Enhancing Evaporator Economy: A Key Strategy for Sustainability and Decarbonization

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Abstract

The Evaporation process is an important section in alumina production using the Bayer process. It consumes a large amount of thermal energy but helps to manage the water balance in a refinery. To produce alumina from bauxite ore, the weak aluminate liquor has to be concentrated through evaporators, so that it can be recycled back to digestion. Reducing energy consumption is always an important research topic in alumina refining. The Renukoot Alumina Refinery is one of the oldest refineries in the world and operates some of the oldest technology evaporation units. It has therefore always been a challenge to achieve benchmark energy performance.

Being the oldest refinery, various evaporation technologies are installed in the plant, i.e., multistage flash evaporation, multistage falling film evaporation and multistage rising film evaporation. A comprehensive analysis was carried out considering drawbacks in existing systems and consequently actionable points were identified for attaining the energy efficiency objectives. In this case we describe the stepwise analytical approach on the successful journey of steam economy improvement by 23 % which helps to reduce the carbon footprints through process re-engineering, refinement in process control through analytical study and improvement of operational practices.

Keywords: Evaporation technology, Steam economy, Process re-engineering, Energy reduction, Lower carbon footprint.

1. Introduction

The cost of alumina production has been rising significantly in recent years, with steam consumption identified as a key cost driver. At the Renukoot Alumina Refinery, steam contributes approximately 17 % to the total production cost, underscoring the critical need for energy optimization. The refinery operates three evaporation units i.e. Evaporation Units #1, #3, and #4 with an average steam economy of approximately 3.0 tonnes of water evaporated per tonne of steam (t/t). However, among these units, Evaporation Units #3 and #4 have consistently demonstrated lower performance. Specifically, Unit #3 has operated in the range of 2.5–2.6 t/t, while Unit #4 has maintained a steam economy between 3.0–3.1 t/t over the past several years. Although the refinery has occasionally achieved an overall steam economy of up to 3.3-3.4 t/t, these improvements have not been consistently maintained under standard operating conditions.

Achieving sustained improvements in steam economy from a baseline of 2.95 t/t to a peak of 3.63 t/t required the implementation of targeted process modifications alongside refined operational practices. This enhancement translated into significant reductions in overall steam consumption across the refinery, contributing directly to cost efficiency.

This paper presents a systematic, stepwise methodology employed to drive steam economy improvements through process re-engineering, control strategy optimization, and operational excellence. The approach outlined herein serves as a representative case study for identifying and mitigating inefficiencies, thereby delivering measurable energy savings within the alumina refining process.

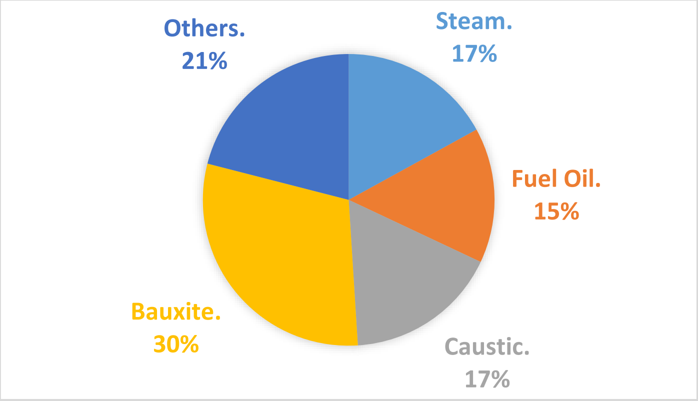


Figure 1. Alumina cost of production elements.

2. Conceptual Approach

A comprehensive analysis was conducted by the operations and process engineering team to assess the inherent limitations of the existing evaporation system at the Renukoot Alumina Refinery. This in-depth review was aimed at identifying opportunities to enhance the overall steam economy and reduce energy costs associated with alumina production. The study revealed several critical shortcomings in the current setup and led to the development of a set of targeted, actionable improvement strategies.

