Technical Assessment of Efficient Steam Recovery from Alumina Calcination for Sustainable Bauxite Digestion

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Abstract

This study presents a technical analysis of steam cleaning and recovery from the calcination process as a means of decarbonization and energy conservation in alumina refining. Steam recovery is highest from H_2 in oxygen-steam (oxy-steam) calcination (Scenario 4) yielding 0.86 t steam/t Al_2O_3, meeting 43 % of steam demand in digestion based on a reference usage of 2 t steam/t Al_2O_3. In a fully electrified calciner (Scenario 3), the calculated steam recovery is 0.64 t steam/t Al_2O_3, followed by natural gas/air calcination (Scenario 1) and hydrogen/air calcination (Scenario 2), at 0.54–0.55 t steam/t Al_2O_3. Recovering high-purity steam in H_2 in oxy-steam or fully electrified calcination demonstrates higher energy efficiency, consuming 0.54 GJ/t steam energy, with 9% allocated to gas cleaning. In contrast, recovering steam from air-based calcination exhibits lower energy efficiency, requiring 0.71 GJ/t steam energy due to the N_2 dilution in exhaust steam, of which 5 % is attributed to gas separation and cleaning. The calculated energy consumption in digestion decreases by 36 %, from 6.63 to 4.25 GJ/t Al_2O_3, when incorporating steam recovery from H_2 in oxy-steam calciner, compared to solely relying on natural gas boilers. Furthermore, CO_2 emissions for digestion steam generation are expected to reduce by 43 %, from 0.37 to 0.21 t CO_2/t Al_2O_3. Zero carbon emissions in digestion can be achieved by replacing gas boilers with electric boilers and integrating with calcination steam recovery, yielding an additional 15 % energy consumption reduction due to the higher efficiency of electric boilers.

Keywords: Steam cleaning, Efficient steam recovery, Decarbonizing digestion

1. Introduction

In the digeston step of the Bayer process, gibbsitic type bauxite ores are leached in a concentrated NaOH solution under steam temperature of 175–230 °C and pressures of 6–13 bar in low-temperature digestion [1–3], consuming approximately 60–70 % of the total energy consumption (10.5 GJ/t Al_2O_3 in average) in current refineries [4]. This steam is primarily generated from natural gas boilers, which is estimated to emit 0.28–0.64 t CO_2/t Al_2O_3 [5]. Accordingly, decarbonizing the process and achieveing energy conservation are both essential. Instead of generating steam from fossil fuels, energy can be conserved by recovering generated steam from gibbsite decomposition, moisture evaporation and fuel combustion during the calcination. However, the steam is diluted with combustion products and is currently vented to the atmosphere, along with its latent energy [6]. Capturing and reusing it in digestion offers a potential to reduce fossil fuel reliance in steam generation and lower overall energy use in digestion.

The conventional calcination process under natural gas/air combustion releases approximately 0.7 t steam/t Al_2O_3, which contains 1.7 GJ/t Al_2O_3 of latent energy [7]. While the exhausted steam is diluted with N_2 and CO_2, complicating the recovery process. Chatfield [5] proposed using a wet scrubber to condense steam from the flue gas to separate N_2 and CO_2, followed by generating low-pressure steam in flash tanks. However, the study does not quantify the amount of recoverable steam or the energy efficiency of the process. This configuration could also be applied to H_2 in air combusted calcination, where the exhaust steam is diluted with ~50 % N_2. In contrast, H_2 in oxygen-steam (oxy-steam) combustion produces high purity steam, with an estimated amount of 0.8 t steam/t Al_2O_3 [8]. Similarly, a fully electrified calcination system eliminates fuel combustion and produces 0.63 t steam/t Al_2O_3 of pure steam. These two decarbonized calcination pathways simplify steam recovery process due to the absence of N_2 and CO_2. Nevertheless, fine particulates in the flue gas pose a technical barrier. Despite the availability of existing particulate control systems such as Electrostatic Precipitator (ESP), or baghouses that remove solid concentrations to below 50 mg/m^3 (typically ranging from 29 to 41 mg/m^3) [9–11], these levels may still impact the operation of a mechanical vapor recompression (MVR) system used for steam compression to digestion pressures. To mitigate this, the current study proposes integrating a venturi scrubber upstream of the MVR unit for further removing fine particle, particularly those smaller than 2 µm, due to its high efficiency [12–14]. However, the energy requirements of such an integrated steam recovery configuration have yet to be quantified.

