

Article

Screening-Level Conceptual, Stoichiometric, and Scenario Assessment of Sulfur-Emission Valorization in Coal-Fired Power Plants in Türkiye

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Abstract

This study presents a screening-level conceptual, stoichiometric, and scenario assessment of a pathway linking sulfur dioxide (SO_2) capture from coal-fired flue gas to sulfuric acid production and the downstream reaction of sulfuric acid with pretreated scrap aluminum. A regenerable sodium sulfite (Wellman–Lord) capture route, followed by gas polishing and drying, catalytic SO_2 oxidation, controlled SO_3 absorption, acid conditioning, and an $\text{Al-H}_2\text{SO}_4$ reactor, is used as the reference configuration. The sulfur balance distinguishes sulfur in coal, ash retention, gaseous SO_x , SO_3 /acid mist, absorber inlet and stack slip, captured sulfur, regenerated sulfur, and sulfate purge. Under the central assumptions, 1 t of sulfur in coal yields 0.849 t of recovered sulfur equivalent, 2.599 t of H_2SO_4 , 0.477 t of aluminum feed, 2.419 t of anhydrous-equivalent $\text{Al}_2(\text{SO}_4)_3$, 4.240 t of commercial aluminum sulfate on a 17 wt% Al_2O_3 basis, and 42.4 kg of H_2 at 80% aluminum conversion. The upstream base-energy screen is 3.3–7.2 GJth and 0.18–0.45 MWhe per tonne of sulfur in coal. Diluting the acid to the selected 0.5–1.0 M aluminum-reaction window and subsequently producing a 17 wt% Al_2O_3 product creates a minimum water-removal load of 21.6–47.6 t and a latent-heat floor of approximately 49–108 GJth/t S. Retail prices are replaced by 2024 customs unit values, and internal-acid-production and sulfuric-acid-opportunity-cost boundaries are evaluated separately. In the central opportunity-cost case, the H_2 value must reach approximately 6.9 USD/kg merely to balance material values before CAPEX, OPEX, energy, purification, transport, and environmental-compliance costs. The Afşin–Elbistan A case is treated as a full-design-throughput illustration based on an historical 18 Mt/y coal requirement, not as a measured current operating average; coal sulfur is tested over 1.0–2.5 wt%. The aluminum step is restricted to cooled and diluted 0.5–1.0 M H_2SO_4 at 40–60 °C, and direct H_2 production from 96 to 98 wt% acid is not assumed. Plant-specific capacity factor, time-matched coal assays, flue-gas flow, oxygen-corrected stack data, reaction kinetics, gas purity, and product quality remain to be verified. The integrated sustainability screening indicates conditional circular-economy potential rather than a demonstrated sustainability advantage: sulfur recovery must be weighed against energy and water demand, sulfate purge and wastewater, diversion of recyclable aluminum from remelting, hydrogen purification, and market-scale product offtake. The pathway therefore remains a research hypothesis requiring experimental validation, process simulation, techno-economic assessment, comparative life-cycle assessment, safety analysis, and market verification.



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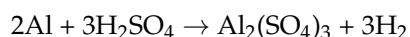
1. Introduction

Coal combustion produces pollutant streams through distinct chemical mechanisms. Fuel sulfur, including pyritic and organic sulfur, is oxidized mainly to SO₂ and partly to SO₃; pyritic sulfur is not the source of CO₂ or NO_x. CO₂ results primarily from oxidation of fuel carbon, whereas NO_x forms from fuel-bound nitrogen and thermal fixation of atmospheric N₂. Coal also contains naturally occurring radionuclides; combustion can concentrate these radionuclides in fly ash and bottom ash, but ash does not create radon. Any radon release would arise from radioactive decay of pre-existing radium in coal or ash [1,2]. SO₂ control remains necessary because sulfur oxides contribute to acid deposition, atmospheric sulfate formation, equipment corrosion, and adverse environmental and health effects [3,4]. Plant-specific fuel properties, combustion conditions, and emission-control performance are therefore essential inputs [1,5,6].

Conventional flue-gas desulfurization (FGD) technologies include wet and dry scrubbing, sorbent injection, spray-dry absorption, and regenerable capture processes [7–9]. Wet limestone FGD is widely applied and generally converts SO₂ into calcium sulfite- or gypsum-containing streams. These systems are designed primarily to meet emission limits rather than to generate a diversified portfolio of chemical products. Their resource-utilization performance depends on gypsum quality and marketability, water use, sludge generation, and residual-waste management [8,9].

An alternative strategy is to recover or concentrate SO₂ and convert it into sulfuric acid. This route requires substantially more than direct contact between stack gas and water. Coal-fired flue gas must undergo particulate removal, cooling and conditioning, SO₂ capture or concentration, gas polishing and drying, catalytic oxidation of SO₂ to SO₃, controlled SO₃ absorption, acid-mist control, corrosion management, and product-acid finishing [7–15]. The low SO₂ concentration and the presence of water vapor, particles, NO_x, metals, halogens, and other impurities distinguish flue-gas-derived acid production from conventional sulfuric acid plants supplied with cleaner and more concentrated sulfur feeds. Consequently, the SO₂-to-H₂SO₄ stage is the principal engineering uncertainty in the proposed valorization pathway.

