Systematic Approaches to Reduce Specific DC Power Consumption at Vedanta Jharsuguda Smelter

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Abstract

The aluminium industry is a very energy intensive industry. Hence, energy management and improving energy efficiency are of utmost importance for any aluminium smelter. A measure of energy efficiency is specific power consumption, i.e. – the amount of DC energy required to produce unit mass of primary aluminium.

Plant-1 of Jharsuguda smelter at Vedanta Aluminium, comprises 608 GAMI technology electrolytic cells, running at 330 kA. Over the past five years, Plant-1 adopted systematic approaches to cut down the specific DC energy consumption (SEC) while concurrently improving process control and productivity. The initiatives encompassed using graphitized cathode blocks, strategic adjustment of process parameters to minimize process variability, the introduction of copper-inserted collector bars in cathode assembly, reduction of external drops through focused improvement projects, upskilling and reskilling both direct and indirect employees in regular intervals, and promoting the concept of sustainable growth and Environment, Social and Governance (ESG) goals. These efforts yielded tangible results; the SEC of Plant-1 reduced to 12 985 kWh/t Al in financial year 2024 from 13 230 kWh/t Al in financial year 2019. The progressive measures contribute to the establishment of an energy-efficient production management system, aligning with Vedanta's commitment to "Zero Harm, Zero Discharge".

Keywords: Vedanta Aluminium Limited, Reduction of specific DC energy consumption, Process control, Graphitized cathode, Copper collector bar insert.

1. Introduction

Vedanta's Jharsuguda Smelter is India's largest single location aluminium production facility. It has produced 1.8 million tonnes of primary aluminum in financial year (FY)2024. This remarkable achievement comes as a result of the continuous efforts from the operation team and embracing technological upgradation at Jharsuguda location. Compared to FY'20, 0.245 kWh/t Al saving in SEC has been recorded in FY'24. With more than 1 900 operational cells, the journey of accomplishing lowest ever specific energy consumption at Jhasruguda smelter started with implementation of graphitic and graphitized cathodes.

The chemistry of Hall-Héroult process says, alumina, under the provision of sufficient energy, breaks down into atomic states and produces aluminium and oxygen. In Hall-Héroult cell, this "sufficient energy" is provided in the form of Joule heating and subsequent electrolysis of the alumina molecule breaks it down into aluminium cation and oxygen anion. Further, the aluminium cation migrates toward cathode and accepts electron to become aluminium-whereas, the oxygen anion moves toward carbon anode and reacts with it to form carbon dioxide.

Ionic dissociation: $2Al_2O_3 + \Delta \rightarrow 4Al^{3+} + 6O^{2-}$

Cathode reaction: $4Al^{3+} + 12e^- \rightarrow 4Al$

Anode Reaction: $3C + 6O^{2-} \rightarrow CO_2 + 12e^-$

Overall Reaction: $2Al_2O_3 + 3C + \Delta \rightarrow 4Al + 3CO_2$

This process, known as Hall-Héroult process, is aided by a constant supply of Direct Current (DC).

Despite the theoretical decomposition potential for alumina to aluminium being -2.21 V, using carbon anode aids in reducing the Gibb's free energy by almost half of the earlier case and therefore sustains with -1.18 V decomposition potential, also known as reversible cell voltage [1].

$2Al_2O_3 \rightarrow 4Al + 3O_2$	Gibb's free energy: 640 kJ/mol (1000 °C)
$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$	Gibb's free energy: 340 kJ/mol (1000 °C)

Still, the practical considerations such as ohmic resistances necessitate operation at higher voltages, accounting for typically around 4.15–4.25 V voltage drop across a cell in a 330 kA smelter. The additional voltage drop is attributed to mainly four components:

- Anode voltage drop (0.3–0.4 V)
- Bath voltage drop (2.2–2.5 V)
- Cathode voltage drop (CVD) (0.25–0.35 V) and
- External voltage drop (0.2–0.25 V).

