AA01 - Complementary Advantages of Steel-Alumina Joint Venture to Achieve Efficient and Low-Carbon Development

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Abstract

This paper assesses potential synergies between the co-location of an alumina refinery and a steel mill in coastal China. Steel mills generate excess steam and blast furnace gases, which can be used by alumina refineries, while alumina refineries can supplement raw material supply to blast furnaces in the form of iron concentrate in red mud waste. Co-location can also reduce capital expenditure because the alumina refinery can avoid the cost of building a dedicated thermal power plant or gas station, which not only reduces investment costs, but also reduces both the carbon footprint and the emission of harmful gases. Iron can be extracted and concentrated from alumina refinery red mud for blending into the steel mill feed, which reduces raw materials costs, as well as reducing the cost and volume of red mud to be stored in red mud dams. Furthermore, a co-located steel mill and alumina refinery could share port resources, further reducing both capital and operating costs. In order to maximise the co-location opportunity, capacity matching of both facilities must be taken into consideration.

Keywords: Alumina refinery, Steel mill, Steel-alumina joint venture.

1. Introduction

China's steel output ranks first in the world, however domestic iron supply is of low grade and high cost, so the proportion of iron ore imports is high. In order to minimise transport costs, many of China's steel mills are located close to port areas to be in close proximity to imported iron ore stocks. At present, many port areas along China's coast have steel mills.

Domestic bauxite faces similar resource depletion challenges, as local grades decline and processing costs increase. As a result, the proportion of imported bauxite processed in domestic alumina refineries is also increasing. Replicating the steel mill model, in order to be close to imported raw materials stocks and to minimise transportation costs, China's alumina refineries are also relocating to port areas. As they do, most are finding they have steel mills already located close by. This presents an opportunity to take advantage of synergies between operations, both from a technical and from a geographical perspective.

A 'steel-alumina' joint venture is a collaboration between a steel mill and an alumina refinery in China to achieve complementary benefits to improve efficiencies and reduce the costs of both operations. The alumina production process requires a large steam load and produces a large amount of red mud discharge. Importantly, if bauxite contains a high proportion of iron, after extracting the alumina in the refinery, the iron oxide content of the red mud will be concentrated. The iron ore reduction process consumes large amounts of iron ore and generates a large amount of gas.

New alumina refineries can take advantage of existing port infrastructure originally built for the steel mill to offload and store bauxite. New alumina refineries therefore avoid the costs associated with building new port infrastructure, which reduces project investment and improves the overall utilization rate of the existing wharf.

Waste heat (or gas) generated during the steel production process can be used to generate electricity through boilers, while also supplying steam to the alumina plant, which improves the efficiency of heat utilization. The red mud generated during the alumina refining process can be used to produce iron concentrate by magnetic separation. It can then be blended with imported iron ore, which not only reduces raw materials costs for steel mills, but also reduces the volume of red mud discharge.

2. Coordination of Steel-Alumina Joint Venture

2.1 Steam Demand for Alumina Production and Iron Concentrate Output

Most alumina refineries built in coastal regions process imported ore. A typical coastal refinery processing imported Guinean bauxite and using a low-temperature (LT) digestion process, would have a design scale of 2 × 1.5 Mt/y alumina trains (or modules), with an hourly flow rate of alumina of approximately 360 t/h, and with one tonne of alumina requiring approximately 1.8 tonnes of steam. The steam demand flow rate is therefore approximately 648 t/h, and the annual steam demand would be approximately 5.4 Mt/y.

