators) which are broken down as follows:

Part 1. Reporting Principles and Guidance with three main elements of the reporting process:

- *Defining Report Content*;
- *Reporting Principles for Defining Quality*; and
- *Reporting Guidance for Boundary Setting.*

Part 2. Standard Disclosures specifying the base content that should appear in a sustainability report with disclosures on the following topics:

- *Strategy and Profile* setting the overall context for understanding organizational performance such as strategy, profile, and governance;

---

[1] Prompted by the Global Mining Initiative (GMI), the board of the metals industry’s representative organization, the International Council on Metals and the Environment agreed in 2001 to broaden its mandate and transform itself into the International Council on Mining and Metals (ICMM).

- *Management Approach* covering how an organization addresses a given set of topics to provide context for understanding performance in a specific area;
- *Performance Indicators* providing comparable information on the economic, environmental, and social performance of the organization.

The sections on Management Approach and Performance Indicators are organized by the categories social (“People”), environmental (“Planet”), and economic (“Profit”). Many of the major companies in the Bauxite and Alumina industry such as Rio Tinto, UC Rusal, Alcoa, Norsk Hydro and BHP Billiton report on their sustainability performance applying GRI reporting guidelines. Figure 1 shows the main subjects for each of the report sections.

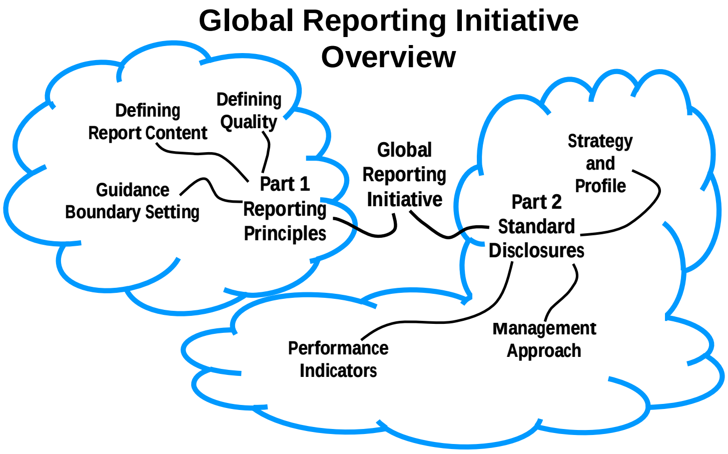

Figure 1. Global Reporting Initiative Overview.

Disclosures on Management Approach and Performance Indicators cover the following aspects:

- **Social**: *Labor Practices*; *Human Rights*; *Society*; and *Product Responsibility*.
- **Environmental***: Materials; Energy; Water; Biodiversity; Emissions, effluents, and waste; Transport; Products and Services; Compliance; and Overall.*
- **Economic***: Economic performance; Market presence;* and *Indirect economic impacts.*

Figure **2** shows the GRI Sustainability performance indicators broken down into major sub-indicators for a Bauxite Mine & Alumina Refinery project. See reference [3] for more details.

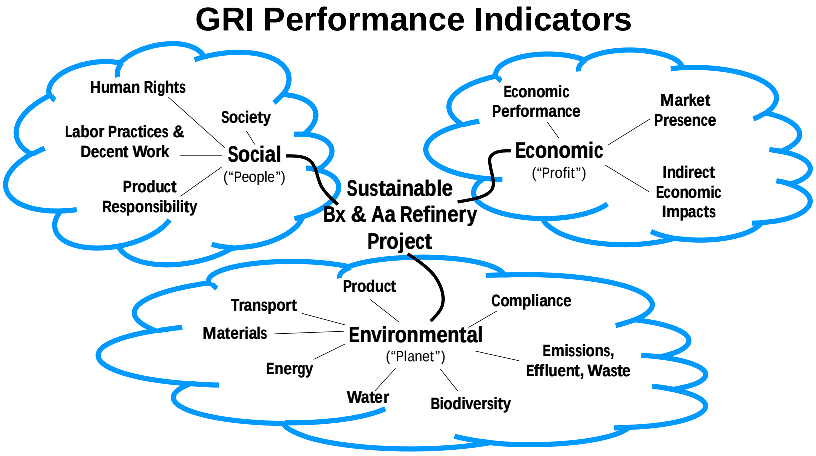

Figure 2. Global Reporting Initiative Performance Indicators.