The specific energy consumption is one of the most important measures to perceive the efficiency of cell operation. It is influenced by the cell voltage drop and current efficiency [2], as described by the following empirical relation:

$$SEC = \frac{2.98 \times V}{CE} \tag{1}$$

where:

SEC	Specific energy consumption, kWh/kg Al
V	Voltage drop across cell + line loss, V
CE	Current Efficiency, decimal number

The measure of specific energy consumption not only affects the economy but also plays a crucial role in environmental sustainability and greenhouse gas (GHG) emissions. Since the Jharsuguda smelter relies on a coal-based power plant for electricity supply, reducing specific energy consumption is a priority for sustainable development as well as important from financial perspective. Over the past five years, Vedanta has undertaken various initiatives to address these opportunities, following a systematic approach to lowering specific energy consumption.

2. Initiative For Reducing Specific Energy Consumption

2.1 Graphitized Cathode Implementation

Since its inception, the Jharsuguda Smelter was equipped with cathode lining that could deliver specific energy consumption of around 13.5 kWh/kg Al. Over 12 years, the lining was progressively upgraded to higher-grade cathodes, transitioning from amorphous and semi-graphitic to graphitic and graphitized cathodes. These advancements have reduced specific energy consumption to 13.1 kWh/kg Al and improved pot life performance. Additionally, these improvements have led to a reduction in Spent Pot Linings (SPL), generated during cell shutdowns [3].

Before 2018, non-graphitized and semi-graphitic cathode blocks were used in the Jharsuguda smelter. The semi-graphitic cathode blocks used to contain 30–50 % of graphite. The addition of more graphite content improves electrical conductivity, and therefore the overall voltage drop across the cathode blocks decreases significantly. Besides that, graphitic and graphitized cathodes are viable options for future current increase. The first 100 % graphitic cathode was implemented in January 2020. Since then, 93.5 % of the cells have been retrofitted with graphitic and graphitized cathode blocks, encompassing more than 1 800 electrolytic cells. The number of cells in operation per financial year is shown in Figure 1.

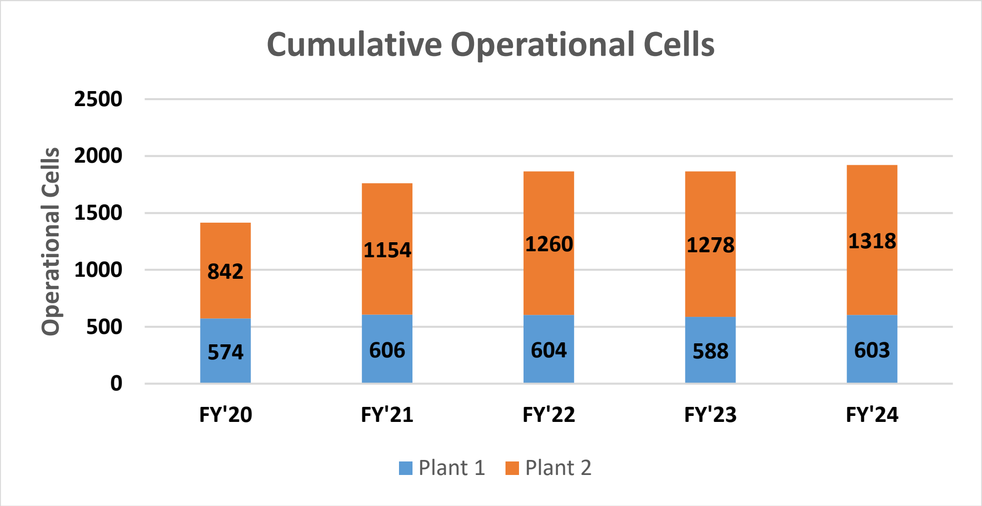


Figure 1. Number of Cells in Operation at Jharsuguda Smelter from FY’20 to FY’24.

Plant-1 of Jharsuguda smelter played an exemplary role in this transformation by achieving 99.67 % graphitization in 2024, as shown in Figure 2.