Sulfur compounds have also been investigated in hydrogen-production systems, including sulfur–iodine, hybrid-sulfur cycles and SO₂-depolarized electrolysis [16–21]. These routes use sulfur-containing intermediates in thermochemical or electrochemical cycles and are fundamentally different from the pathway examined here. In the present pathway, hydrogen is not produced directly from flue gas or through a sulfur-based electrolysis cycle; SO₂-derived H₂SO₄ is instead used as an intermediate that reacts with scrap aluminum to co-produce aluminum sulfate and hydrogen. Hydrogen is an energy carrier that must be produced from another energy or material source, not a primary energy source [22]. Steam-methane reforming and water electrolysis are used as benchmark hydrogen-production routes [23].



The Al–H₂SO₄ reaction is chemically established, but practical aluminum dissolution and hydrogen evolution depend on acid concentration, temperature, alloy composition, surface-oxide behavior, impurities, and mass-transfer conditions [24–26]. The stoichiometric equation therefore defines only theoretical maximum quantities; it does not establish the actual hydrogen yield, reaction rate, product purity, or reactor performance.

The relevant literature can be grouped into three largely separate areas. Conventional FGD focuses primarily on compliance with SO₂ emission limits and commonly generates gypsum or other sulfur-containing by-products and waste streams [7–9]. Flue-gas-based

sulfuric acid production focuses on gas cleaning, SO_2 recovery or concentration, catalytic oxidation, SO_3 absorption, acid quality, corrosion, and acid-mist control [7,9,11–15]. Sulfur-based hydrogen research investigates sulfur-iodine cycles, hybrid-sulfur cycles, and SO_2 -depolarized electrolysis [16–21]. The underlying reactions are established, although the technological maturity of the complete process routes varies.

The contribution of this study is a screening framework that connects these otherwise separately evaluated domains. Within a common system boundary, the framework links sulfur recovered from coal-fired flue gas to H_2SO_4 production and then to the use of pretreated scrap aluminum for the co-production of $\text{Al}_2(\text{SO}_4)_3$ and by-product H_2 . The pathway is evaluated as a material-flow and scenario hypothesis under Türkiye-specific coal-fired-power-plant conditions, not as a proven process design.

More specifically, the study contributes by:

1. Defining the process boundary and theoretical material relationships among recovered SO_2 , H_2SO_4 , scrap Al, $\text{Al}_2(\text{SO}_4)_3$, and H_2 ;
2. Applying the framework to an illustrative Afşin–Elbistan case using explicit assumptions for coal consumption and sulfur content;
3. Examining how sulfur-recovery efficiency, Al– H_2SO_4 conversion, and input–product price assumptions affect the screening result;
4. Comparatively positioning the proposed pathway against wet-limestone flue-gas desulfurization, conventional contact-process sulfuric acid production, and sulfur-based hydrogen-production routes; and
5. Identifying the experimental, process-simulation, techno-economic, life-cycle, and safety evidence required before technical feasibility or sustainability claims can be made.

Accordingly, the contribution should be understood as a Türkiye-specific comparative screening and research-prioritization framework. It is not a new sulfuric-acid-production method, a new hydrogen-production reaction, or an industrially validated process.

Plant-level emission studies show that sulfur-control and resource-utilization proposals must be assessed in a technology- and site-specific context. Tong et al. [5] demonstrated that mitigation pathways depend on unit characteristics, fuel quality, control technology, coal demand, and retrofit or retirement strategies. Filonchyk and Peterson [6] likewise showed that aggregate emission trends can conceal substantial differences among individual plants. Time-matched, unit-level data on fuel, load, flue gas, and control-device operation are therefore required before the present pathway can be generalized.

The objective of this screening-level conceptual, stoichiometric, and scenario assessment is to integrate the established SO_2 -to- H_2SO_4 and Al– H_2SO_4 steps within a common analytical boundary; quantify the associated sulfur, material, water, and energy flows; test sensitivity to recovery, conversion, and price assumptions; and identify the evidence required for experimental and engineering validation.

Unlike conventional $\text{Al}_2(\text{SO}_4)_3$ -production studies, this work evaluates a route in which sulfur recovered from SO_2 -containing flue gas is converted to H_2SO_4 and then reacted with pretreated scrap aluminum. Potential heat recovery from absorbent regeneration, catalytic oxidation, acid absorption, and power-plant waste heat is treated as a conditional integration opportunity rather than an automatic energy credit [9,13,15].

Accordingly, the study addresses six questions: (1) How is sulfur distributed among ash retention, SO_2 , SO_3 /acid mist, capture, regeneration, purge, and stack emissions? (2) What operating window is technically plausible for a regenerable SO_2 -capture and enrichment route? (3) What material and screening-level energy balances follow per tonne of sulfur in coal? (4) How should aluminum-feed composition, reaction conditions, side reactions, and aluminum sulfate product form be represented? (5) How do the internal-acid-

production-cost and acid-opportunity-cost boundaries affect the economic interpretation? (6) Are the required scrap-aluminum supply and product offtake compatible with the scale of the Türkiye market?

The assessment provides a closed screening sulfur/material balance, a route-specific operating envelope, an energy range, customs-based material-value proxies, market-capacity checks, and explicit uncertainty scenarios. The formal scope and evidence-status categories are defined in Section 2.

2. Materials and Methods

This study is a screening-level conceptual, stoichiometric, and scenario assessment of the conversion of sulfur recovered from SO₂-containing flue gas into H₂SO₄ and the subsequent reaction of H₂SO₄ with pretreated scrap aluminum to produce Al₂(SO₄)₃ and H₂. The calculations include sulfur, material, water, screening-energy, market, and economic-boundary indicators. They do not assume that sulfate (SO₄^{2−}) exists as an isolated feedstock or that sulfuric acid can be obtained directly from untreated stack gas.