2. Bauxite Feed Quality and Alumina Refinery Design

Bauxite feed quality influences alumina refinery design in several important ways, refer e.g. [1], [4], and [5], in other words the selection of a (range of) specific bauxite feed(s) affects several key refinery design criteria. Other design criteria however are chosen independent of bauxite feed quality or are based on considerations other than bauxite quality alone. Examples:

- **Some important process conditions** such as plant liquor productivity (yield);
- **Equipment technologies and layout design** for individual process areas (e.g. digestion, bauxite residue settling, precipitation) and the overall plant;
- **Location specifics** affecting plant design such as rainfall and net precipitation impacting on the method of residue disposal; the overall water balance playing an important in the design; country legal requirements with respect to emission standards, etc.;
- **Operating and maintenance philosophies** of project owners e.g. with respect to outsourcing activities, integration of maintenance and operational activities (multi-skilling), maintenance shop integration, etc.

3. Alumina Refinery Design Criteria, Benchmarks, and Sustainability Facets

As it is not possible to cover all alumina refinery design criteria, ten of the most important ones with benchmarks are shown in Table 1 with references to relevant GRI sustainability performance indicators [3], illustrating the relationship between these design criteria and sustainability. Refer to the Appendix for a description of the indicators used.

Table 1. Alumina refinery design criteria & sustainability performance indicators.

Refinery Design Criterion	**Target / Benchmark**	**Related GRI Performance Indicator**		
		Economic	**Environmental**	**Social**
1. Plant liquor Productivity/Yield	90^+ kg/m^3	EC1	EN1, EN3/EN5, EN4/EN7, EN6, EN16, EN20, EN22-MM3	MM11
2. Digestion Temperature	Refer [1], Bauxite Deposit criterion 5	EC1	EN3/EN5, EN16, EN20	
3. Digestion Technology	Slurry heating (“Single Streaming”)	As 1 (Liquor Yield)		
4. Bauxite Residue Settling & Washing Technology	High rate Thickeners (Settlers) / Washers	EC1	EN1, EN4/EN7, EN8, EN12-MM1, EN21, EN22-MM3	SO1, SO1-MM9, SO1-MM10
5. Heat Interchange Technology	Direct Heat Transfer	As 1 (Liquor Yield)		
6. Precipitation Technology	High solids tanks; Seed filtration; Inter-stage cooling; Green liquor split; Split seeding; Classification by hydrocyclones	As 1 (Liquor Yield)		
7. Power and Steam Generation	- Refer [1], Bx Deposit criterion item 5	EC1	EN3/EN5, EN16, EN20	
	- Gas as energy carrier (if available)	EC1	EN1, EN3/EN5, EN16	SO1
	- Off-gas de-sulphurisation		EN16, EN20	SO1
8. Calcination Technology	Stationary Calciner(s)	EC1	EN1, EN3/EN5, EN16, EN20	MM11

Refinery Design Criterion	**Target / Benchmark**	**Related GRI Performance Indicator**		
		Economic	**Environmental**	**Social**
9. Bauxite Residue Disposal Technology	Dry disposal in areas lined with clay or HDPE/PP seal, with underdrains; rehabilitation / re-vegetation afterward; sea water neutralization if applicable	EC1	EN4/EN7, EN12-MM1, EN21, EN22-MM3	SO1, (SO1-MM9), SO1-MM10
10. Overall Plant: **10A** Design & layout	*Conventional*: design accommodates future digestion / process units. *New approach*: dedicated design & layout for a specified production capacity Design for disassembly	EC1	EN1,EN3/EN5, EN4/EN7, EN12-MM1	LA1, SO1, (SO1-MM9), SO1-MM10
10B Production Capacity	*General*: depends on deposit size, plant considerations, economies of scale, infrastructure requirements, and market economics; *New approach*: compact capacity ~300 - 600 kt/y alumina	EC1, EC4	EN1,EN3/EN5, EN4/EN7, EN12- MM1, EN16, EN22 EN22-MM3	LA1, SO1, (SO1-MM9), SO1-MM10
10C Equipment and Additives	- Mechanical Seal Pumps - Low-NO_x burners - Mechanical vapor compression - Anti-scaling chemicals	EC1	EN1, EN3/EN5, EN20, EN22	
10D Control Equipment	Variable Speed Pump Drives	EC1	EN1, EN3/EN5, EN4/EN7, EN16	

4. Rationale Design Criteria

See reference [2] for more details.

4.1. Liquor Productivity (Yield)

See reference [6] for more details. Figure 3 illustrates that the caustic liquor in the alumina refining process is used in Digestion to dissolve alumina from bauxite at typically 145 – 150 °C for Low Temperature (LT) digestion plants processing Gibbsitic bauxites, and 240 – 270 °C for High Temperature (HT) plants using Boehmitic or Diasporic bauxites, while the dissolved alumina is crystallized from the solution in Precipitation through cooling and seeding. The “spent” solution is recycled to the front end. In other words, the higher the productivity of the liquor that is pumped around, the more cost effective the use of installed equipment. A key design objective of an alumina refinery is therefore to maximize alumina dissolved in the liquor in Digestion and alumina crystallized from the liquor in Precipitation, i.e. maximize the alumina produced per cubic meter of circulated liquor (liquor productivity).