Given these technical and operational challenges, this study aims to conduct a comparative evaluation of steam recovery across four calcination pathways: natural gas/air, H_2/air, fully electrified and H_2 in oxy-steam calcination. The analysis focuses on net steam recovery rates, energy penalties from gas separation and cleaning, and the potential energy savings and CO_2 emission reductions in digestion through steam recovery integration.

2. Methodologies

2.1 Exit Flue Gas across Different Calcination Scenarios

Table 1 summarizes the flue gas compositions for four calcination pathways, based on process simulations performed in Aspen Plus. In conventional natural gas/air calcination, the flue gas comprises approximately 47 % N_2 and 9 % CO_2, together with 43 % steam. Switching to H_2/air combustion eliminates CO_2 emissions, however, the flue gas still contains 48 % N_2 introduced from air. In contrast, H_2 in oxy-steam calcination generates high-purity steam (above 99 %) and completely avoids nitrogen dilution by using pure oxy-steam combustion atmosphere, with recirculated superheated steam for solids transport. The fully electrified calcination eliminates combustion entirely, generates pure steam. The exhausted gas conditions from the calciner provide a comparative basis for evaluating the steam recovery potential from each calcination scenarios.

Table 1. Exit gas condition from calcination (with 120 t/h Al_2O_3 capacity).

		Scenario 1	Scenario 2	Scenario 3	Scenario 4
		Natural gas/air	H_2/air	Fully electrified	H_2 in oxy-steam
Gas volume	m^3/s	87	90	85	85
Temperature	°C	165	165	176	167
Pressure (Absolute)	bar	1.06	1.06	1.06	1.06
Gas components (Mass Fraction)					
N_2	%	46.9 %	47.9 %		
CO_2	%	9.3 %			
O_2	%	1.1 %	4.2 %		0.8 %
H_2O	%	42.8 %	47.9 %	100.0 %	99.2 %
Total gas flow	t/h	210	205	159	163
Density of gas	kg/m^3	0.67	0.64	0.52	0.53

2.2 Steam Recovery for Scenarios 1 and 2

Figure 1 illustrates the integrated gas separation and steam recovery system, adapted from the previous study [5]. Exit gas from the calciner is directed into a spray tower by a fan, which overcomes the tower's pressure drop, approximately 0.04 bar [14]. Inside the tower, cooling water is sprayed from the top and flows counter-currently to the rising gas stream, enabling heat transfer and condensation of water vapor at the bottom of the tower. The condensate warm water passes through a series of fine-particle filters to remove entrained solids before being pumped to flash tanks [15, 16], where a portion of the water is evaporated to low-pressure steam. The resulting vapor is subsequently compressed to 8 bar using multi-stage mechanical vapor recompression (MVR) units. To support continuous operation, the process water is cooled to 40 °C in a cooling tower and recirculated to the spray tower. A recirculation tank is also used to automatically supply make-up water as needed.