The quantitative scope comprises sulfur/material balances, water and screening-energy calculations, market-scale comparators, and material-value boundaries. Integrated experiments, pilot testing, engineering-grade simulation, equipment sizing, TEA, LCA, and HAZOP are outside the present scope. The principal engineering uncertainty is the SO₂-to-H₂SO₄ train, including gas cleaning, regeneration, catalytic oxidation, absorption, corrosion, product finishing, and waste handling [7–9,11–15].

Evidence status is distinguished throughout as: (i) calculated results derived from stated equations and balances; (ii) the literature-supported screening parameters; (iii) author-defined exploratory assumptions; and (iv) unavailable or unverified plant-specific data. Table 1 identifies these categories for the sulfur-balance parameters; the Results section reports calculated outputs, while transferability and validation needs are reserved for the Discussion and Limitations

2.1. Conceptual Process Flow Configuration

The proposed pathway is represented as a conceptual process flow rather than a detailed engineering design. It begins with SO₂-containing flue gas leaving coal combustion and proceeds through particulate removal, flue-gas cooling and conditioning, regenerable SO₂ capture, absorbent regeneration and sulfur recovery, gas polishing and drying, catalytic oxidation of SO₂ to SO₃, controlled sulfuric acid absorption, acid conditioning, the Al–H₂SO₄ reaction, gas–liquid separation, hydrogen purification and compression, and aluminum sulfate finishing [7–9,11–15].

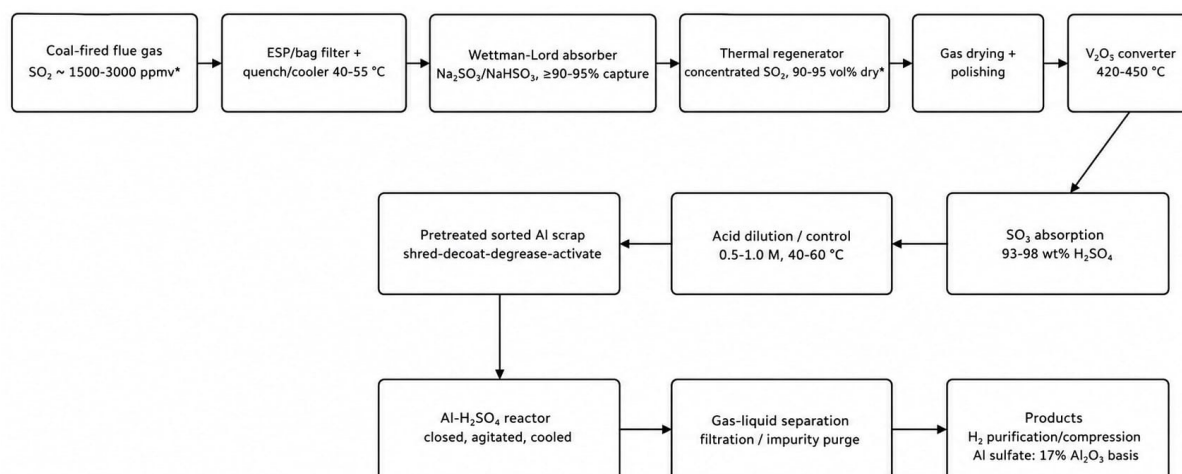
The conceptual process flow is summarized in Figure 1.

2.1.1. System Boundary, Functional Unit, and Reporting Basis

The primary functional unit is 1 metric tonne of sulfur contained in coal entering combustion (1 t S). All sulfur streams are reported on a sulfur-mass basis so that coal sulfur, ash-retained sulfur, gaseous SO₂/SO₃, captured sulfur, recovered sulfur, purge sulfur, and stack sulfur can be reconciled without mixing sulfur mass with molecular SO₂ mass. Molecular products are then derived from the recovered-sulfur stream. Plant-scale quantities are secondary scale-up results. The downstream aluminum sulfate balance is reported both as anhydrous Al₂(SO₄)₃ equivalent and as a commercial product standardized to 17 wt% Al₂O₃; the commercial basis is used only for the customs-value screening [27].

The functional unit is referenced to sulfur in coal entering combustion, whereas the quantitative process boundary begins with the SO₂-containing flue gas entering the sulfur-control train and ends at the plant gate with aluminum sulfate product and puri-

fied/compressed hydrogen. The boundary includes particulate removal, flue-gas cooling, SO₂ absorption, absorbent regeneration, gas polishing and drying, catalytic oxidation, SO₃ absorption, acid conditioning, scrap-aluminum pretreatment, reaction, gas-liquid separation, filtration, product finishing, recycle, wastewater, purge solids, and stack emissions. Coal mining, boiler operation, electricity generation, product transport, product use, and end-of-life are outside the quantitative boundary. Coal combustion is used only to define the sulfur reference flow and is not included as an energy or cost burden of the valorization process.



* Screening design values; plant-specific inlet concentration and recovered gas composition require stack testing and vendor design.

Figure 1. Selected reference route for the screening assessment. The diagram specifies a sodium-sulfite Wellman–Lord absorber/regenerator, concentrated-SO₂ polishing, V₂O₅-catalyzed oxidation, controlled acid absorption, acid dilution, a pretreated-aluminum reactor, gas-liquid separation, hydrogen purification/compression, and aluminum sulfate finishing. Values marked with an asterisk are screening design values rather than Afşin–Elbistan measurements.