One of the key measures identified is that the increasing in feed liquor temperature of evaporation unit will enhance thermal efficiency for reducing the overall steam requirement. In parallel, a data-driven optimization of feed flow rates, vacuum levels, and associated process parameters was undertaken. Advanced data analytics and historical process performance reviews enabled the identification of optimal operating windows that directly impact steam economy.

Another major initiative was the utilization of feed flash vapor enthalpy by redirecting its thermal energy into the evaporation process. This approach reduces the demand for live steam by recovering otherwise wasted heat. Furthermore, a significant process re-engineering effort involved the replacement of traditional steam ejectors with mechanical vacuum pumps. This change improved vacuum control and stability while eliminating the need for motive steam, resulting in both energy and operational efficiency.

Collectively, these interventions formed the foundation for a sustainable improvement framework, enabling the refinery to move towards its goal of achieving a consistently higher steam economy across all evaporation units.

3. Methodology Adopted

The following multi-faceted approach was implemented to enhance the steam economy and overall process efficiency:

- Process re-engineering: redesigning process flows and system configurations to eliminate inefficiencies and optimize energy utilization.

- Refinement of process control: fine-tuning control strategies for better regulation of critical parameters such as temperature, vacuum, and flow rates.
- Enhanced operational practices: implementing standard operating procedures, training programs, and best practices to ensure consistent and optimized plant operation.
- Data analytics: leveraging historical and real-time data to identify performance trends, detect anomalies, and support data-driven decision-making for continuous improvement.

4. Step Towards Improvements:

4.1 Improvement in Evaporation Feed Liquor Temperature

The temperature of evaporation feed liquor is a critical factor influencing steam consumption and, consequently, the steam economy of the evaporators. An increase in feed temperature directly enhances thermal efficiency, thereby reducing the amount of live steam required for evaporation. To achieve this, an in-house process modification was implemented. An existing Plate Heat Exchanger (PHE) was repurposed to elevate the temperature of the hot spent liquor. This was accomplished by utilizing good-quality condensate from the Digestion area, which is available at approximately 125 °C. Through this modification, the temperature of the feed liquor to evaporation unit was successfully increased from 67 to 75 °C, contributing significantly to improved energy performance across the evaporation system.

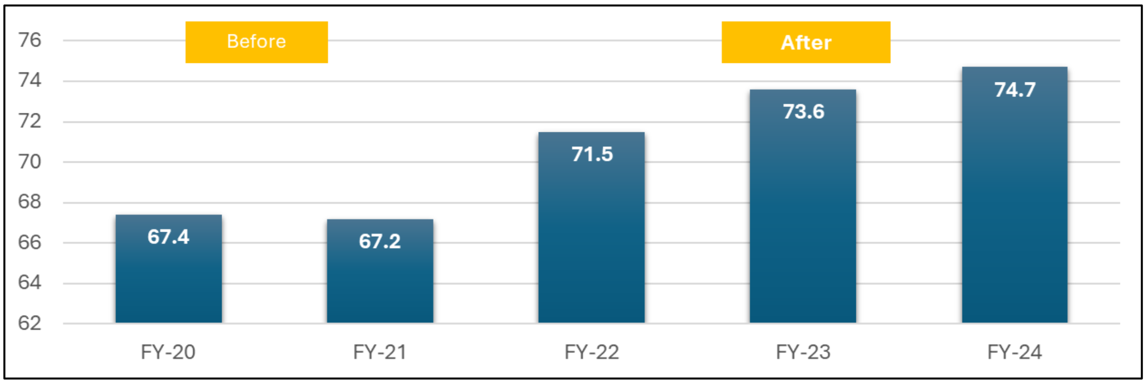


Figure 2. Evaporation feed temperature over the years.

4.2 Utilization of Feed Flash Vapor Enthalpy as Evaporation Feed

During operational analysis, it was observed that a temperature drop occurred due to the inclusion of the evaporation feed flash tank in the process. To address this inefficiency, the operational strategy was shifted from a conventional approach to an innovative method. By bypassing the feed flash tank and directly supplying high temperature liquor to the evaporation circuit, steam consumption was significantly reduced.