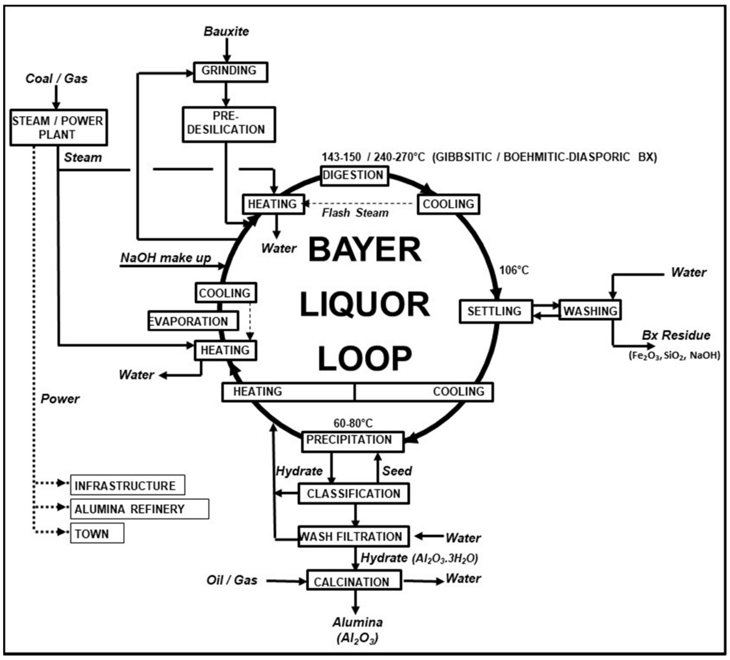

Figure 3. Alumina Refinery Process Schematic.

Increasing plant liquor yield has significant advantages such as increased plant capacity (lower capital cost per annual ton production capacity), the potential to improve alumina product quality, and lower specific (= per tonne Al_2O_3) consumption of energy, labor, maintenance materials, overheads, and other costs. Lower specific energy consumption also means a reduction of greenhouse gas emissions per tonne Al_2O_3, i.e. an improvement of direct environmental performance (refer [2] for more details). The focus for maximizing liquor productivity is mainly on precipitation yield because the reaction kinetics of precipitation (alumina tri-hydrate crystallization) are more difficult to control and enhance than those of the digestion reaction (dissolution of alumina from bauxite).

Precipitation yield increases are feasible of ~9 – 20 kg/m^3 for LT respectively 15 – 30 kg/m^3 for HT digestion plants raising typical current precipitation yield levels of ~65 – 75 kg/m^3 to a benchmark level of ~90 kg/m^3 and beyond, by implementing plant design adaptations (refer [6]). These yield increases are equivalent to energy savings of ~0.8 – 1.9 GJ/tA for LT respectively 1.8 – 3.5 GJ/tA for HT digestion plants, substantial compared with typical total steam and power energies of ~6 – 9 GJ/tA for LT respectively 8 – 11 GJ/tA for HT plants. Maximum achievable yield may be constrained by liquor impurities originating from the bauxite such as oxalate, carbonate and sulphate. Various impurity removal options may be considered to mitigate their effects.

4.2. Digestion Temperature

Mainly the consequence of bauxite quality, see reference [1], Table 1, item 5. Other process considerations could play a role as well e.g. related to the plant water balance.

4.3. Digestion Technology

Benchmark digestion technology is slurry heating (also referred to as “single streaming”) comprising heating of a combined bauxite/liquor slurry rather than heating the bauxite slurry separately and in parallel with the liquor, both of which are mixed only in the digester vessel (often referred to as liquor heating or “double streaming”).

Slurry heating has significant advantages over Liquor Heating: 1. Improved recovery of heat exchanged in the train of flash vessels and heat exchangers between the slurry exiting the last digester vessel being cooled down and the slurry to the digester vessel being heated up (put differently: a better heat balance between the flows being heated up and cooled down), i.e. lower energy consumption and lower capex per tonne Al_2O_3 produced; 2. The slurry flow through the heater tubes keeps them clean from scaling for a longer period of time due to the erosive effect of the slurry (scaling inhibitors may have a similar effect) – especially the heat exchangers operating at higher temperatures, i.e. plant on-line time improves (improving plant efficiencies) and less heater cleaning is required (i.e. lower steam consumption due to an overall improvement in heat transfer rates, and less waste, maintenance materials); and 3. An improved digestion yield potential (no Free Caustic (FC) constraint because the Gibbsite in the combined bauxite/liquor slurry rapidly dissolves during the passage through the heater tubes thus reducing the extraction liquor’s FC, meaning that the caustic concentration of the liquor to digestion and therefore the digestion liquor productivity can be significantly increased impacting positively on opex, capex and environment as discussed in item 1 above. Refer to [2] for further details.