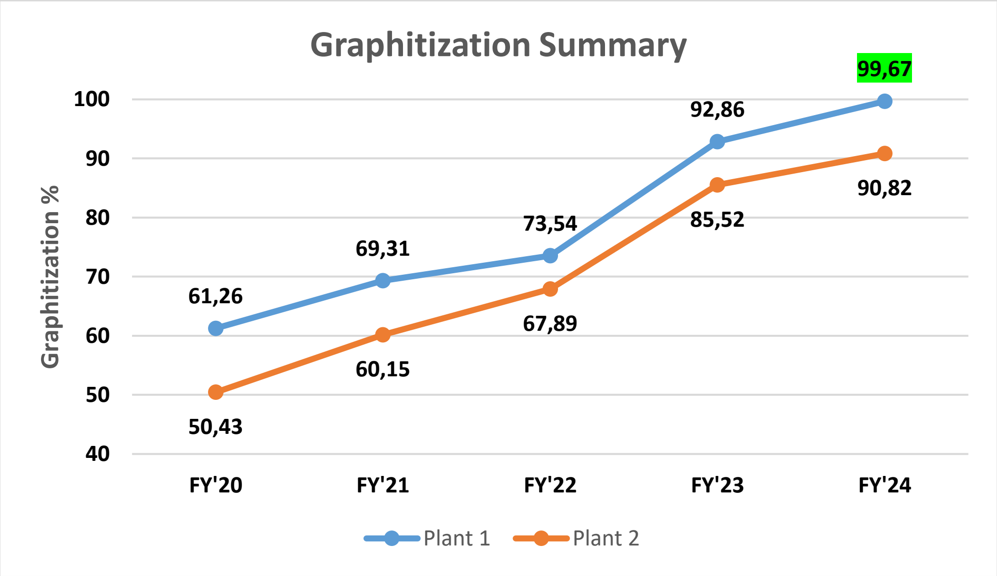


Figure 2. Graphitization summary at Jharsuguda Smelter from FY 2020 to FY 2024.

This initiative resulted in 20–30 % reduction in CVD, converting up to 100-200 kWh/t Al energy savings in terms of SEC. Also, an improvement in current efficiency is observed due to better distribution of cathode current density and reduction in noise. With better current distribution, the cell parameters are also optimized. Noise is reduced by 10 % and current efficiency improved by 0.2–0.3 %. The main performance indicators are described in Table 1.

Table 1. Plant-1 performance for graphitized and non-graphitized cells (6 months average).

Parameter	Unit	Graphitized	Non-Graphitized
Amperage	kA	332.06	331.42
Current efficiency	%	95.15	94.93
Pot voltage	V	4.09	4.14
Specific DC energy consumption	kWh/t Al	12872	13072
Bath temperature	°C	956.6	959.0
Excess AlF_3	%	10.85	10.5
Noise	mV	12.2	13.5
Cathode voltage drop	mV	252	326

2.2 Adjustment in Process Parameters

Thermal balance is an important aspect of cell control, enabling optimal operation with minimal deviation in bath temperature, optimized noise levels, adequate alumina feed, and proper covering. Various measures were implemented to identify opportunities for energy savings and outline debottlenecking actions.

2.2.1 AlF_3 Feeding Strategy

Aluminium fluoride balance is very crucial for maintaining pot temperature. Due to the 32-hour measurement cycle, bath temperature can be recorded every 32 hours. Excess AlF_3 in each cell is measured every 96 hours. This creates an uncertainty in accurately predicting excess AlF_3 in the cell and subsequent AlF_3 feeding amount at any instant. To overcome this challenge, two types of AlF_3 addition models have been introduced. One is based on technical considerations and data analysis; the latter is based on Artificial Intelligence and Machine Learning Model (AIML) approach. The last 2 years' historical data is used as input for the models. Different models were implemented in different sections of the potroom to validate performance. Among those models, the best ones are selected based on performance results and deployed horizontally. Using these models, cell thermal balance has been improved and average specific AlF_3 consumption is also reduced, as shown in Figure 3.