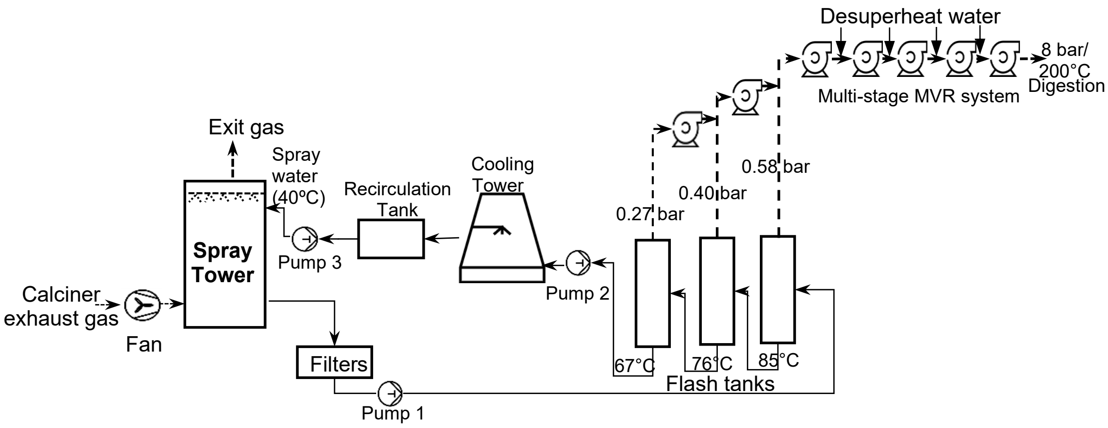

Figure 1. Integrated spray tower and steam recovery system (adapted from the study [5]).

2.3 Steam Recovery for Scenarios 3 and 4

Figure 2 presents the proposed integrated system for fine particle removal and steam compression. A venturi scrubber is used to achieve further particle removal, while a multi-stage MVR handles steam compression. To overcome the pressure drop across the calciner, a blower is used to raise steam pressure to 1.1 bar, enabling partial recirculation to the calciner circuit [8, 17, 18]. A steam ejector can also serve this function. However, its reliance on motive steam reduces the overall system efficiency by approximately 20 %, despite slightly increase in steam mass flow with the additional motive steam. Therefore, a centrifugal blower is selected in this study [19–21]. A portion of the superheated steam, ~62 t/h in the H_2 in oxy–steam and 84 t/h in the fully electrified calcination, is recirculated to the calciner circuit as the carrier gas. Prior to the particle removal, de-superheating water is sprayed into the steam to bring it close to saturation conditions. Inside the venturi scrubber, a pressure drop of 0.2 bar is assumed in present study, induced by high-velocity gas flow. This enhances particle-droplet interactions and enables over 80% capture efficiency for particles smaller than 2 μm [12–14]. After that, cleaned steam exits the scrubber and is compressed in a four-stage MVR system, reaching 8 bar and 200°C for reuse in low-temperature digestion.

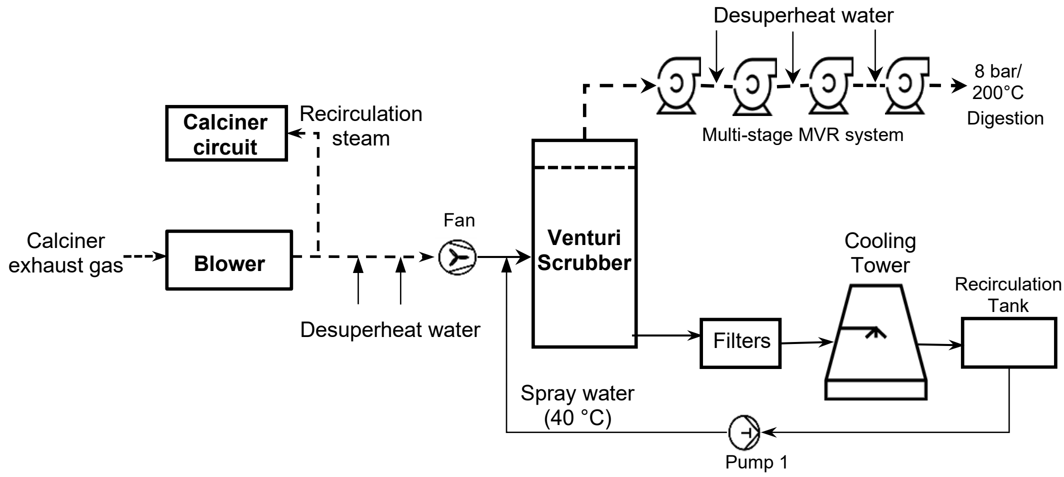

Figure 2. Integrated venturi scrubber and steam recovery system.