Despite their slightly smaller heat transfer coefficient, vertical heat exchangers are overall more attractive for slurry heating than horizontal heaters because they prevent solids blocking up the tubes and they are easy to maintain using an overhead crane. An alternative, notably in the case of HT digestion, is the use of tube digestion employing jacketed pipes for heat transfer [7].

Although not discussed here as separate item the technology selection for bauxite crushing and grinding should be driven primarily by the requirement to handle the range of expected bauxite feed ore characteristics (e.g. top size ROM ore, ore “stickiness”, strength, targeted grind size, etc.). With single streaming digestion, closed circuit grinding is generally preferred whereas open circuit grinding is more suited to double streaming digestion. Pre-desilication of the slurry after the grinding mills at high solids density (50 % – 55 % m/m) and ~100 °C is benchmark.

4.4. Bauxite Residue Settling and Washing Technology

Bauxite residue slurry discharging from Digestion is separated in a Solid/Liquid separation (decantation) step and the residue (“red mud”) is washed counter-currently with water to recover dissolved alumina and caustic soda values in the solution adhering to the residue solids (refer also [1], section 3.2, criterion 4B). High rate thickening and washing technology (incl. the use of appropriate flocculants, and the recycle of thickener overflow to dilute the tank feed) is benchmark and has several advantages over conventional large-diameter thickeners, resulting in lower capex and opex, a smaller acreage required for the residue settling, and reduced alumina losses. Refer to [2] for further details.

To maximize recovery of caustic soda and alumina values and to further increase solids in the residue to disposal, thus minimizing residue disposal acreage, the inclusion either of bauxite residue filtration downstream of the wash train or of a “super-thickener” or “deep thickener” at the storage disposal site may be considered. Although not mentioned separately here, a proposed plant design modification encompasses by-passing or excluding the Security Filtration process area which has economic (capex, opex) and environmental (scale, cleaning liquor, etc.) advantages [8].

4.5. Heat Interchange Technology

Direct heat transfer (e.g. plate Heat Exchangers) rather than indirect heating (e.g. by vacuum flash steam) in the Heat Interchange area between liquor to precipitation and spent liquor returning to digestion has several advantages resulting in a potential for higher precipitation yield and thus lower capex, opex, energy consumption, and greenhouse gas emissions per tonne Al_2O_3 produced. Refer to [2] for further details.

4.6. Precipitation Technology

In addition to the process adaptations for this area indicated in [6], the following features are included in the design of a benchmark precipitation area:

- For yield increase reasons: Precipitation tanks designed for 600-800 kg/m^3 solids and more (currently typically ~400-600 kg/m^3), including appropriate agitators; and use of additives (e.g. crystal growth modifiers);
- For improved product quality control: pregnant liquor feed split (control of soda inclusion) and split fine / coarse seeding (control of particle size and strength); and separate agglomeration (focus: quality control) and growth (yield increase) sections;
- Product / seed classification by hydrocyclones rather than gravity classifiers for reasons of both yield and product quality control improvement.

The advantages of benchmark technology in the precipitation area are covered in item 1 above (Liquor Productivity).

4.7. Power and Steam Generation

See reference [1], section 3.2, criterion 5, for more information. Using gas as energy carrier enables the use of gas turbines in combination with co-generation of steam and power. A gas-fired co-generation facility comprises a gas turbine linked to an electrical generator (producing power required by the alumina refinery), and a heat recovery steam generator recovering waste heat from the gas turbine exhaust which is used to produce steam for the refinery, with surplus electricity exported to the local power grid. This electricity has about one-third the emissions intensity of coal-fired electricity. This type of co-generation technology or ‘combined heat and power’ technology provides greater conversion efficiencies than conventional generation methods, by using heat that would otherwise be wasted and reducing greenhouse gas emissions. The result is a reduction of about 26% in the operation’s greenhouse gas intensity compared with electricity and steam generated from coal (refer [9] - Yarwun). When applicable: off-gas de-sulphurisation to be included to reduce SO_2 emissions.

4.8. Calcination Technology

Alumina hydrate from precipitation is washed and calcined to smelter grade (“sandy”) alumina for benchmark performance of aluminium smelters. Calcination in stationary calciners is benchmark, incorporating effective heat recovery from combustion gases (i.e. improved opex and less greenhouse gas emissions per tonne Al_2O_3 produced), and improved product quality control over rotary calciners. Energy consumption is ~2.7 − 3 GJ/tA [10]. The selection of energy carrier (natural gas, coal gas, heavy fuel oil) should be based on an economic evaluation of availability, price, and capital cost (coal gas fired calciners require coal gasification and calciner adaptations), environmental footprint (CO_2 emission, coal fly ash), and product quality (e.g. with respect to coal impurities ending up in the product alumina).