The corresponding discharge of red mud is approximately 396 t/h (dry red mud), with an annual discharge of 3.3 Mt/y. The estimated composition of red mud is shown in Table 1:

Table 1. Composition of red mud

Composition	Al_2O_3	SiO_2	Fe_2O_3	TiO_2	LOI	Other	Total
%	16.59	4.21	56.33	4.47	8.67	7.81	100

Once the magnetic separation process is applied to the red mud, the resultant composition of iron concentrate would be approximately 45 % iron, as shown in Table 2:

Table 2. Composition of iron concentrate

Composition	Al_2O_3	SiO_2	Fe_2O_3	Na_2O	CaO	LOI	Other	Total
%	10.80	3.26	65	1.98	1.29	5.57	12.1	100

The yield of iron concentrate is therefore around 50 %, and the annual yield of iron concentrate in the alumina plant is approximately 1.65 Mt/y.

2.2 The Current Situation of Waste Heat Utilization in Steel Mills and the Use of Red Mud Iron Concentrate

Taking a typical steel mill with an annual output of 10 Mt/y of steel as an example, the waste heat blast furnace gas volume is estimated to be 1.28 million Nm^3/h, corresponding to a steam output of around 1,577 t/h, which is well-suited to meet the demand for a 3 Mt/y alumina operation.

Iron concentrate in red mud has a low iron content and high impurity content, which is unsuitable for direct ironmaking. This material needs to be blended with high-grade iron ore. The proportion of iron concentrate with an iron content of 45% to 48% is only around 3-5%, while the annual demand for iron ore in steel making plants with an output of 10 Mt/y is approximately 16 Mt/y, corresponding to a red mud iron concentrate requirement of between 480 000 and 800 000 t/y.

2.3 Coordination of Steel-Alumina Joint Venture

Steel mills and alumina refineries have a good level of industrial complementarity in terms of demand and output of raw materials and energy. However, there are some significant challenges in coordinating and matching the scale of the production capacity for each. Taking the alumina refinery with a capacity of 3 Mt/y as an example, the steam demand can be fully matched with the iron and steel mill with a capacity of 6.5 Mt/y, although from the perspective of matching the consumption of red mud iron concentrate, the capacity of 3 Mt/y of alumina is about 3.3 Mt/py of red mud, while the capacity of red mud iron concentrate is around 1.65 Mt/y, which would be ideally matched to a steel mill with a capacity of between 20 and 34 Mt/y. There is a significant mismatch in production requirements, making it difficult to maximise red mud iron concentrate into the steel mill.

3. Economic Analysis

3.1 Investment Analysis of Alumina Refinery

By co-location, the steam load required by the alumina refinery can be fully provided by the steel mill without the need for a dedicated thermal power plant. Taking the 3 Mt/y alumina refinery as an example, the corresponding investment in a dedicated thermal power plant is estimated at approximately RMB850 million (120 million USD). Therefore, taking the joint venture approach, the investment in alumina refining can be reduced by around RMB850 million.

The investment in the red mud iron concentrating process is estimated at RMB150 million (21 MUSD). After reducing the amount of red mud by red mud iron concentrating, the volume of red mud sent to the red mud dam can be proportionally reduced. The cost to build a red mud dam is greatly affected by the terrain and is therefore difficult to estimate. However, we can assume that some of the investment in the red mud iron concentrating process will offset the cost of the red mud dam and therefore not greatly affect the investment.

3.2 Cost-Benefit Analysis of Alumina Refinery

Taking a similar example in a specific port location in China, when operating a thermal power plant, the total cost of steam is estimated at 140–150 RMB/t (19–21 USD/t) excluding taxes. According to data provided by one Chinese domestic alumina refinery, steam provided by the steel mill is suitable for use by the refinery. According to local electricity prices in Hebei Province converted into corresponding steam power generation costs, the price of steam supplied by steel mills is around 120 RMB/t (16.5 USD/t), then the tax exclusive price is 110.09 RMB/t (15.1 USD/t). In other words, the price to the alumina refinery of steam supplied by a steel mill would be around 30–40 RMB/t (4–5.5 USD/t) lower than that of a dedicated thermal power plant. For an alumina refinery with a production capacity of 3 Mt/y, with annual steam consumption of around 4.5 Mt/y, operating costs can be reduced by about RMB90-135 million (12.4–18.6 MUSD) per year.