2.4 Steam Supply Scenarios in Digestion

Table 5 summarizes the various steam supply scenarios in digestion. The reference case represents the current steam generation method, in which natural gas-fired boilers are used to generate 2 t steam/t Al_2O_3 [5]. Scenarios 1 to 4 explore alternative steam recovery options from different calcination pathways: natural gas/air, H_2/air, fully electrified, and H_2 in O_2-steam calcination. Each scenario is modelled under two sub-scenarios, "a" which uses natural gas boilers to supply steam when recovery is insufficient, and "b" which replaces gas boilers with electric boilers.

Table 2. Steam supply scenarios in digestion usage.

	Steam recovery from calciner	Supplementary steam from boilers "a" Natural gas boiler, "b" Electric boilers	
Reference	N/A	Natural gas-fired boilers	
Scenario 1	Natural gas/air	S 1a	S 1b
Scenario 2	H_2/air	S 2a	S 2b
Scenario 3	Fully electrified	S 3a	S 3b
Scenario 4	H_2 in O_2-steam	S 4a	S 4b

2.5 Process Simulation

The steam recovery flowsheets shown in Figures 1 and 2 were modelled using Aspen Plus. An overview of the parameters assumed is summarized in Table 3.

Table 3. Overview of Aspen Plus Process Simulation Parameters Based on 120 t/h Al_2O_3 Calciner Capacity.

Scenarios	Unit	Blocks and assumptions used
Reference	Gas boiler	• Gas-fired boilers produce steam with temperature of around 200 °C and pressure around 8 bar. • Assuming an efficiency of 82 % [22, 23]. • A heater is used to model and calculate the energy demand for boiler with inlet water temperature of 40 °C.
Scenarios 1,2	Pumps	• Assuming an overall efficiency of 70 %, including both the pump hydraulic and motor efficiencies.
	Spray tower	• A two-outlet flash block operated at 1.06 bar pressure is used to simulate the heat exchange between gas and water in spray tower.
	Flash tanks	• Three connected two-outlet flash units operated at 0.58, 0.4, and 0.27 bar are used to simulate the evaporation process.

	MVR system	• A compressor with a specified compression ratio and a flash block operating at the post-compression pressure, where desuperheating water injected at each stage, to simulate a single stage of the compression process.
		• For multi-stage MVR, the units are connected in sequence.
		• 7-stage of MVR is used to compress low pressure vapor from 0.27 bar to 8.2 bar.
		• Assuming a modest isentropic efficiency of compressors of 76 % [24–26].
		  • Pressure ratio of stage 1: 1.48
		  • Pressure ratio of stage 2: 1.45
		  • Pressure ratio of stage 3–5: 1.76 for each stage
		  • Pressure ratio of stage 6: 1.68
		  • Pressure ratio of stage 7: 1.55

Scenarios 3,4	Venturi scrubber	• A two-outlet flash block operated at 1.1 bar pressure was used to simulate water condensation in venturi scrubber.
	Blower	• Assuming an overall blower efficiency of 70 %, accounting for both mechanical and motor efficiencies.

	MVR system	• For compressing low pressure vapor from 1.1 bar to 8.2 bar, 4-stage MVR is used.
		• Assuming a modest isentropic efficiency of compressors of 76 % [24–26].
		  • Pressure ratio of stages 1–2: 1.76 for each stage.
		  • Pressure ratio of stage 3: 1.7
		  • Pressure ratio of stage 4: 1.42

	Electric boiler	• Assuming efficiency of 98 % [27, 28]. • A heater is used to estimate energy consumption with inlet water temperature of 40 °C.
Note: all pressures in this study are absolute pressures.		