4.9. Bauxite Residue Disposal Technology

Both so-called “wet” and “dry” residue disposal technologies are applied worldwide, however thickened tailings / “dry” disposal (deposition of bauxite residue layer by layer) is generally considered benchmark, among others for cost and environmental reasons (e.g. acreage limitation, residue area control, impact on the environment). Depending on residue characteristics and local conditions (e.g. rainfall), dry stacking (residue slope formed “naturally”) or slope deposition (discharge onto a slope with an angle equal to the residue’s natural angle of repose) may be more appropriate.

Dry disposal requires the formed layer of residue to consolidate by solar drying (assisted by so-called “amphirolls” to plough the residue promoting the drying process) prior to the deposition of the next layer on top. Rotating between residue discharge points with intervals achieves this. Perimeter dikes of a Residue Disposal Area (RDA) prevent contamination of the surrounding environment; when an area is filled up a next lift is created on top. An RDA is lined with clay or HDPE/PP to prevent seepage of alkaline solution into the ground water. The lining is covered with a layer of sand housing a network of porous pipes to collect the alkaline drainage from the residue which is returned to the refinery. Once an RDA has been totally utilized, it may be capped with clay and covered with top soil for re-vegetation. The run-off from a de-commissioned RDA is returned to the process until its composition is acceptable for discharging into the environment. Thickened Tailings / “Dry” Disposal of bauxite residue has several advantages over wet disposal (refer [2] for further details), and various technologies are in use in the world e.g. in Brazil, Australia, Jamaica, and Ireland.

Sea water neutralization followed by dry stacking may be applicable in case a refinery is located close to the sea: magnesium and calcium components in sea water neutralize alkaline constituents of the bauxite residue. The neutralized slurry is subsequently thickened to a high solids concentration, and the saline overflow is returned to the sea. The thickener underflow is discharged to a conventional dry stacking area. Control of the rain water runoff from the storage area (solids, pH, heavy metals) is required because this cannot be recycled to the refinery and needs discharging into the sea. Advantages of sea water neutralization include a significant reduction of long term liability and management issues related to a storage area and its rehabilitation (refer to [2] for further details).

4.10.1. Overall Plant Design and Layout

Conventional plant designs aim at accommodating additional future digestion and other process units, i.e. plant design incorporates provisions for future expansions resulting in significantly increased capital cost of the design / initial production capacity thus negatively affecting economics [11].

A new approach is based on a dedicated refinery design and layout for a specified production capacity, i.e. tailored to the equipment and infrastructure requirements (such as earth works, power, water supply, piperacks, roads, cable trays, etc.) of the selected production capacity [12], [13]. This enables optimizing plant layout e.g. with respect to positioning similar equipment close to each other, and the use of common spare equipment. And it results in a focus on a “lean” design positively impacting on commodity volumes: for the same production capacity, commodity volumes for steel, concrete, piping, etc. for a greenfield plant designed this way are like that of a brownfield expansion of an existing refinery. In other words, per annual tonne Al_2O_3 production capacity significantly lower amounts of commodities are required for greenfield projects compared with conventional designs. Figure 4 provides an example for a 400,000 t/year plant capacity. Dedicated design also excludes provisions for future expansions (which must be based on their own economic justification). As commodities represent a significant element of refinery capex, this results in a reduction of capex (indicatively by ~10%) and opex, more effective use of available space for the plant, and avoidance of unnecessary energy consumption (e.g. pumping power) and maintenance costs.

This approach is independent of preferred / selected refinery technologies, and includes the following main design and layout elements, some of which can be observed in Figure 4 (see reference [13] for further details):

- Digestion and Evaporation areas positioned next to each other, using similar equipment, and sharing a common spare bank of Heat Exchangers;
- Bauxite residue settler and washers placed in a horseshoe shape;
- Filters for hydrate to calcination, for fine seed to precipitation and for oxalate removal located in one building;
- Last two on-line precipitation tanks operating with purpose designed agitators allowing varying slurry levels;
- Facility in the center of the plant accommodating plant control room, operations offices, and plant laboratory;
- Equipment cleaning / de-scaling represents a key role, including mechanical cleaning of the precipitator tanks; Advantages: no major plant volume / plant liquor caustic concentration changes required, i.e. better control of both, allowing a narrower "safety range" for liquor super-saturation target; put into another context: the controls of precipitator cleaning and plant volume / liquor concentration have been separated; other advantages: no further spare precipitators are required (or tanks of similar size), and steam required for caustic cleaning purposes is saved;
- Hydrate storage facility between the precipitation and calcination areas ensuring that hydrate production (Bayer Loop) operates independently from the calcination operation.
- The operational period of an alumina refinery is generally substantial (50+ years). Its disassembly costs are significant and in some countries project owners are legally bound to accrue financial reserves for a refinery's final disassembly. If an alumina plant is designed for disassembly from the outset, disassembly costs could be significantly lowered with little effect on the project's initial capex. In addition, this approach is environmentally more attractive.