Before Optimization:

- When the Evaporation-3 feed flash tank was in operation with a vacuum of -0.78 bar (g), it facilitated an evaporation rate of 6 t/h, resulting in a 10 °C temperature drop, see Figure 3.

After Optimization:

- When the Evaporation-3 feed flash tank was operated without vacuum, the evaporation feed temperature remained equal to the hot spent liquor temperature, see Figures 4 and 5.
- The Live Steam Heater inlet temperature increased by 5 °C, improving from 104 to 110 °C

This modification led to enhanced thermal efficiency, reducing steam requirements while optimizing energy utilization within the evaporation process.

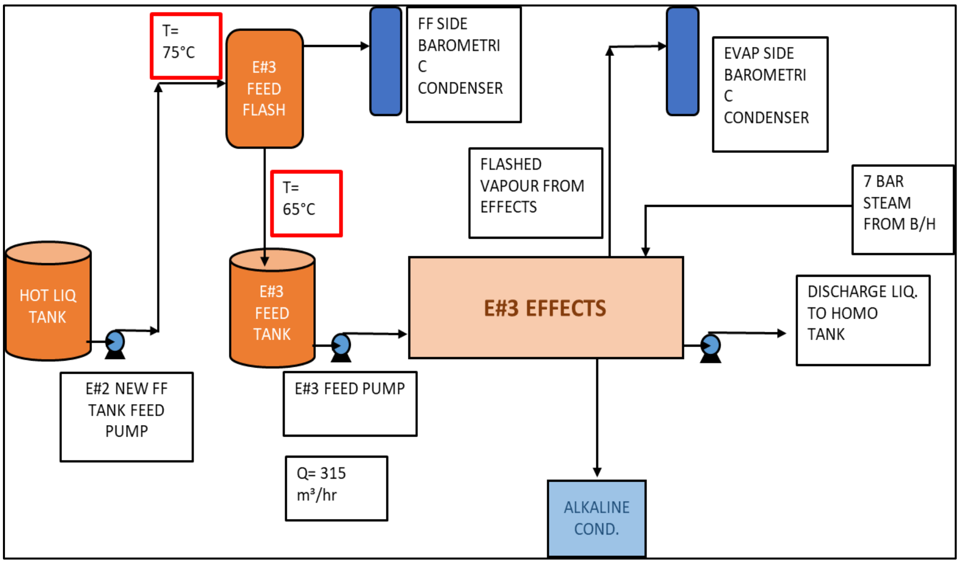


Figure 3. Feed flash tank in line.