The process of concentrating iron from red mud uses magnetic separation, which is a physical separation process. The major cost items in the production of iron concentrate are electricity, circulating water, and steam. The cost of iron concentrate is around 60 RMB/t (8.3 USD/t) and the price for iron concentrate with 45 % iron content is estimated at 150 RMB/t (20.7 USD/t). Therefore, the profit margin of iron concentrate is estimated at 90 RMB/t (12.4 USD/t), with a direct annual economic benefit estimated at RMB175 million (24 MUSD).

In addition to these economic benefits, red mud iron separation can also bring significant environmental benefits. The example alumina refinery used above could reduce red mud emissions by 50 % every year, about 1.95 Mt/y. It means that during the production of alumina, 3.9 Mt/y of red mud were produced, and 1.95 Mt/y of iron concentrate were separated through magnetic separation. This part of iron concentrate will be used as raw materials in steel mills, and only 1.95 Mt/y of red mud will be stored in the yard. While reducing the solid waste discharge in the alumina refining process, it can significantly extend the life of the red mud storage dam, reducing the difficulty in project land approvals, and also reducing the impact on the environment.

3.3 Improving the Efficiency of the Steel Mill

Blending red mud iron concentrate with high-grade iron ore can also reduce the cost to produce steel. Assuming a price for 62 % iron ore of 850 RMB/t (117 USD/t), and assuming a 45 % red mud iron concentrate is blended at a rate of 3 %, the iron grade falls to 61.5 %, the equivalent price falls to 829 RMB/t (114 USD/t) and the unit consumption of ore is 1.613 tonnes and 1.626 tonnes, respectively. The raw material cost per tonne of product can be reduced by about 23 RMB/t (3.2 USD/t). Based on a steel mill production capacity of 10 Mt/y, annual cost savings of approximately RMB230 million per year (31.7 MUSD/y) could be achieved (Table 3).

Table 3. Comparison of steel mill Costs.

	Iron ore	**Red mud iron concentrate**	**Blend**
iron content (%)	45	62	61.5
Price(RMB/t)	850	150	829
Price (USD/t)	116.87	20.62	113.98
Consumption (t/t Fe)	1.613		1.626
Cost (RMB/t Fe)	1371.05		1347.95
Cost (USD/t)	188.51		185.33

4. Case Study Analysis of Steel-Alumina Co-location

Consider an alumina refinery located in Hebei Province producing SGA with a design capacity of 2.4 Mt/y in Phase I and 1.2 Mt/y in Phase II, with a total capacity of 3.6 Mt/y which is separated by a road from a steel mill with a capacity of 5 Mt/y.

The total steam loading required in the production process can be provided by the steel mill, thus the alumina refinery can avoid building a dedicated thermal power plant.

Annual production of red mud from this refinery is approximately 3.9 Mt/y, with the supporting construction of the red mud iron separation process. The iron concentrate output is used for blending with the steel mill iron ore feed, while the remaining red mud can be supplied to other steel mills nearby.

4.1 Alumina Refinery Steam Demand

The alumina refinery steam demand for Phase I Phase II operations are summarised in Table 4.

Table 4. Steam Demand Summary.

	Alumina Capacity (Mt/y)	**Average (t/h)**	**Maximum (t/h)**	**Pressure (MPa)**	**Temperature (°C)**
Steam - Phase I	2.4	497.5	606.8	1.1	220
Steam - Phase II	1.2	238.4	292.2	1.1	220
Total	3.6	735.9	899.0	1.1	220

4.2 Steel mill Installation and Steam Supply

Configuration of the steel mill boiler: Three boilers are running, namely;

- 2 × 110 t/h high-temperature and high-pressure boilers, with steam temperature of 540 °C and pressure of 9.8 MPa, after high-temperature and pressure steam enters the turbine for power generation, the steam with a pressure drop to 1.2 MPa is sent to the alumina refinery.
- 1 × 220 t/h ultra-high temperature and ultra-high pressure boiler, with steam temperature of 570 ℃ and pressure of 13.7 MPa, after high-temperature and pressure steam enters the turbine for power generation, the steam with a pressure drop to 1.2 MPa is sent to the alumina refinery.