An overall process plant layout for a compact 400 kt/y alumina refinery based on the dedicated design approach such as shown in Figure 4 illustrates that the approach leads to a compact, simple and efficient layout with a small Bayer loop, demonstrating that the goal to tailor the design to the equipment and infrastructure requirements of the specified production capacity is achievable: most of the infrastructure is integrated in the process areas and only limited infrastructure is required outside those [13].

4.10.2. Plant Production Capacity

Key selection criteria to decide on the capacity of an alumina refinery usually include bauxite deposit size, plant considerations (e.g. facilities with one or more "trains"), economies of scale, infrastructure requirements (both "external" such as port (extension), consumables & alumina transport, and personnel housing; and "internal" e.g. piperacks, power distribution, water supply, buildings), and market economics.

A new Dedicated Compact Sustainable (DCS) approach applies a dedicated and sustainable design to a compact refinery of ~300 − 600 kt/y alumina, resulting in a project with a simple and limited scope [13]. As a result, plant capital cost decreases significantly, indicatively by another ~10 % on top of the capex decrease from the dedicated-design approach mentioned in the previous item [13].

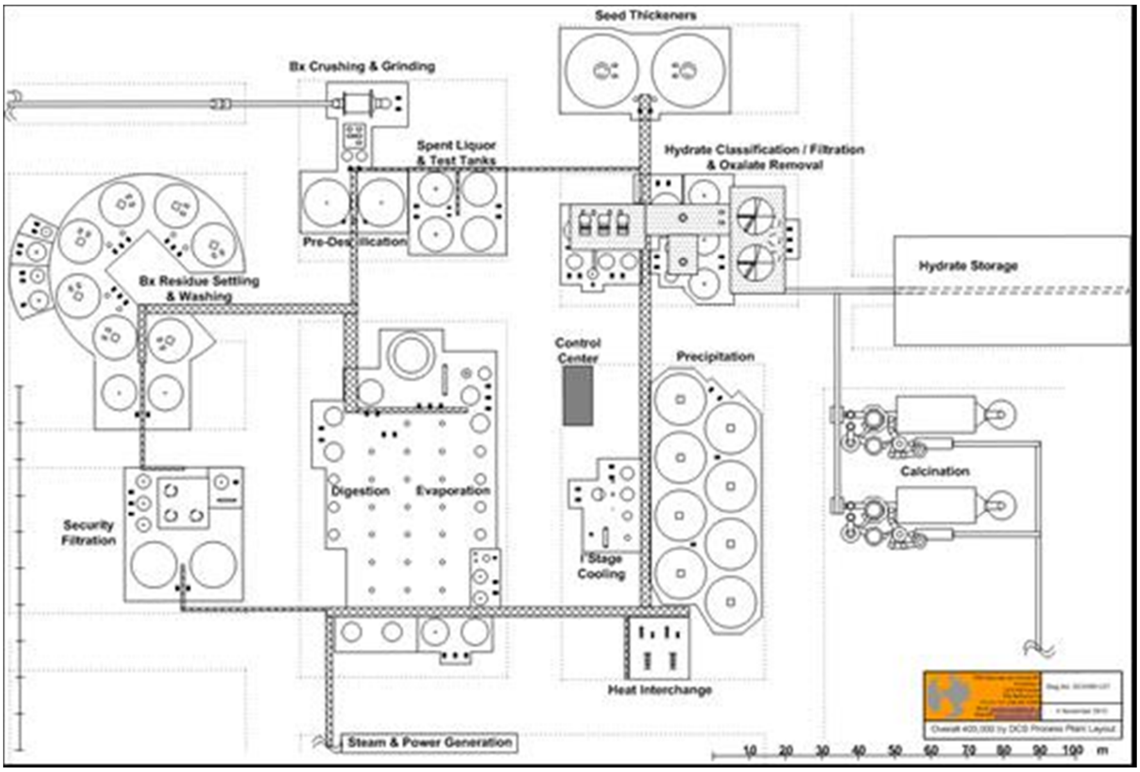

Figure 4. Dedicated plant layout for 400kt/y alumina refinery.