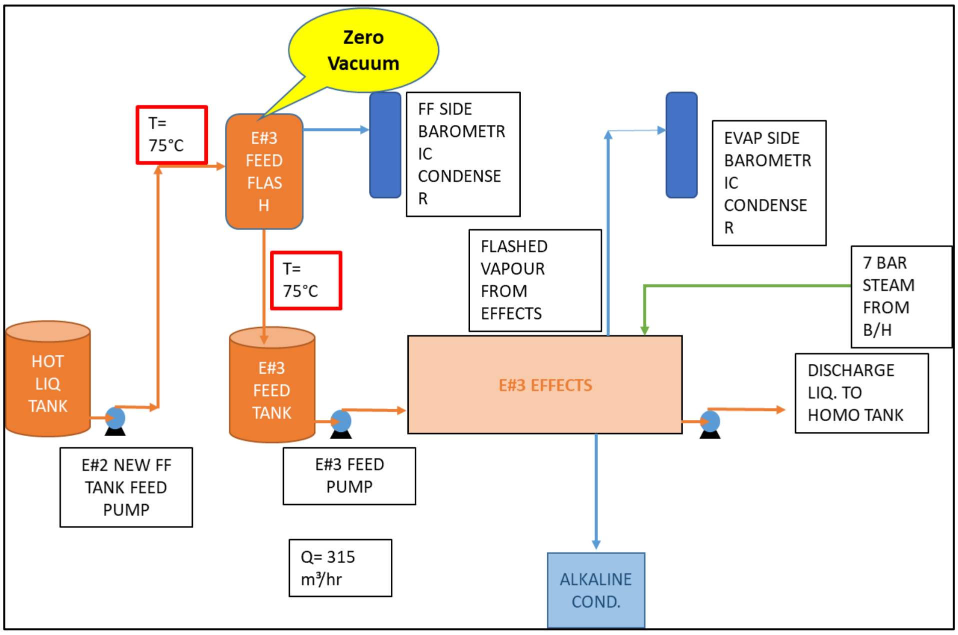
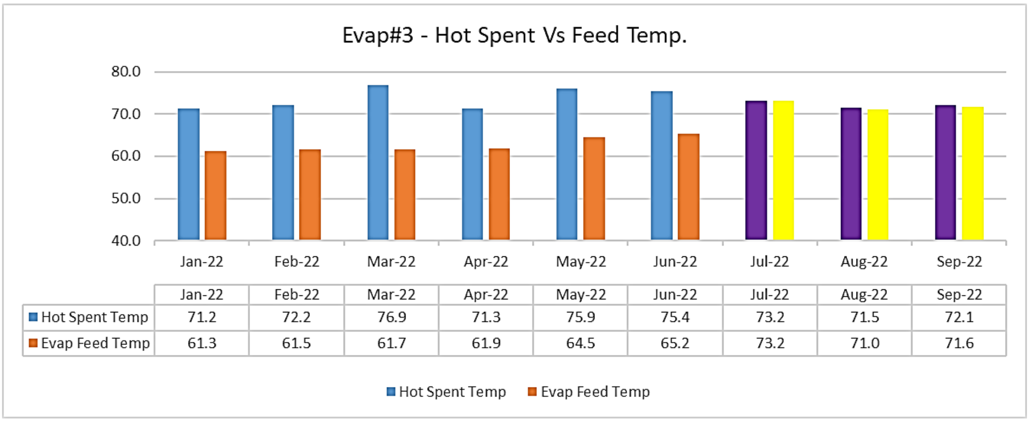


Figure 4. Feed flash operated at zero vacuum.



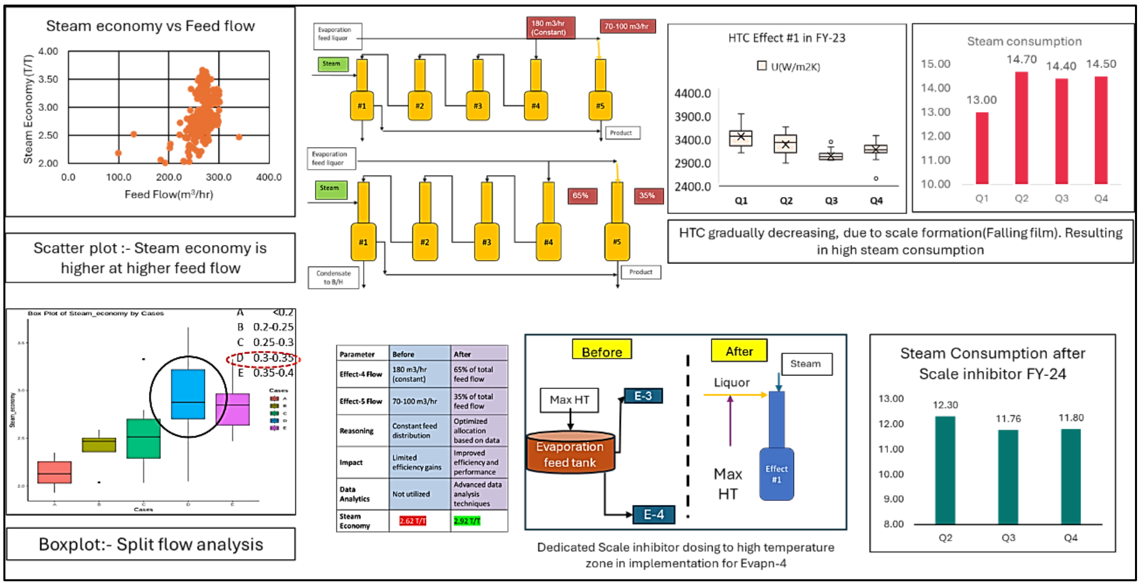
	Jan-22	Feb-22	Mar-22	Apr-22	May-22	Jun-22	Jul-22	Aug-22	Sep-22
Hot Spent Temp	71.2	72.2	76.9	71.3	75.9	75.4	73.2	71.5	72.1
Evap Feed Temp	61.3	61.5	61.7	61.9	64.5	65.2	73.2	71.0	71.6