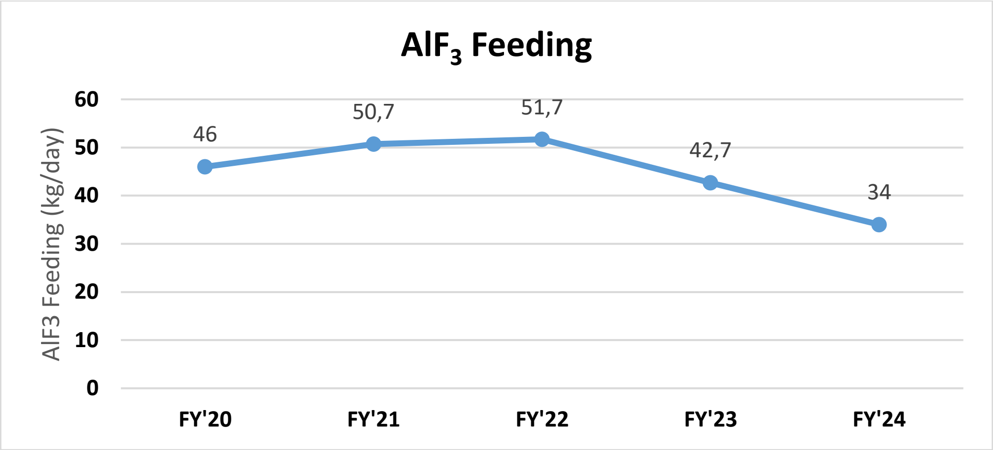


Figure 3. AlF_3 feeding trend at Jharsuguda Smelter from FY'20 to FY'24.

2.2.2 Cathode-Wise Parameter Setting Strategy

At Vedanta, multiple cathode grades are used, each with distinct physical and thermal properties, exhibiting unique behaviour under similar conditions. Previously, a generalized process control strategy was applied to all cathode types, relying on bath temperature and excess %AlF_3 to determine other parameters like set voltage, AlF_3 feeding, and tapping, regardless of cathode blocks. This practice was replaced with a cathode-grade-specific process control strategy. From the normalization period through normal operations, process parameters are now determined based on cathode grade in addition to other factors. The cathode-specific approach was set after cavity measurement, impact analysis of bath and metal level and noise level. This initiative enabled graphitized cells to operate at lower set voltages, maintain a more controlled bath temperature range, and improve productivity.

Since the addition to cathode grade-specific strategies, parameters are now also controlled based on the age of the cathodes. Older cells have different requirements compared to newly started and mid-aged cells. This approach has improved cell life. Furthermore, high energy-consuming cathode grades were phased out in favour of graphitized ones, reducing energy requirements and optimizing resource allocation.

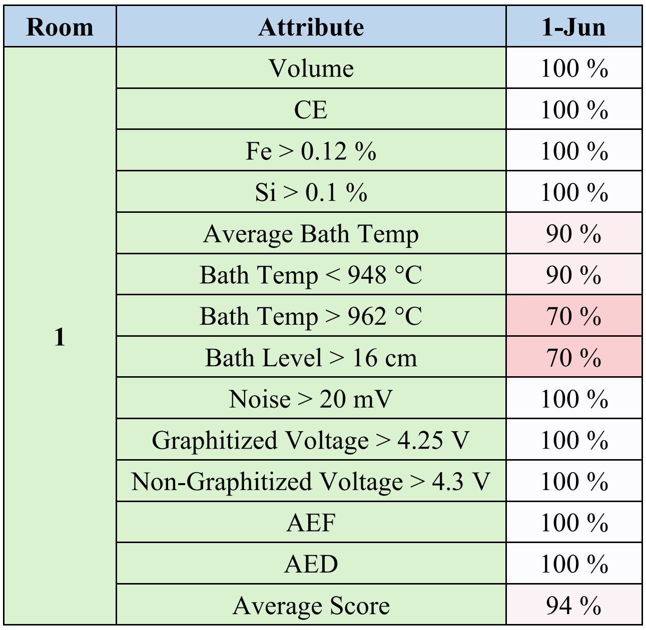
2.2.3 Process Audit and Operation Audit

All changes were regularly reviewed to evaluate the performance of the cells and assess the effectiveness of actions taken to enhance energy efficiency. Two essential programs, Process Audit and Process Review, were implemented to validate whether the process strategies were effectively addressing energy efficiency bottlenecks.