For acceptable economics of the overall project, infrastructure capital should be limited. At the same time, such a project has only limited infrastructural requirements, especially if located close to an existing port. Advantages of the DCS-approach:

- Lower project capex enables development of bauxite & alumina projects by smaller companies without a need to form (complex) joint ventures, thus increasing the number of companies potentially interested in developing bauxite deposits; Competition increases, resulting in a more efficient use of (capital and bauxite) resources;
- Small and simple projects carry less risk; require less time to develop, construct & start up, positively impacting on economics;
- Long term alumina refining projects based on this approach require a small deposit (~40 million tonne would support a 400 kt/y project for 30 years), i.e. worldwide the number of deposits lending themselves to development increases, improving the use of resources and employment opportunities;
- This approach may also be applied to the development of part of a large deposit;
- In some cases, this approach could enable value creation through alumina refining rather than limiting a project to bauxite export sales which is attractive to the host country and to companies developing bauxite & alumina projects;
- An adapted version of the approach may in some cases enable bauxite deposit development even in locations with little existing infrastructure, albeit at a larger than compact scale (e.g. at ~1.5 – 1.6 Million t/y alumina production capacity);
- This approach is independent of selected refinery technologies.

4.10.3. Equipment and Additives

Equipment related design criteria include mechanical seal pumps instead of pumps with water-purged glands (less process dilution, less infrastructure, lower water consumption), low-NOx burners in power & steam generation (improved NOx emissions), and mechanical vapor compression in case of low-cost power from cogeneration (if there is no excess steam to be condensed in condensing turbines). Additives-related design criteria include using appropriate chemicals e.g. anti-scalants in Liquor Evaporation.

4.10.4. Control Equipment

variable speed pump drives instead of control valves for level control, flow control, etc. This reduces pumping energy, improves erosion and cavitation (i.e. less wear). In other words, lower opex, capex and greenhouse gas emissions.

5. Conclusions

Table 1 and the rationale behind it illustrate that some of the key criteria of alumina refinery design comprise the three pillars of sustainable development: economic ("profit"), environmental ("planet") and social (People") aspects. In other words, sustainability in the context of refinery design can be qualified and quantified once bauxite characterisation test work has been completed and project size decided. Table 1 also illustrates that economic and environmental aspects are two sides of the same coin, while social aspects are often also integral to refinery design. Stated differently: optimum refinery design from an economic perspective is (long term) often also the most attractive environmentally (and to some extent socially).

Most of the criteria of Table 1 are consistent with the issues for the upstream steps of the aluminium value chain from the Responsible Aluminium Scoping Phase RASP (e.g. bauxite residue management; SO_2, CO_2, and NOx emissions; energy efficiency, and caustic soda management for alumina refining – refer [14]). And most are also in accordance with the long-term / strategic company targets of the industry majors. See reference [1], section 2.4.

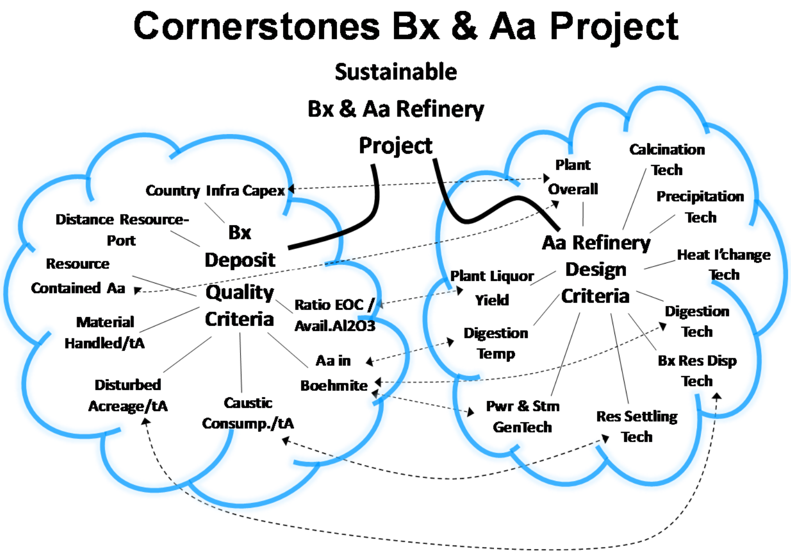

Figure 5. Two cornerstones of a Sustainable Bauxite & Alumina Project and interactions.

Interestingly the above conclusions are also consistent with those of the paper on sustainability and bauxite deposits [1]. This is a key finding because bauxite deposit quality criteria and alumina refinery design criteria are two cornerstones of a sustainable Bauxite & Alumina project, and affect each other as illustrated in Figure 5.

Summarizing it appears that sustainability is playing a growing role in future decisions on the design of brownfield and greenfield (bauxite and) alumina projects. Illustrations of that trend include: a continuing push to increase precipitation liquor yield (item 1, Table 1); finding new approaches and technologies to improve plant and process efficiencies (e.g. item 10), including a growing thrust to improve bauxite residue disposal (items 9 and 10); and developing more sustainable energy supplies (e.g. Integrated Solar Combined Cycle allowing a power plant to generate solar power when the sun is shining and to switch over to natural gas / coal when solar power cannot be produced).