Figure 5. Trend of spent liquor temperature vs evaporation feed temperature.

4.3 Process Refinement Using Data Analytics

A comprehensive analysis of historical operational data was conducted using advanced data analytics techniques. Through detailed brainstorming sessions among team members, key insights were extracted to identify optimal operating parameters that would enhance steam economy and maximize evaporation rates.

By leveraging data-driven methodologies, the team systematically evaluated process performance trends, detected inefficiencies, and established refined control strategies. This approach enabled precise adjustments to critical parameters, leading to improved thermal efficiency and reduced steam consumption across the evaporation system.



Parameter	Before	After
Effect-4 Flow	180 m3/hr (constant)	65% of total feed flow
Effect-5 Flow	70-100 m3/hr	35% of total feed flow
Reasoning	Constant feed distribution	Optimized allocation based on data
Impact	Limited efficiency gains	Improved efficiency and performance
Data Analytics	Not utilized	Advanced data analysis techniques
Steam Economy	2.62 T/T	2.92 T/T

Figure 6. Detailed study through data analytics and implementing the outcomes.

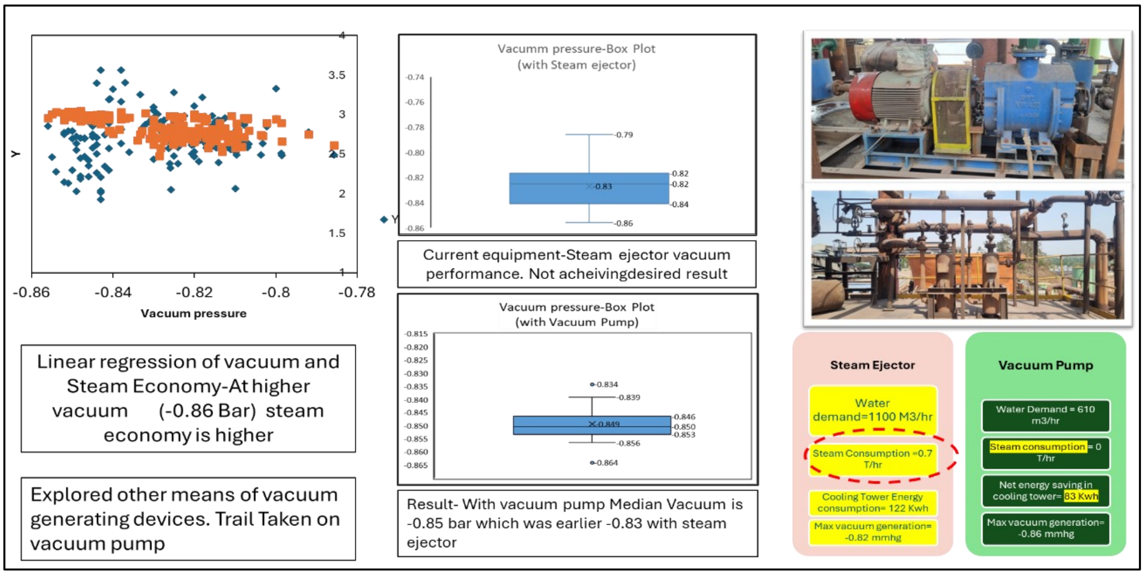
4.4 Installation of Vacuum pump in place of Steam jet ejector in Evaporation-4

As part of the refinery's process optimization efforts, the steam jet ejector was replaced with a vacuum pump to enhance operational efficiency and reduce steam consumption.