There are 2 set of 440 t/h internal thermal reactors (gas boilers) under construction: 2 × 600 000 Nm^3/h hot block flue gas deep purification device, equipped with internal heating reactor (gas boiler), 2 × 440 t/h internal heating reactor, steam temperature 571 ℃, pressure 17.4 MPa, supporting 1 × 95 MW subcritical ultra-high temperature and high pressure back pressure steam turbine.

These boilers can provide stable external steam of approximately 900 t/h, meeting the steam demand of the refinery.

4.3 Gas Source and Composition

The main sources of boiler fuel are blast furnace and converter gas, as well as dust removal ash sourced from the metallurgical coal industry, urban sludge, chemical sludge, and a small amount of coal gangue.

Blast furnace gas used in the boiler is a by-product of combustible gas during the ironmaking process. In addition to ensuring the self-use of steel production, there is still 515 000 Nm^3/h. The existing three boilers of Special Steel consume 357 000 Nm^3/h of gas, while the new reactors utilize the remaining 158 000 Nm^3/h. The make-up portion is sourced from gas or natural gas from adjacent steel mills. The composition of blast furnace gas is shown in Table 5.

Table 5. Blast Furnace Gas Composition.

Composition	CO	H_2	CH_4	C_2H_2	CO_2	N_2	O_2	H_2O
%	23.4	2	0	0	20.3	53.8	0	0.5

4.4 Comparison of Steam Utilization Methods in Steel Mills

If the steel mill is not operating together with the alumina refinery, its blast furnace offgases and converter gas are mainly used for steelmaking and steam power generation within the steel mill.

If the steel mill is co-located with the alumina refinery, then the waste steam generated by the steel mill can be used for the production of alumina. The steam can be heated using a back pressure machine.

After the steam heat exchange, the condensed water returns to the steel mill for boiler reuse.

The main difference between the two utilization modes is (i) when the steel mill is not operating together with the alumina refinery, the power generation for the steel mill is mainly from the condensing unit, (ii) when the steel mill is operating together with the alumina refinery, the power generation is mainly from the back pressure. The energy utilization efficiency of the condensing unit is about 45 %, and the energy utilization efficiency of the back pressure unit is 70–85 %.

The by-product gas from the steel mill has a calorific value of approximately 800 kcal/Nm^3 and the flow rate of the gas used for the boiler is estimated at 515 000 m^3/h. The total calorific value is approximately 412 Gcal/h. Based on a 30 % increase in energy efficiency, it can save around 123.6 Gcal/h of energy, equivalent to approximately 17.66 tce/h of standard coal, resulting in a saving of 147 000 tonnes of standard coal annually.

When operating in the JV mode, the waste heat utilization has changed from the original waste heat power generation to cogeneration, with significant energy savings and lower carbon emissions in the region.

4.5 Red Mud Composition

According to the alumina refining mass balance model, the composition of red mud is that presented in Table 6.

Table 6. Composition of red mud.

Composition	Al_2O_3	SiO_2	Fe_2O_3	TiO_2	LOI	Other	Total
%	16.59	4.21	56.33	4.47	8.67	7.81	100

4.6 Red Mud Iron Concentrating Process

The main processes for concentrating iron from red mud are

- magnetic separation,
- gravity separation, and
- wet process (acid leaching).

The first two are mainly used to recover iron from red mud, while the wet process mainly recovers rare and precious metal elements such as scandium, yttrium, and various other rare earth elements from red mud.