The process review program involved a thorough evaluation of the current process control strategies. This review aimed to identify any areas for improvement and modify the strategies as necessary. These modifications were adopted and tested until they were proven to surpass previous performance barriers. Regular reviews ensured that the adopted strategies were continually refined and optimized for maximum efficiency. Also, process scorecard has been introduced to summarize the performance of each potroom. It is a matrix of out-of-range process parameters used to check process compliance. Figure 4 shows the process scorecard of Potroom-1 for 1st June 2023.

The process audit program focused on verifying that on-floor practices aligned with the newly adopted control strategies. This involved detailed inspections and assessments to ensure that the operational team adhered to the updated procedures. The audits ensured that the theoretical improvements from the process strategies were realized in practical application.

This approach aimed to achieve significant energy savings and improved productivity while maintaining the integrity of process parameters. The combination of continuous review, strategic modifications, and stringent audits enabled the process team to implement a robust system focused on sustainable energy efficiency and operational excellence.



Room	Attribute	1-Jun
1	Volume	100 %
	CE	100 %
	Fe > 0.12 %	100 %
	Si > 0.1 %	100 %
	Average Bath Temp	90 %
	Bath Temp < 948 °C	90 %
	Bath Temp > 962 °C	70 %
	Bath Level > 16 cm	70 %
	Noise > 20 mV	100 %
	Graphitized Voltage > 4.25 V	100 %
	Non-Graphitized Voltage > 4.3 V	100 %
	AEF	100 %
	AED	100 %
	Average Score	94 %

Figure 4. Process scorecard.

2.3 Copper Insert in Collector Bar

After the successful transition to graphitized blocks, the focus shifted towards cell life improvement, minimization of horizontal current flow and better magnetohydrodynamic (MHD) stability. Copper insert in the collector bar was the key solution at this stage. High electrical conductivity of copper facilitates current to flow along a vertical path in the cathode block, rather than to a horizontal path. This further leads to improved MHD stability, substantial reduction in cathode.voltage drop and increased cell life.

To explore this opportunity, the concept of "Vedanta Lining Design" (VLD) was proposed. It is an in-house developed lining design that includes copper insert in collector bars with cold sealing and modification in lining refractory layers without major changes in materials or method of construction. Thermoelectric evaluation of VLD model shows the reduction in specific energy consumption by 200–300 kWh/t Al due to reduction in CVD by 70–80 mV compared to existing graphitized cathode lining design and expected improvement in current efficiency (Table 2). Design has added the advantage of stable cell operation and running at lower metal inventory. Also, the existing design gives flexibility and future readiness for current increase of 15 kA and improved cell life by 200–400 days can reduce specific hazardous waste generation associated with cell shutdowns and further costs incurred on processing [3].

Table 2. Plant -1 Performance for VLD pots (6 months rolling average).

Parameter	Unit	Value
Amperage	kA	331.94
Current efficiency	%	95.24

Pot voltage	V	4.065
Specific DC energy consumption	kWh/t Al	12 532
Bath temperature	°C	957.9
Excess AlF_3	%	10.83
Noise	mV	11.4
Cathode voltage drop	mV	188