3. Results and Discussion

3.1 Energy Consumption in Steam Recovery

Figure 3 compares the energy consumed in steam recovery and the corresponding recoverable steam across the four scenarios. Scenario 4 achieves the highest steam recovery, exceeding Scenarios 1 and 2 by 38 % and surpassing Scenario 3 by 25 %. This improvement is primarily due to the additional steam generation from hydrogen-oxygen combustion. In contrast, Scenario 3, based on fully electrified calcination, has lower net steam recovery of 77 t/h per calciner without the additional steam from fuel combustion. Scenarios 3 and 4 requires recirculation steam back to calciner circuit to transport solids and maintain volumetric flow rates and gas velocities comparable to those in natural gas/air calcination. As there are no additional combustion products from fuel burning in fully electrified calcination, a greater volume of recirculated steam is required to match the gas flow rates. The required recirculated steam flow rates are approximately 84 t/h and 60 t/h for Scenarios 3 and 4 based on calcination process simulations, respectively. In Scenarios 1 and 2, the lower efficiency of the flash vessels limits steam recovery of 70 % of the exhaust steam from the calciner, resulting in net amount of approximately 65 t/h and 66 t/h, respectively. Although Scenario 4 achieves the greatest steam recovery, it requires the highest electrical input of 15.4 MW, which is approximately 14 % higher than Scenarios 1 and 2, and 25 % higher than Scenario 3. The energy breakdown shows that electric power required in MVR system dominates overall energy consumption, accounting for 91–95 % of the energy input. The electrical energy to the fans contributes approximately 5% in Scenarios 1 and 2 and increases to 9% due to the higher pressure drop across the venturi scrubber in Scenarios 3 and 4. Power input in pumps remain negligible (~0.04 MW).

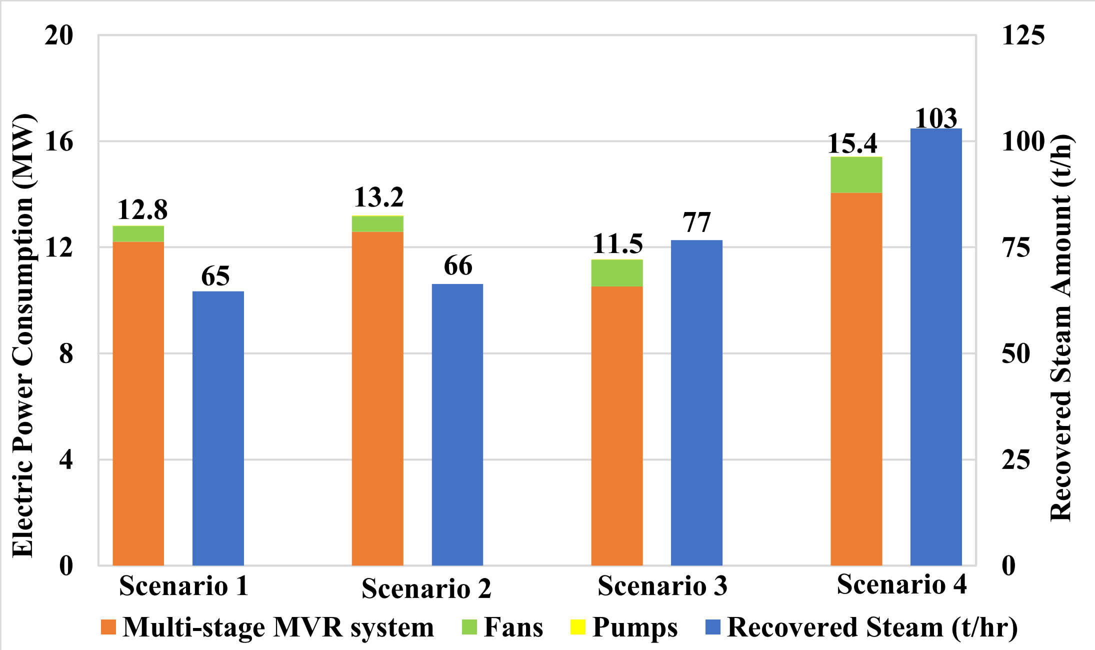

Figure 3. Energy consumption breakdown, and recovered steam in Scenarios 1 to 4.

As shown in Figure 4, when normalized by energy consumption per tonne of recovered steam, Scenarios 3 and 4 demonstrate the highest energy efficiency, requiring approximately 0.54 GJ/t steam, compared to 0.71 GJ/t steam in Scenarios 1 and 2. This improved performance is due to the elimination of unnecessary condensation and re-evaporation steps, which preserves the evaporation enthalpy. Additionally, flashing water to low-pressure steam in scenarios 1 and 2 results in larger overall steam compression ratio, thereby requiring higher MVR energy input for compression. Steam recovery configurations show significant energy efficiency improvement compared with steam generation from natural gas boilers, conserving 89–84 % energy. Compared to electric boilers, energy savings range from 74 to 80 %.