Magnetic separation is the main process for recovering useful iron-bearing minerals from red mud. The iron in red mud is mainly in the form of hematite, followed by goethite and magnetite. Although calcium iron ore and hydrated garnet also contain some iron, the iron content in these minerals is relatively low, and they are not the target minerals for iron concentrating. According to the magnetism of iron bearing minerals in red mud, weak magnetic separators are needed to recover magnetite, while strong magnetic separators are needed to separate hematite and limonite.

The alumina refinery directly recovers iron from red mud by using a high gradient strong magnetic separation process. The output rate of red mud is approximately 50 %, and the grade of iron concentrate (Fe) is approximately 45–48 %. The alumina refinery produces approximately 3.9 Mt/y red mud (total of Phase I and Phase II), and the annual discharge reduction of red mud can be approximately 1.95 Mt/y after iron separation.

Tailings from the alumina process is red mud liquid, which is pumped to the red mud iron separation process. The red mud liquid is separated from the red mud using equipment such as a cylindrical sieve, high gradient vertical ring magnetic separator, thickener, filter, etc.

The red mud liquid is pumped to the feeding tank for stirring, and then pumped to the slag screen. The bottom of the screen flows automatically to the vertical ring high gradient magnetic separator for the first stage of strong magnetic separation. This first stage magnetic separation concentrate flows automatically to the vertical ring high gradient magnetic separator for two stages of strong magnetic separation, and the second stage magnetic separation concentrate flows automatically to the concentrate thickener. The overflow of the concentrate thickener is pumped to the feed tank, and the bottom flow is pumped to the filter press for dehydration to obtain iron concentrate. Iron ore concentrate is then transported by truck to the refinery (Figure 1).