Traditionally, steam jet ejectors have been used for vacuum generation, but they rely on high-pressure motive steam, leading to significant energy consumption. By transitioning to a mechanical vacuum pump, the system achieved superior vacuum stability while eliminating the need for motive steam, resulting in improved energy efficiency.

Key benefits of this modification include:
- Reduction in Steam Consumption: Eliminating the steam-driven ejector minimized overall steam usage, contributing to lower operating costs.
- Improved Vacuum Control: The vacuum pump provided more precise and consistent vacuum regulation, optimizing evaporation performance.

This strategic re-engineering initiative played a vital role in enhancing steam economy, improving process reliability, and aligning with the refinery's sustainability objectives.



Linear regression of vacuum and Steam Economy-At higher vacuum (-0.86 Bar) steam economy is higher

Explored other means of vacuum generating devices. Trail Taken on vacuum pump

Current equipment-Steam ejector vacuum performance. Not acheivingdesired result

Result- With vacuum pump Median Vacuum is -0.85 bar which was earlier -0.83 with steam ejector

Figure 7. Detailed study for replacing vacuum pump in place of ejector.

4.5 Electricity vs Steam Trade-off:

As detailed in section 4.4, thermal energy is the form of steam was replaced with electrical energy by installing a vacuum pump in place of steam ejectors. A comparative energy trade-off analysis was conducted by converting both steam and electrical energy consumption into Giga Joule (GJ). The result indicated a significant reduction in total energy usage – approximately 94.2 %. When steam ejectors were in use, the energy consumption was 1.9 GJ/h, whereas with vacuum pump, it was reduced to only 0.11 GJ/h.

5. Challenges and Resolution

5.1 To Increase Feed Spent Liquor Temperature

The Feed liquor temperature to Evaporator was initially available at 67 °C, to enhance the steam economy, it was necessary to increase the temperature by approximately 10 %. Following a detailed material and energy balance assessment along with process data analysis, the team identified waste heat from condensate as a viable energy source to raise the feed liquor temperature effectively.

5.2 Contamination in Flash Vapor from Effects

While implementing the required set parameters, team observed contamination in flash vapours originating from the evaporation effects. The root cause identified as feed flash tank, which was directly connected to the vacuum system, allowing soda carryovers into the vapours. Data analysis and Heat balance calculations indicated that better efficiency could be achieved by excluding the feed flash tank from the process. As a corrective measure, the feed flash tank was completely isolated from the system. This intervention not only resolved the contamination issue permanently but also contributed to an improvement in steam economy of the evaporation process.

5.3 Optimization of Evaporation Feed Flow While Maintaining Plant Performance

Balancing evaporation feed flow without disrupting plant operations requires a data-driven approach to maximize steam economy and evaporation efficiency. By leveraging real-time analytics and process simulations, feed distribution can be optimized to enhance evaporation rates while ensuring overall system stability. Dynamic adjustments to feed parameters can minimize thermal losses and improve process efficiency without affecting production throughput.

6. Mass and Energy Balance

A detailed mass and energy balance was conducted to evaluate the expected outcome and proposed process modification for smooth execution of field trials. Based on the operational data observed outcomes, certain parameters were further optimized to minimize variability and ensure sustainable performance improvements.

The site trial was implemented in alignment with the process model developed through material balance analysis, and actual performance data was recorded. While the initial projection from the energy balance estimated a 15 % improvement in steam economy compared to the baseline, the actual results demonstrated a significant higher gain of 23 %. Below indicates the before and after implementation outcomes.