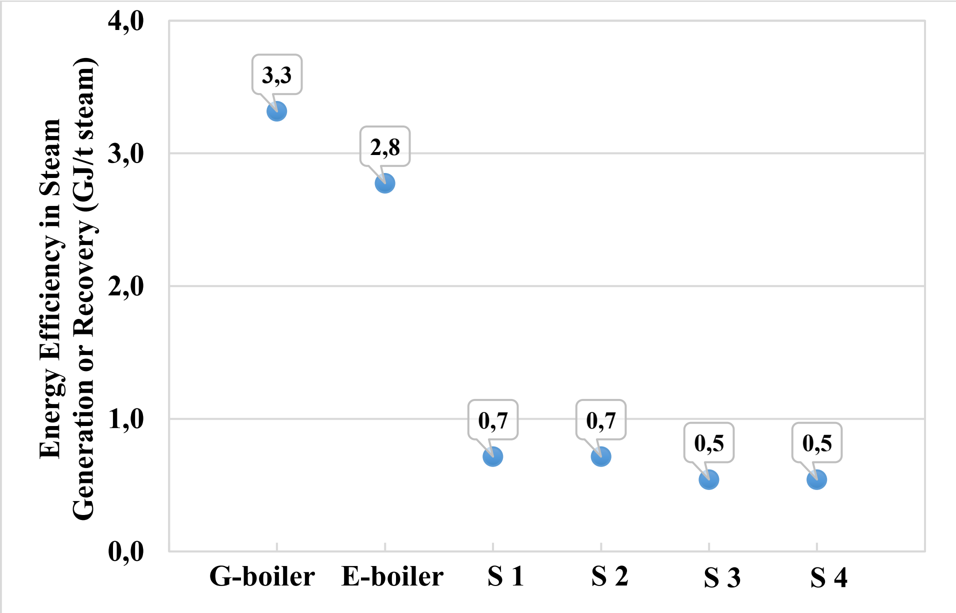

Figure 4. Energy efficiency of steam generation and recovery in Scenarios 1 to 4. (S 1-S 4: Scenario 1-Scenario 4)

3.2 Steam Supply in Scenarios 1 to 4

Figure 5 presents the amount of recoverable steam, and the supplementary steam supply from boilers across Scenarios 1 to 4. In the reference case, where no steam recovery is implemented, approximately 2 t steam/t Al_2O_3 is consumed in digestion, all supplied by natural gas boilers. In Scenario 1, partial steam recovery is achieved, with 0.54 t steam/t Al_2O_3 recovered from the calciner. This satisfies only approximately 27 % of the total digestion steam demand, leaving the remaining 73 % supplied from boiler-generated steam. Scenario 2 shows a similar recovery level at 0.55 t steam/t Al_2O_3. Scenario 4, based on H_2 in oxy-steam calcination, achieves the highest steam recovery, reaching 0.86 t steam/t Al_2O_3. This significantly reduces the supply steam from boilers by 43 %.