2.1.2. Sulfur-Balance Parameters, Sources, and Evidence Levels

Five process-performance parameters and one recycle-recovery assumption are used. The sulfur-conversion rate (η_{conv}) is the fraction of sulfur in coal converted to gaseous SO_x; f_{SO_3} is the fraction of gaseous SO_x represented as SO₃/acid mist; η_{cap} is absorber SO₂ capture; η_{rec} is recovery of captured sulfur as concentrated SO₂; η_{Al} is downstream aluminum conversion; and η_{recycle} is recovery of unreacted acid and aluminum. Evidence levels are defined as follows: Level A, plant-specific measured or official operating data; Level B, established regulatory or industrial-performance evidence; Level C, peer-reviewed laboratory or the literature-derived evidence; and Level D, an author-defined exploratory assumption. Table 1 identifies the source, evidence level, and applicability limit for each parameter. No Level A value is available for the integrated Afşin–Elbistan configuration.

Table 1. Parameter sources, evidence levels, and screening ranges used in the sulfur balance.

Parameter and Definition	Conservative	Central	Optimistic	Source and Evidence Type	Evidence Level/Applicability
η_{conv} —coal S converted to gaseous SO _x	0.90	0.95	0.98	AP-42 coal-combustion guidance [1]	B—regulatory default; not a plant-specific sulfur balance
f_{SO_3} —SO ₃ /acid-mist fraction of gaseous SO _x	0.020	0.010	0.005	The coal-boiler SO ₃ literature [10,11]	C—fuel, boiler, catalyst, and control-system dependent

Table 1. Cont.

Parameter and Definition	Conservative	Central	Optimistic	Source and Evidence Type	Evidence Level/Applicability
η_{cap} —SO ₂ capture in absorber	0.90	0.95	0.98	FGD review and EPA Wellman–Lord report [9,15]	B–C—published process range; not a vendor guarantee
η_{rec} —captured sulfur recovered as concentrated SO ₂	0.90	0.95	0.98	Wellman–Lord regeneration evidence [22,23]	B–C—affected by oxidation, purge, and regenerator operation
η_{Al} —Al–H ₂ SO ₄ conversion	0.60	0.80	0.90	Dilute-acid laboratory studies [24–26]	C—not validated for mixed scrap or the integrated process
η_{recycle} —recovery of unreacted acid and Al	0.80	0.90	0.95	Author-defined mass-accounting sensitivity	D—exploratory assumption; no measured recovery data

The recovered-sulfur fraction is calculated as $\eta_{\text{S,rec}} = \eta_{\text{conv}}(1 - f_{\text{SO}_3})\eta_{\text{cap}}\eta_{\text{rec}}$. Stack SO₂ slip, SO₃/acid mist, ash retention, and sulfate purge are reported separately; consequently, the sulfur balance closes to 1.000 t S per functional unit. The parameter ranges are screening bounds, not probability distributions; only η_{recycle} is a purely author-defined assumption.

2.1.3. Selected SO₂ Capture, Enrichment, and Acid-Production Route

The reference configuration uses a regenerable sodium-sulfite Wellman–Lord route because it separates SO₂ capture from sulfur recovery and produces a concentrated SO₂ stream suitable for a sulfuric acid plant (Table 2). Flue gas is cleaned of particulate matter and cooled to approximately 40–55 °C. SO₂ is absorbed in aqueous Na₂SO₃ to form NaHSO₃. The rich solution is filtered and thermally regenerated, returning lean Na₂SO₃ to the absorber and releasing concentrated SO₂. A sulfate-rich purge is required because oxygen and SO₃ irreversibly oxidize part of the sulfite. The recovered gas is polished and dried, heated to the catalytic operating window, oxidized over a vanadium catalyst, and absorbed under controlled sulfuric acid conditions [9,15].

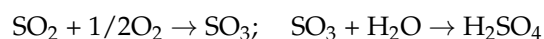
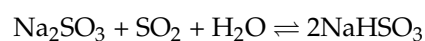


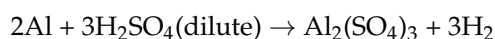
Table 2. Reference operating window for the selected route.

Unit Operation	Screening Operating Window	Specified Output/Control Point
Pretreatment and quench	Particulate removal; 40–55 °C absorber inlet	Low solids; temperature below absorbent degradation/evaporation range
Wellman–Lord absorber	Aqueous Na ₂ SO ₃ /NaHSO ₃ ; counter-current packed beds	90–98% SO ₂ capture; outlet commonly targeted below 100–200 ppmv
Regeneration	Vacuum/steam-assisted thermal evaporation	Concentrated SO ₂ , approximately 90–95 vol% on a dry screening basis; Na ₂ SO ₃ recycle
Gas polishing/drying	Demisting, trace contaminant removal, acid drying	Catalyst-protection specification; low moisture and particulates
Catalytic oxidation	V ₂ O ₅ catalyst; approximately 420–450 °C; excess O ₂	High SO ₂ -to-SO ₃ conversion with inter-bed heat management
Absorption/acid finishing	SO ₃ absorbed in circulating 97–98 wt% acid; controlled dilution	93–98 wt% H ₂ SO ₄ product; acid-mist control

The illustrative absorber-inlet range of 1500–3000 ppmv SO₂ and the recovered-gas concentration are screening design assumptions rather than Afşin–Elbistan measurements. Plant-specific stack testing must establish flue-gas flow, moisture, SO₂/SO₃, particulate matter, halogens, metals, oxygen concentration, and load dependence before equipment sizing.