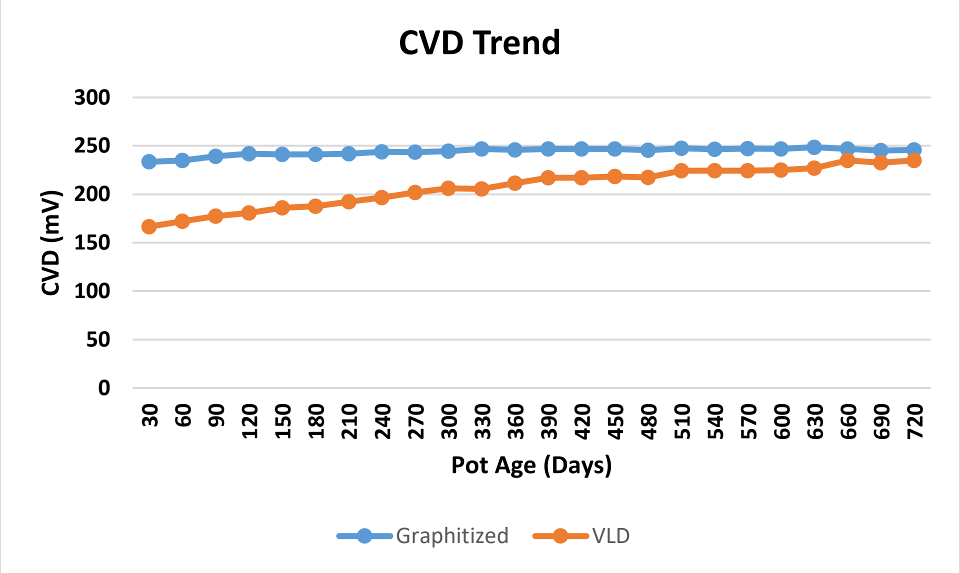


Figure 5. Comparison of cathode voltage drop for VLD cathode design vs non-VLD cathode design.

2.4 Initiatives for External Voltage Drop (EVD) Reduction

External voltage drop (EVD) is an important aspect when one looks at the overall power consumption of the smelter. EVD accounts for 2–4 % of total power consumption. The main sources of EVD are:

- Dead cells;
- Additional drop due to bad busbar welding;
- Improper insulation and current leakage and
- Clamp drop at anode-clamp joints.

Due to series connection of cell, while current passes through dead cells, a small amount of voltage drop is observed due to obvious ohmic resistances. Earlier, the drop used to reach 30–40 mV. After proper implemented measures, the drop is around 20–25 mV.

For busbar welding, weak welds are identified and those are re-welded by technicians highly skilled at welding under high magnetic field. Proper insulation checks in regular intervals are mandated and thus a significant milestone achieved by ensuring zero incidents of current leakage due to improper insulation in 2023.

Clamp drop, which is the voltage drop between the anode rod and anode beam, occurs due to ohmic resistance at the anode clamp, accounting for 10–25 mV of voltage drop. High drop is observed due to dust accumulation on the clamps and corrosion of the clamps. Corrosion makes the contact surface between the anode and clamp to become uneven, allowing the provision of trapping air between these surfaces. Air, being a bad conductor of electricity, increases the clamp drop eventually. Hammering at regular intervals and blowing compressed air at clamp joint turned up as feasible and impactful solutions to tackle this challenge. The drop, which earlier had a constant range of 12–20 mV, has come down to 8-12 mV in recent years. Those practices ensure no dust accumulates on the clamp and if any corroded surface is present, the amount of air trapped gets minimized.

3. Upskilling and Reskilling of Employees

As Vedanta was continuously adopting new technologies, new process control strategies and novel practices, it is necessary to upskill and reskill employees at a regular interval. Introducing the basics of operation and continuously made changes for operational excellence to the employees and business partners improves understanding of process and subsequently improves the standard of work. Upskilling involves enhancing the existing skill sets of employees to meet the demands of evolving technologies within the smelter. Meanwhile, reskilling involves teaching employees new process control strategies. By investing in upskilling and reskilling initiatives, Vedanta keeps its employees valued, engaged, and equipped to navigate the challenges of tomorrow.

With an upward trend, more than 400 technical training sessions (Figure 6) were conducted in the last three years encompassing the following topics:

1. Advanced potroom technology
2. Basics of bath chemistry
3. Process control strategies
4. Best operational practices
5. Pot relining and delining
6. Pot autopsy
7. 5S practice in potroom
8. Potroom safety