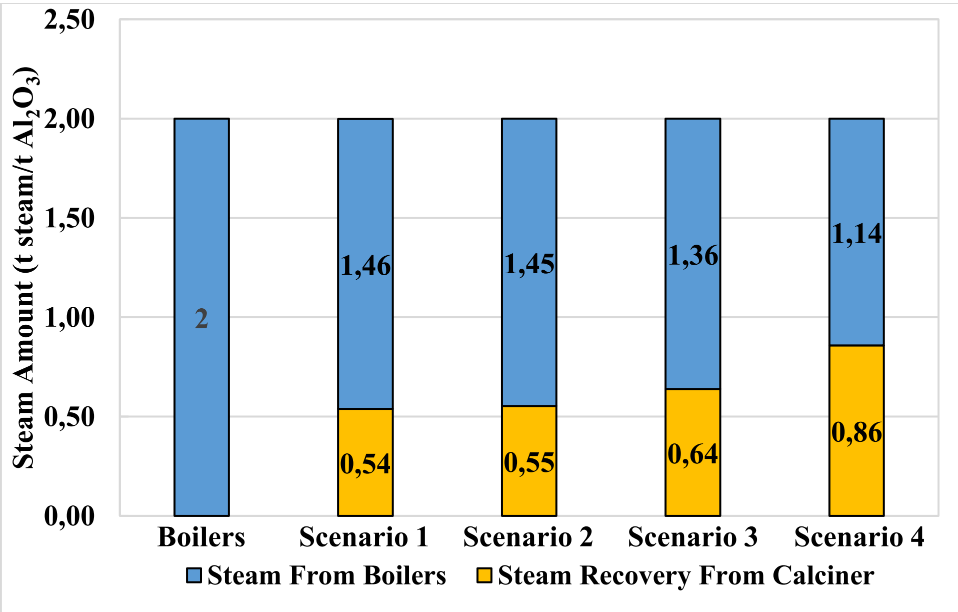

Figure 5. Recovered and supplementary steam amount in Scenarios 1 to 4.

3.3 Energy Consumption in Digestion in Scenarios 1a to 4b

Figure 6 presents the calculated energy consumption in digestion across Scenarios 1a to 4b, highlighting the impact of steam recovery. Natural gas boilers consume approximately 6.63 GJ/t Al_2O_3 to generate 2 t steam/t Al_2O_3 at 200 °C and 8 bar. Scenarios 1a and 2a lower the energy consumption to 5.2 GJ/t Al_2O_3, when partial steam recovery is implemented along with gas boilers. Scenario 3a achieves a 27 % energy reduction, lowering energy consumption to 4.9 GJ/t Al_2O_3. Scenario 4a achieves the lowest digestion energy use, at 4.2 GJ/t Al_2O_3, representing a 36 % reduction relative to the baseline. This improvement is primarily attributed to reduced steam supply from boilers and efficient steam recovery processes. Replacing gas boilers with electric boiler achieves an additional 15 % energy reduction. Scenario 4b demonstrates the lowest energy demands, at 3.6 GJ/t Al_2O_3, corresponding to a 45 % reduction relative to the reference gas boilers case. These results emphasize the significant energy savings potential by integrating high-efficiency steam recovery systems.

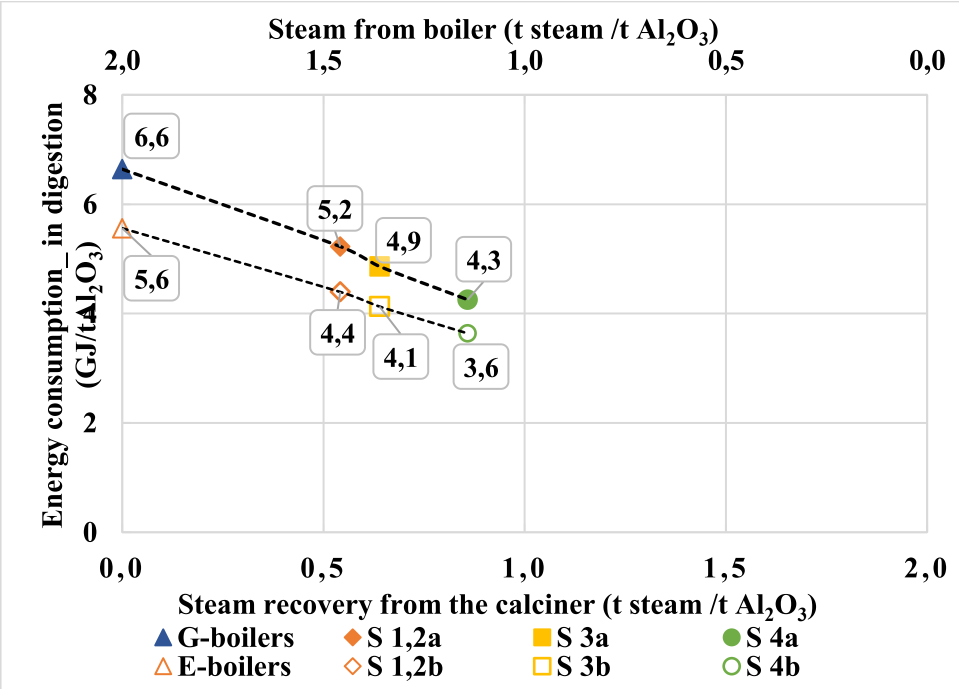

Figure 6. Energy consumption in digestion in Scenarios 1a to 4b. (G-boilers: Natural gas boilers, E-boilers: Electric boilers)