2.2. Aluminum–Sulfuric Acid Reaction Conditions and Side Reactions

The upstream sulfuric acid product and the aluminum-reactor feed are treated as distinct process streams. The contact/absorption section may produce approximately 93–98 wt% H₂SO₄, but this acid must be cooled and diluted before the reference hydrogen-producing reaction. The reactor is evaluated only at 0.5–1.0 M H₂SO₄ (approximately 5–10 wt%), 40–60 °C, controlled agitation, and a freshly activated aluminum surface. Studies conducted in 0.1–1.0 M sulfuric acid media [24–26] support this dilute-acid screening window; they do not validate direct use of 96–98 wt% acid. Reactor temperature, pressure, acidity, induction time, gas-evolution rate, and hydrogen concentration must be monitored continuously. Dilution creates a major water-management burden unless a dilute aluminum sulfate solution is marketable or a different experimentally validated reactor/product configuration is selected.



Concentrated sulfuric acid is excluded from the reference hydrogen case. Aluminum may passivate in concentrated acid at low temperature, whereas hot concentrated sulfuric acid may act as an oxidizing acid and generate SO₂ rather than H₂. The relevant side reaction is:



Consequently, the model does not assume that increasing acid concentration or temperature increases hydrogen yield. The crude reactor gas may contain H₂, water vapor, sulfuric acid aerosol or entrained droplets, air-derived N₂/O₂ introduced through leakage, and—if coatings or unsuitable acid conditions are present—VOCs and SO₂. It is therefore not a saleable hydrogen stream. A closed, pressure-relieved system with ignition control, demisting, cooling, drying, gas analysis, purification, and compression is required. Saleable hydrogen must be calculated by multiplying crude H₂ by a measured purification/recovery efficiency; no purification efficiency is assumed in the stoichiometric result.

At 298.15 K, the standard potential of the Al³⁺/Al couple is −1.677 V, whereas the H⁺/H₂ standard electrode is 0 V [28]. For the ideal ionic reaction 2Al(s) + 6H⁺(aq) → 2Al³⁺(aq) + 3H₂(g), E°_{cell} = 1.677 V and ΔG° = −nFE° = −(6)(96,485 C/mol)(1.677 V) ≈ −970.8 kJ per reaction as written, or −485.4 kJ per mole of Al. This value applies only to standard aqueous ionic states at 25 °C and 1 bar H₂. It is not a Gibbs-energy value for 96–98 wt% sulfuric acid, a specific aluminum sulfate hydrate, or a passivating alloy system. Activities, sulfate complexation, alloying elements, oxide films, and side reactions must be included in a rigorous thermodynamic and kinetic model.

2.2.1. Scrap-Aluminum Source, Composition, and Pretreatment

The reference feed is sorted post-industrial or post-consumer wrought-aluminum scrap with documented provenance. AA6061 is proposed as one reproducible reference alloy, with the following composition limits (wt%): Si 0.40–0.80, Fe ≤ 0.70, Cu 0.15–0.40, Mn ≤ 0.15, Mg 0.80–1.20, Cr 0.04–0.35, Zn ≤ 0.25, Ti ≤ 0.15, other elements ≤ 0.05 each and ≤ 0.15 total, balance Al [29]. This benchmark is not assumed to represent mixed scrap. Each batch must be characterized by supplier certification and/or XRF. Mixed cast scrap,

laminated foil, heavily painted architectural scrap, oily turnings, and copper- or steel-attached components should be excluded unless separately characterized. Pretreatment comprises magnetic and density separation, removal of fasteners and copper attachments, shredding, validated thermal or mechanical decoating, alkaline degreasing, rinsing, drying, and fresh abrasion or controlled chemical activation immediately before acid addition. Induction time, exposed surface area, oxide-removal method, and evidence of repassivation must be reported. Pretreatment wastewater, off-gas, coatings, fines, and insoluble residue remain within the material-accounting boundary (Table 3).

Table 3. Expected effects of common scrap-aluminum constituents.

Constituent/Condition	Expected Process Effect	Required Control
Mg	Reacts readily with acid; increases H ₂ evolution but changes stoichiometry and sulfate composition	Alloy assay; separate Mg balance; gas-rate control
Zn	Acid dissolution and additional H ₂ ; ZnSO ₄ contaminates product	Limit high-Zn alloys; analyze Zn in solution/product
Si	Partly insoluble silica/silicate residue; filtration and gel risk	Solid–liquid separation; filterability testing
Fe	Colored/metallic impurity; may prevent water-treatment-grade product	Feed specification; oxidation/precipitation or product downgrade
Cu	Galvanic acceleration, possible H ₂ contamination pathway and product-quality concern	Remove copper attachments; strict Cu limit
Coatings/oils/plastics	VOC, foam, organic carbon, odor, gas contamination, wastewater load	Decoating, degreasing, off-gas treatment, TOC monitoring
Oxide layer	Induction period and incomplete conversion	Fresh abrasion/activation and controlled acid addition

Hydrogen purity and aluminum sulfate quality must be demonstrated experimentally. The gas-analysis plan should quantify H₂, O₂, N₂, water, SO₂, acid mist, CO/CO₂, hydrocarbons/VOCs, and sulfur-bearing trace contaminants. A buyer-specific product specification must be defined before a saleable quantity is reported. Fuel-cell-grade hydrogen may be claimed only if the applicable ISO 14687/SAE J2719 requirements are met [30,31], including the 99.97% dry-basis hydrogen benchmark and contaminant limits [32]. The aluminum sulfate product must be analyzed for Al₂O₃, free acid, Fe, Cu, Zn, Mg, Si, oils/TOC, insolubles, moisture, and physical form.