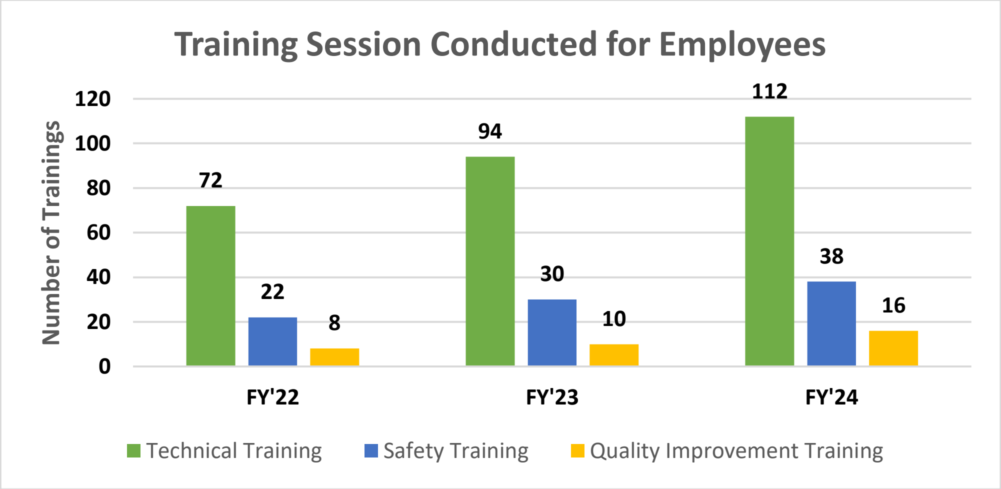


Figure 6. Training session conducted for employees at Jharsuguda smelter from FY'22 to FY'24.

More than 2 000 manhours have been invested for upskilling and reskilling trainings. The passive impact of these sessions can be envisaged with increased number of participations in QC/KAIZEN/5S competitions and promptness during emergencies. Ideas generated through such competitions collectively contributed to achieving operational excellence, reduced energy consumption and better safety practices.

4. Results

As a result of the continuous efforts to improve energy efficiency and operational practices, significant drop in SEC is observed (Figure 7). Reduction in net carbon consumption is also achieved in these years. Retrofitting cathodes aids in increasing Plant-1 amperage by 3 kA without impacting process parameters. Better magnetohydrodynamic (MHD) stability results in lowering noise of cells and enhanced productivity (Table 3).

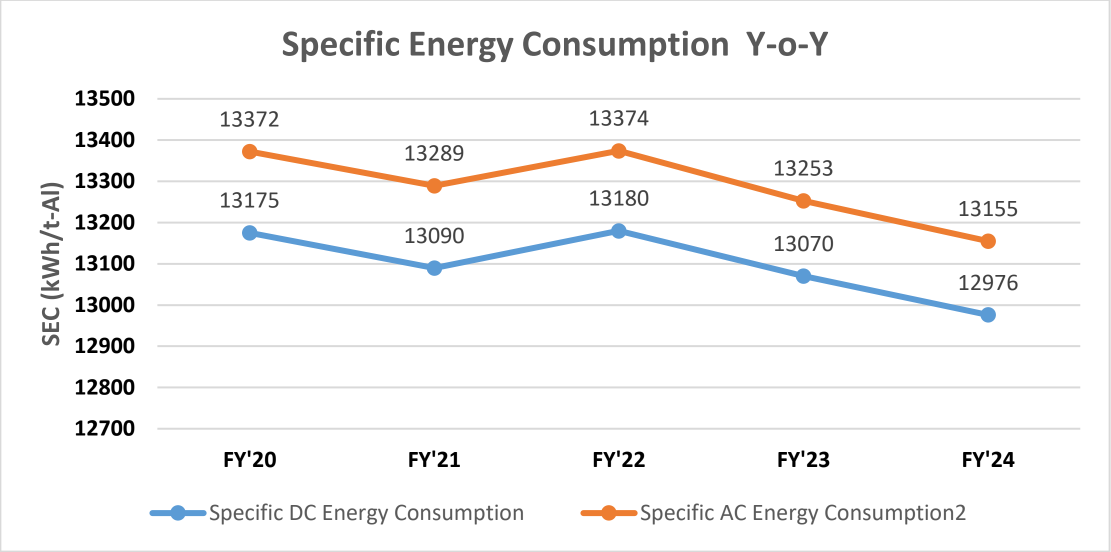


Figure 7. Specific energy consumption trend for Plant-1 from FY’20 to FY’24.

Table 3. Amperage, current efficiency and noise trend for Plant-1 from FY’20 to FY’24.

Parameter	Unit	FY’20	FY’21	FY’22	FY’23	FY’24
Amperage	kA	331.7	329.8	330.3	330.8	330.8
Current efficiency	%	94.5	94.7	94.1	94.9	95.13
Noise	mV	15.2	15.5	15.8	13.7	12.5

Intensive training and significant employee engagement in improvement projects contribute to sustainable operation. Anode effect frequency is remarkably reduced by more than 50% (Figure 8). Tight process control strategies allowed to achieve reduction in bath height and metal height variability (Figure 9).