6. Appendix – GRI Performance Indicators used in Table 1

Note: “MM” denotes Mining & Metals sector specific.

Performance Indicator	**Economic (“Profit”)**	**Aspect: Economic Performance**
	EC1	Direct economic value generated and distributed, including revenues, operating costs, employee compensation, donations, and other community investments, retained earnings, and payments to capital providers and governments.
	EC4	Significant financial assistance received from government.
Performance Indicator	**Environmental (“Planet”)**	**Aspect: Materials**
	EN1	Materials used by weight or volume.
		Aspect: Energy
	EN3	Direct energy consumption by primary energy source.
	EN4	Indirect energy consumption by primary source.
	EN5	Energy saved due to conservation and efficiency improvements.
	EN6	Initiatives to provide energy-efficient or renewable energy based products and services, and reductions in energy requirements as a result of these initiatives.
	EN7	Initiatives to reduce indirect energy consumption and reductions achieved.
		Aspect: Water
	EN8	Total water withdrawal by source.
		Aspect: Biodiversity
	EN12 - MM1	Amount of land (owned or leased, and managed for production activities or extractive use) disturbed or rehabilitated.
		Aspect: Emissions, Effluents, and Waste
	EN16	Total direct and indirect greenhouse gas emissions by weight.
	EN20	NO, SO, and other significant air emissions by type and weight.
	EN21	Total water discharge by quality and destination.
	EN22	Total weight of waste by type and disposal method.
	EN22 - MM3	Total amounts of overburden, rock, tailings, and sludges and their associated risks.
Performance Indicator	**Social (“People”)**	**Aspect: Labor – Employment**
	LA1	Total workforce by employment type, employment contract, and region.
		Aspect: Society – Community
	SO1	Nature, scope, and effectiveness of any programs and practices that assess and manage the impacts of operations on communities, including entering, operating, and exiting.
	SO1 - MM9	Sites where resettlements took place, the number of households resettled in each, and how their livelihoods were affected in the process.
	SO1 - MM10	Number and percentage of operations with closure plans.
		Aspect: Product – Customer Health and Safety
	MM11	Programs and progress relating to materials stewardship.

7. References

1. P.J.C. ter Weer, Sustainability and bauxite deposits, paper presented at *Light Metals 2014*, San Diego, USA, pp 149-154.
2. P.J.C. ter Weer, Sustainability and alumina refinery design, paper presented at *Light Metals 2015*, Orlando, USA, pp 137-142.
3. Global Reporting Initiative (website https://www.globalreporting.org/resourcelibrary/G3-English-Mining-and-Metals-Sector-Supplement.pdf), RG & MMSS, Sustainability Reporting Guidelines & Mining and Metals Sector Supplement, RG Version 3.0/MMSS Final Version.
4. V.G. Hill and R.J. Robson, The Classification of Bauxites from the Bayer Standpoint, paper presented at *Light Metals 1981; Essential readings in Light Metals, Volume 1*, pp 30-36.
5. A.N. Adamson, E.J. Bloore, and A.R. Carr, Basic Principles of Bayer Process Design, *Extractive Metallurgy of Aluminum 1963, Essential readings in Light Metals, Volume 1,* pp 100-117.
6. P.J.C. ter Weer, Relationship between Liquor Yield, Plant Capacity Increases, and Energy Savings in Alumina Refining, *Journal of Metals, Vol.66, Issue 9 (2014)*, pp 1939-1943, DOI: 10.1007/s11837-014-1069-x.
7. R. Kelly, M. Edwards, D. de Boer, P. McIntosh, New Technology for Digestion of Bauxites, paper presented at *Light Metals 2006*, San Antonio, USA, pp 59-64.
8. P.J.C. ter Weer, Redundancy of Security Filtration, paper presented at *Light Metals 2010*, Seattle, USA, pp 113-118.
9. Website http://bauxite.world-aluminium.org/refining/case-studies/yarwun.html.
10. L. Perander et al., Application of Optimized Energy Efficient Calcination Configuration, paper presented at Alumina Quality Workshop 2012, Perth, pp 371-377.
11. P.J.C. ter Weer, Greenfield Dilemma - Innovation Challenges, paper presented at *Light Metals 2005*, San Francisco, USA, pp 17-22.
12. P.J.C. ter Weer, New Development Model for Bauxite Deposits, paper presented at *Light Metals 2011*, San Diego, USA, pp 5-11.
13. P.J.C. ter Weer, New Development Model for Bauxite Deposits – Dedicated Compact Refinery, paper presented at *Light Metals 2013*, San Antonio, USA, pp 97-102.
14. Responsible Aluminium Scoping Phase, Main Report, Track record, December 2010.