2.2.2. Aluminum Sulfate Product Basis

Stoichiometric calculations first report anhydrous Al₂(SO₄)₃ equivalent (molar mass 342.15 g/mol). Commercial comparisons use a product containing 17 wt% Al₂O₃, consistent with the product forms covered by AWWA B403-24 (liquid, ground, or lump) [27]. Because anhydrous Al₂(SO₄)₃ contains 29.80 wt% Al₂O₃, 1.000 t of anhydrous equivalent corresponds to 1.753 t of a product standardized to 17 wt% Al₂O₃. Product water is therefore not treated as a newly created chemical value. A liquid product could instead be reported on an Al₂O₃-concentration basis, but it would require a different transport and price basis.

$$m(\text{product, 17\% Al}_2\text{O}_3) = m(\text{anhydrous Al}_2(\text{SO}_4)_3) \times 0.2980/0.17$$

2.3. Complete Material Accounting and Recycle Logic

The central material balance is based on 1 t S in coal, the central sulfur parameters in Table 1, and $\eta_{Al} = 0.80$. The same flows are normalized per tonne of recovered concentrated SO_2 . Aluminum and pure-acid equivalent are fed at the stoichiometric ratio corresponding to recovered acid. The unreacted 20% is reported explicitly; 90% of each unreacted stream is assigned to recycle and 10% to purge or loss. Theoretical oxygen demand and the dilution, product-carrier, separation/recycle, and latent-heat calculations are reported separately.

Dilution, Water-Separation, and Latent-Heat Calculation

For the central case, the pure H_2SO_4 equivalent entering the downstream section is $m_{H_2SO_4} = 2.5995$ t/t S. For a target acid mass fraction w_{acid} of 0.05–0.10, the total reactor-solution mass and added dilution water are:

$$m(\text{solution}) = m(H_2SO_4)/w_{acid}$$

$$m(\text{dilution water}) = m(H_2SO_4) \times (1/w_{acid} - 1)$$

These equations give 25.995–51.990 t of total dilute reactor solution and 23.396–49.391 t of added dilution water per tonne of sulfur in coal. The central reaction produces 2.4191 t of anhydrous-equivalent $Al_2(SO_4)_3$, corresponding to 4.2405 t of commercial product on a 17 wt% Al_2O_3 basis. The non-anhydrous carrier allowance in that commercial product is therefore:

$$m(\text{product carrier}) = m(\text{product, 17\% } Al_2O_3) - m(\text{anhydrous equivalent}) = 1.8214 \text{ t/t S}$$

The minimum downstream water-separation or recycle load is calculated as:

$$m(\text{water separation/recycle}) = m(\text{dilution water}) - m(\text{product carrier}) = 21.574\text{--}47.569 \text{ t/t S}$$

Using a water latent heat of vaporization of 2.257 GJ/t at approximately 100 °C [33], the evaporation-only thermodynamic lower bound is:

$$Q_{latent} = m(\text{water separation/recycle}) \times 2.257 = 48.7\text{--}107.4 \text{ GJ/t S}$$

The rounded values reported in Tables 4 and 5 are 21.6–47.6 t/t S and 49–108 GJ/t S. This quantity is explicitly a separation/recycle load, not a claim that all water must be evaporated. The exact split among acid recycle, purge liquor, product water, evaporator condensate, wash water, and wastewater remains unverified and must be closed in a process simulation. Sensible heat, boiling-point elevation, heat losses, and equipment inefficiency are excluded from the latent-heat floor.

Table 4. Central material and water-accounting screen per tonne of sulfur in coal and per tonne of recovered SO_2 .

Stream	t per t S in Coal	Interpretation	t per t Recovered SO_2
Sulfur retained in ash/other non-gaseous forms	0.050	$1 - \eta_{conv}$	0.0295
Sulfur as SO_3 /acid mist	0.0095	1% of gaseous SO_x ; separate control requirement	0.0056
SO_2 -sulfur entering absorber	0.9405	Gaseous sulfur less SO_3 /acid mist	0.5540
SO_2 -sulfur captured	0.8935	$\eta_{cap} = 0.95$	0.5263
SO_2 -sulfur emitted as absorber slip	0.0470	Uncaptured SO_2	0.0277

Table 4. Cont.