- Evaporation Duty increased by 8.04 %, more water evaporated.
- Steam input decreased by 15.05 %, a clear efficiency gain.
- The steam economy improved by 23 %.
- Electrical energy used by vacuum pumps (108 MJ/h) is minimal compared to steam energy saved.

7. Estimated CO_2 Reduction

By reducing steam consumption and switching from steam ejectors to an electric vacuum pump, the Renukoot refinery achieved an estimated CO_2 emissions reduction of over 17.67 kt/y, based on Indian CEA emission factors (94 kg CO_2/GJ)

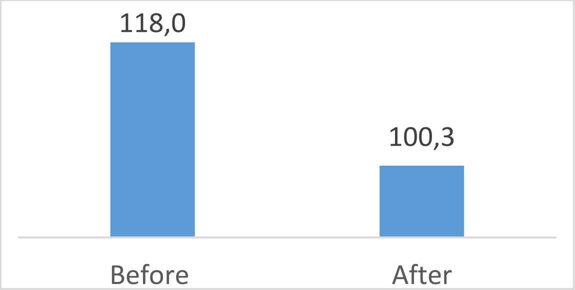


Figure 8. Before and after the annual CO_2 emissions.

8. Results and Outcomes

Significant improvements were achieved in the steam economy and evaporation rates across multiple units following the implemented process optimizations.

The combined steam economy of all Evaporation units increased from 2.95 t/t to 3.63 t/t, resulting in a net reduction in total steam consumption of 7.1 t/h. Overall, the total evaporation rate increased from 144.1 to 155.9 t/h.

These results confirm the effectiveness of the implemented measures, demonstrating substantial energy savings and supporting the refinery's broader goals of operational efficiency and sustainability.

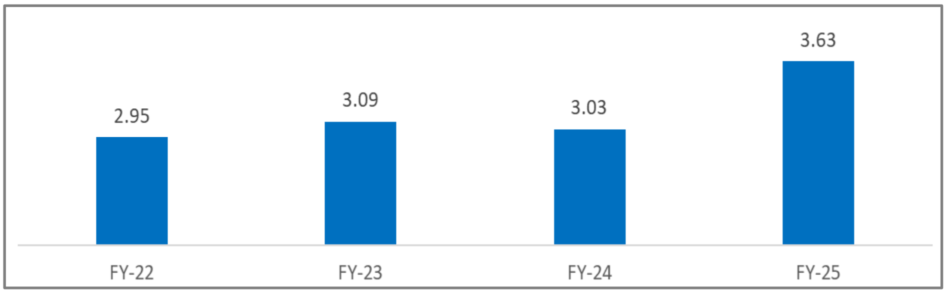


Figure 9. Steam economy (t/t) improvement trend.

9. Conclusion

The optimization of evaporation technology at the Renukoot Alumina Refinery has led to substantial improvements in steam economy and energy efficiency. Through systematic process re-engineering, data analytics-driven refinement, and enhanced operational practices, significant reductions in steam consumption have been achieved across multiple evaporation units.

Key modifications—such as bypassing the feed flash tank, utilizing feed flash vapor enthalpy, optimizing evaporation feed flow, and replacing steam jet ejectors with vacuum pumps – have collectively contributed to enhanced thermal efficiency and sustainability. These changes resulted in measurable gains, including a 23 % improvement in steam economy, substantial reductions in carbon footprint from evaporation area (CO_2 emission reduction by 15 %), and enhanced process stability. The successful implementation of these strategies reinforces the importance of continuous innovation in alumina refining. By leveraging advanced process control methodologies and adopting energy-efficient technologies, the refinery has demonstrated how targeted interventions can drive operational excellence while reducing environmental impact.

These findings offer valuable insights into energy optimization, serving as a benchmark for future refinements in evaporation systems within the alumina industry. Further advancements in digitalization, predictive analytics, and automation could potentially unlock even greater efficiencies, paving the way for sustainable and cost-effective refinery operations.

10. References

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