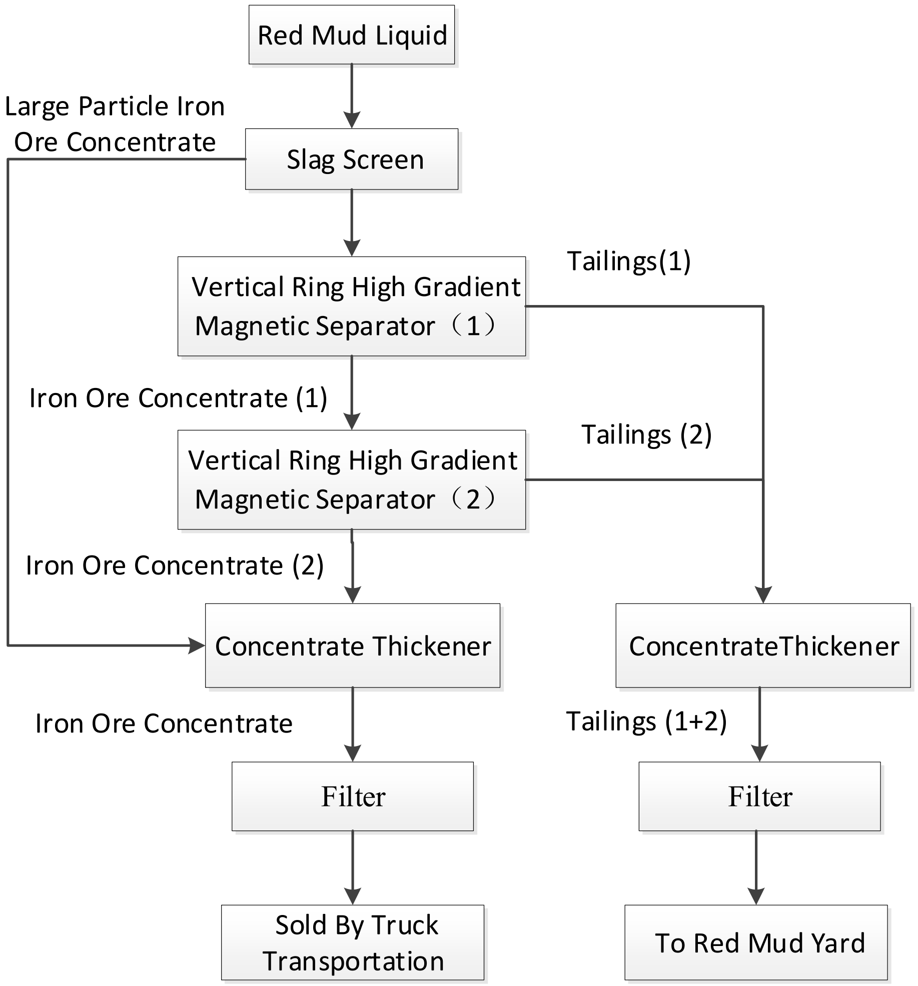

Figure 1. Process Flow Chart.

4.7 Composition and Dosage of Iron Concentrate

The elemental iron content of the iron concentrate can be controlled by adjusting the iron concentrating process and magnetic field intensity. The higher the elemental iron content in the iron concentrate, the lower the corresponding output rate of red mud iron concentrate. Combined with the environmental benefits of reducing the amount of red mud through red mud iron concentrating, the iron concentrate grade of red mud is designed based on an iron content of 45 %. According to mass balance calculations, the composition of iron concentrate is shown in Table 7.

Table 7. Composition of iron concentrate.

composition	Al_2O_3	SiO_2	Fe_2O_3	Na_2O	CaO	LOI	Other	Total
%	10.80	3.26	65	1.98	1.29	5.57	12.1	100

The content of Al_2O_3 and Na_2O in the iron concentrate produced by red mud iron beneficiation is considered too high and the particle size too fine, so it cannot be directly used in ironmaking. It needs to be blended with high-grade iron concentrate, with a blend rate of around 3–5 %. The ore consumption for ironmaking is approximately 1.6 tonnes of ore per tonne of iron. The annual iron concentrate production of alumina refining is about 1.95 Mt/y, and the corresponding iron smelting capacity of about 24.4 million to 40.6 million per year would be required to consume all the iron concentrate produced by the refinery.

4.8 Emission Indicators

Taking as a further example the operation of a coal-fired thermal power plant for a similar project in a southern port in China (with an alumina production capacity of 2 Mt/y), after preliminary calculations, the annual pollutant emissions, based on the ultra-low emission concentration limit, are shown in Table 8.

Table 8. Emission reduction data.

		Refinery 1	**Refinery 2**
SO_2	t/y	180.5	324.9
NO_x	t/y	258	464
Dust	t/y	51.6	92.9
Mercury and its compounds	t/y	0.003	0.005

The refinery 1 in the table is the aforementioned alumina refinery with capacity of 2 Mt/y alumina at a port in southern China, this refinery builds its own thermal power plant, the data in the table represents the annual emissions of major pollutants from the thermal power plant. Refinery 2 is an alumina refinery operated in JV mode with a steel mill, with a production capacity of 3.6 Mt/y alumina. The data in the table is based on the emissions of reference refinery 1, calculated based on the production capacity ratio of the two refineries.

5. Conclusions

China's alumina refineries are likely to become increasingly more reliant on imported bauxite over the next decade. As they do, they are more likely to be built (or relocate) to coastal areas, where imported bauxite is delivered and stockpiled. This provides an opportunity to co-locate alumina refineries adjacent to existing steel mills in and around port industrial parks, where they can take advantage of many synergies between operations, including lower capital costs, lower operating costs and an improved environmental performance.

This research concludes that co-location offers comprehensive energy utilization efficiency for both the steel mill and the alumina refinery, while reducing net carbon emissions and reducing refinery capital costs by avoiding the need for a dedicated power plant and sharing port infrastructure and other related facilities. Co-location also meets China’s criteria for high-quality industry development under China’s "carbon peak, carbon neutrality" policy by direct application in the steel and alumina industries.

6. Reference

1. The data used in this paper is sourced from the feasibility study report and preliminary design of the production project of an alumina refinery in Hebei province in China, and the investigation of the iron and steel mills in Tangshan.