Stream	t per t S in Coal	Interpretation	t per t Recovered SO ₂
Sulfur recovered as concentrated SO ₂	0.8488	$\eta_{\text{rec}} = 0.95$	0.5000
Sulfur in sulfate purge/by-products	0.0447	Captured but not regenerated	0.0263
Recovered SO ₂ gas	1.6976	Molecular SO ₂ mass	1.0000
H ₂ SO ₄ to downstream section	2.5995	Theoretical acid from recovered sulfur	1.5313
Total dilute reactor solution at 5–10 wt% H ₂ SO ₄	26.0–52.0	$m(\text{H}_2\text{SO}_4)/w_{\text{acid}}$; before liquid recycle split	15.3–30.6
Al feed	0.4775	Stoichiometric to acid feed	0.2813
Al reacted	0.3820	$\eta_{\text{Al}} = 0.80$	0.2250
Unreacted Al	0.0955	0.0859 recycle; 0.0095 purge/loss at $\eta_{\text{recycle}} = 0.90$	0.0563
Unreacted H ₂ SO ₄	0.5199	0.4679 recycle; 0.0520 purge/loss at $\eta_{\text{recycle}} = 0.90$	0.3063
Al ₂ (SO ₄) ₃ , anhydrous equivalent	2.4191	Reaction product at $\eta_{\text{Al}} = 0.80$	1.4250
Al sulfate product, 17% Al ₂ O ₃ basis	4.2405	Commercial reporting basis	2.4979
Non-anhydrous carrier retained in 17% Al ₂ O ₃ product	1.8214	Commercial product mass minus anhydrous equivalent	1.0729
H ₂	0.04244	42.4 kg before purification losses	0.0250
O ₂ for catalytic oxidation	0.4244	Stoichiometric O ₂ corresponding to recovered sulfur; supplied as air in practice	0.2500
Net reaction water for H ₂ SO ₄ formation	0.4775	Stoichiometric chemical water incorporated into acid	0.2813
Added dilution water for 5–10 wt% H ₂ SO ₄ reactor feed	23.4–49.4	$m(\text{H}_2\text{SO}_4)(1/w_{\text{acid}} - 1)$; before recycle partition	13.8–29.1
Minimum water separation/recycle load to reach 17% Al ₂ O ₃ basis	21.6–47.6	Dilution water minus product-carrier allowance; lower-bound load	12.7–28.0

Table 4 identifies the pure-acid feed, total dilute solution, added water, product-carrier allowance, and minimum water separation/recycle load. Additional streams requiring pilot measurement include carrier flue gas, Na₂SO₃ makeup, Na₂SO₄ purge, catalyst replacement, acid mist, wash water, spent cleaning solution, filter cake, dissolved impurity salts, vent gas, hydrogen-purification reject, evaporator condensate, and wastewater-treatment residues.

Table 5. Screening energy demand per tonne of sulfur in coal (central material balance).

Process Block	Basis/Assumption	Screening Demand
Flue-gas cooling, booster fan, absorber circulation	Carrier-gas dependent	0.07–0.18 MWhe
Wellman–Lord regeneration	1.5–3.0 GJth per t recovered SO ₂	2.55–5.09 GJth
Gas drying, reheating, catalytic section, acid finishing	0.3–0.8 GJth per t H ₂ SO ₄	0.78–2.08 GJth
Acid/aluminum mixing, filtration, pumping	Equipment allowance	0.02–0.06 MWhe
H ₂ purification and compression	2–5 kWh per kg H ₂	0.085–0.212 MWhe

Table 5. Cont.

Process Block	Basis/Assumption	Screening Demand
Base total excluding downstream reconcentration	Sum of capture, acid, mixing, purification, and compression ranges	3.3–7.2 GJth and 0.18–0.45 MWhe
Acid dilution/product reconcentration (conditional)	21.6–47.6 t minimum water separation/recycle load; Section Dilution, Water-Separation, and Latent-Heat Calculation	≥ 49 –108 GJth latent-heat floor [33]
Combined thermal screen if evaporative reconcentration is required	Base duty plus evaporation-only lower bound; no heat-recovery credit	≥ 52 –115 GJth plus 0.18–0.45 MWhe

2.4. Screening-Level Energy Balance

The energy balance is expressed as a range because flue-gas flow, heat integration, absorbent concentration, evaporation ratio, and hydrogen-delivery pressure are unknown. The principal upstream thermal load is absorbent regeneration; principal electrical loads are fans, pumps, gas drying, hydrogen purification, and compression. Catalytic SO₂ oxidation and SO₃ absorption are exothermic, but no heat-recovery credit is taken. The conditional water-separation duty follows the equations in the Dilution, Water-Separation, and Latent-Heat Calculation section. The ranges are the literature-informed screening allowances rather than vendor guarantees [9,13,15,32,33].

The base 3.3–7.2 GJth range excludes product-liquor reconcentration. If the full acid stream is diluted to 5–10 wt% and a 17 wt% Al₂O₃ product is required, the evaporation-only latent-heat floor for the minimum water separation/recycle load is approximately 49–108 GJth/t S [33]. This is not a complete evaporator duty and excludes sensible heating, boiling-point elevation, process inefficiency, and wastewater treatment. Alternative product forms, crystallization, condensate recovery, and heat integration must be evaluated before selecting a concentration train.

2.5. Scenario, Sensitivity, and Uncertainty Analysis

Conservative, central, and optimistic scenarios use the parameter ranges in Table 1 and independent industrial price assumptions. Feed quantities are calculated from recovered acid; reaction conversion affects reacted material and product quantities, whereas unreacted feed is assigned to recycle and purge rather than removed from the original feed. Single-factor sensitivities are reported for coal sulfur content (1.0, 1.8, and 2.5 wt%), hydrogen value (2, 5, and 7 USD/kg), and aluminum conversion (0.60–0.90). The break-even hydrogen value is calculated before process cost and is therefore a lower bound.

$$P(\text{H}_2, \text{BE}) = [\text{CAI} + \text{Cacid/opportunity} + \text{Cprocess} - \text{VAI-sulfate} - \text{Vrecycle}]/\text{mH}_2$$

2.6. Material-Value Screening Boundaries and Price/Quality Basis

The calculation is limited to a material-value screening and is not a profitability, cash-flow, or techno-economic assessment. Two mutually exclusive boundaries are used. In the internal-acid-production-cost boundary, H₂SO₄ is not purchased or assigned a transfer value; capture and acid-production costs would instead be included as capture + acid. In the sulfuric-acid-opportunity-cost boundary, recovered acid is assigned a plant-gate opportunity value and its upstream production cost is not charged again. The two boundaries are not combined, thereby preventing double counting of internally produced acid.