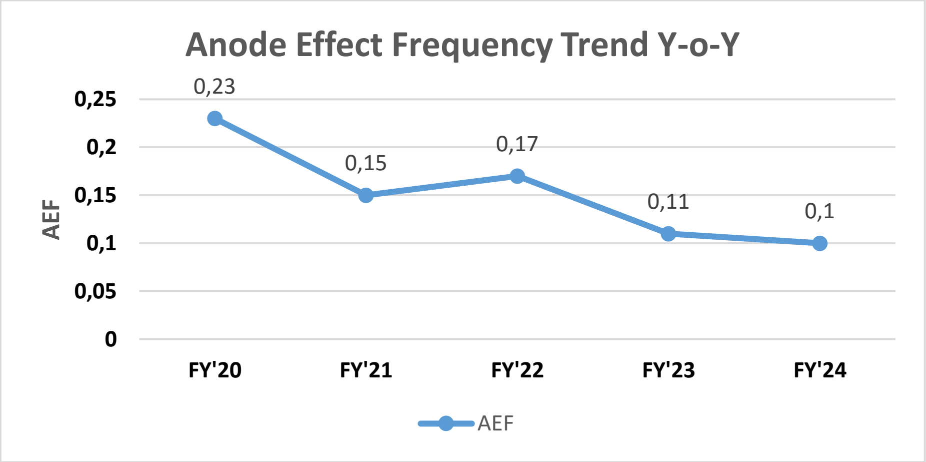


Figure 8. Anode effect frequency trend for Plant-1 from FY’20 to FY’24.

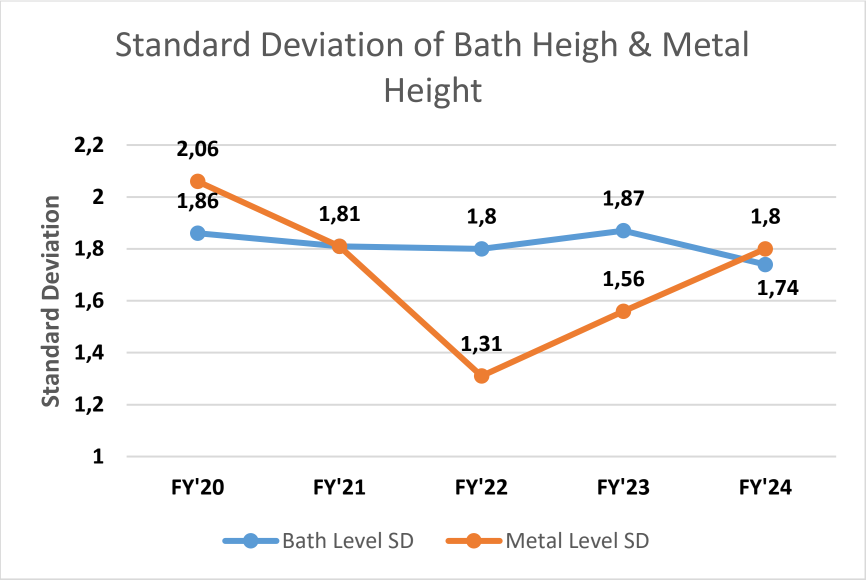


Figure 9. Bath and metal height variability trend for Plant-1 from FY'20 to FY'24.

5. Conclusions

Plant-1 of Jharsuguda Smelter started a journey of reducing specific energy consumption which once seemed to be almost impossible to achieve due to design implications. But systematic approaches taken to reduce energy consumption gradually has shown excellence of both process and operation teams which did not only break the barrier of specific energy consumption constraints, but also achieved upward trend in current efficiency. Replacing graphitic cathodes with graphitized ones have a significant role in this scenario. But process control strategy review and implementation are indispensable parts of the whole journey. Training and skill development of employees reflect a positive change in operational practices enabling employees to make knowledge-based decision making. Summing up all the efforts that were chased in the last 5 years, landed Vedanta to successfully achieve landmarks and it is continuing efforts for further reduction in specific energy consumption.

6. References

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