3.4 Carbon Emission Reduction in Scenarios 1a to 4b

Figure 7 presents the CO_2 emissions intensity across the four scenarios. In the reference case without recovery, emissions are highest at 0.37 t CO_2/t Al_2O_3, reflecting full reliance on natural gas boilers. In Scenarios 1a and 2a, with partial steam recovery (~27 %), emissions decrease to 0.27 t CO_2/t Al_2O_3. Scenarios 3a and 4a further lowers emissions to 0.25 and 0.21 t CO_2/t Al_2O_3, respectively, due to higher steam recovery rate. Furthermore, zero CO_2 emissions can be achieved in digestion when replacing natural gas boilers with electric boilers. Overall, the results clearly show that increasing steam recovery, combined with transitioning to low-carbon or renewable energy sources, substantially reduces the carbon footprint in alumina refining.

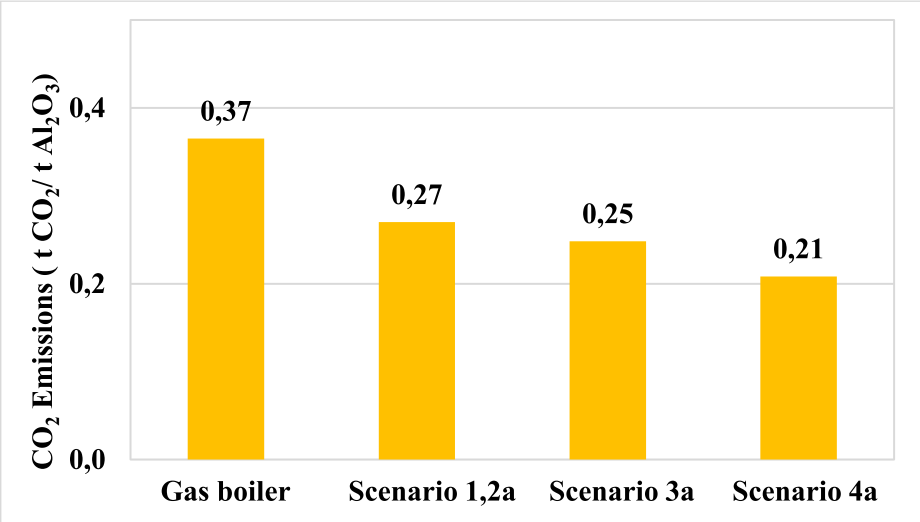

Figure 7. CO_2 emission in Scenarios 1a to 4a compared with natural gas boilers.

4. Conclusions

Integrating efficient steam recovery from air-combusted calcination, such as natural gas/air and H_2/air, can meet approximately 27 % of the steam demand in digestion, thereby reducing digestion energy use from 6.63 to 5.2 GJ/t Al_2O_3. Recovering high purity steam from fully electrified or H_2 in oxy-steam calcination can meet 32 % and 43 % of the steam usage respectively, reducing energy consumption to 4.8 and 4.2 GJ/t Al_2O_3. This corresponds to a CO_2 emissions reduction of 27–43 %. Compared to recovering diluted steam from air-combusted calciners, recovering pure steam demonstrates higher energy efficiency and yields a greater amount of recoverable steam. The process consumes 0.54 GJ/t steam for pure steam recovery, compared to 0.71 GJ/t steam for diluted steam recovery. Furthermore, replacing natural gas boilers with electric boilers achieves an additional 15% energy reduction, reducing digestion energy use to 3.6 GJ/t Al_2O_3 when incorporating steam recovery. The study highlights the potential of calcination steam recovery integration for both decarbonization and energy saving in alumina refining.

5. Acknowledgements

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