Retail laboratory prices are excluded. The 2024 customs unit values for aluminum scrap, sulfuric acid, and aluminum sulfate are used only as transparent bulk-trade prox-

ies [34–36]. They are not harmonized quotations: the flows differ in trade direction, grade, concentration, product form, delivery point, taxes, and Incoterms. Hydrogen is treated separately. The 2 USD/kg case is an author-defined optimistic lower sensitivity, whereas 5–7 USD/kg brackets DOE-modeled PEM-electrolysis production costs in 2022 dollars [37]; these values are not equivalent to customs unit values or a saleable by-product price. Table 6 records the quality and delivery limitations for each proxy.

Table 6. Material-value screening inputs and non-comparability limits (2024 USD basis unless stated).

Item	Central Proxy	Sensitivity	Source/Trade Direction	Product or Quality Basis	Delivery and Limitation
Scrap aluminum	1.876 USD/kg	1.60–2.10	Türkiye imports, HS 760200 [36]	Customs category includes mixed grades; not equivalent to certified AA6061	Border unit value; excludes sorting, pretreatment, inland freight, and plant delivery
Sulfuric acid opportunity value	0.084 USD/kg	0.06–0.11	Türkiye exports, HS 280700 [34]	Acid/oleum product mix and concentration are not harmonized with the internal stream	Opportunity-value proxy only; not purchase price or internal production cost
Aluminum sulfate product	0.194 USD/kg	0.14–0.25	Türkiye exports, HS 283322 [35]	Customs grade/form may differ from the 17 wt% Al ₂ O ₃ reporting basis	Product-mass proxy; not a buyer quotation or delivered price
Hydrogen	5.0 USD/kg	2–7	DOE Program Record 24005 [37]	5–7 USD/kg: modeled PEM production costs in 2022 USD; 2 USD/kg: author sensitivity	Not customs-equivalent, not by-product sale price, and excludes purity/delivery reconciliation

Taxes, inland transport, insurance, storage, working capital, financing, price escalation, product-grade discounts, purification, and contractual delivery terms are excluded. Accordingly, the reported balance is a pre-process material-value indicator only.

2.7. Market-Capacity and Logistics Screening

Market compatibility is evaluated for both an ideal all-sulfur/complete-conversion case and the central screening case. The ideal case requires 499.2 t/d of scrap Al and produces 3161.4 t/d of anhydrous-equivalent Al₂(SO₄)₃. At 330 full-load-equivalent days, these flows correspond to 164.7 kt/y of scrap Al and 1.043 Mt/y of anhydrous-equivalent product. The central case requires 423.7 t/d of Al feed and produces 3763 t/d of a commercial product containing 17 wt% Al₂O₃. These quantities are compared with 330 kt/y of recycled-scrap supply reported for Türkiye in 2021, 194.463 kt of scrap imports in 2024, and 122.352 kt of aluminum sulfate exports in 2024 [35,36,38]. Export quantity is used only as a scale comparator, not as a measure of total domestic demand. Türkiye's Hydrogen Technologies Strategy provides policy context but does not establish a contracted buyer for the hydrogen by-product [39]. These scale comparisons emphasizes the need for named suppliers, product-grade specifications, long-term offtake agreements, storage, and transport planning.

2.8. Comparison with Scrap Remelting and Conventional Sulfur Management

The proposed chemical-consumption route is compared with closed-loop scrap remelting, conventional aluminum sulfate manufacture, wet-limestone FGD with gypsum, regenerable FGD with sulfuric acid sale, steam-methane reforming, and water electrolysis. The International Aluminium Institute reports primary-energy demand of approximately

8.3 GJ/t for recycled aluminum versus 186 GJ/t for primary aluminum, a 95.5% reduction [40]. The proposed route has a base screening duty of 3.3–7.2 GJth and 0.18–0.45 MWhe per tonne of sulfur in coal; normalized by the central 0.4775 t Al feed/t S, this corresponds to approximately 6.9–15.1 GJth/t Al plus 1.36–3.39 GJe/t Al before product reconcentration. If evaporative reconcentration is required, the combined thermal screen becomes approximately 109–241 GJth/t Al. Because the products and system boundaries differ, these figures are not a direct process-efficiency comparison; they indicate the opportunity cost of removing recyclable aluminum from the metallic loop. Chemical conversion is therefore considered only for contaminated or off-specification scrap that cannot be economically remelted.

2.9. Integrated Sustainability Interpretation Framework

The sustainability interpretation integrates five dimensions: (i) sulfur-emission control and material recovery; (ii) energy and carbon implications; (iii) water demand, purge streams, and residual waste; (iv) circularity, market absorption, and logistics; and (v) occupational and public health relevance. Quantitative indicators are taken directly from the sulfur/material balance, energy screen, material-value boundary, and market-capacity results. Environmental and health implications remain qualitative because the study does not perform a life-cycle inventory or impact assessment, avoided-emission accounting, atmospheric dispersion, population-exposure, dose-response, or health-cost modeling [41,42].

The pathway is interpreted relative to wet-limestone FGD, regenerable sulfur recovery with acid sale, closed-loop scrap-aluminum remelting, conventional aluminum sulfate manufacture, steam-methane reforming, and water electrolysis [8,9,15,23,40]. Resource exchange or recovery is not assumed to be inherently sustainable; industrial symbiosis requires verified net benefits across the relevant material, energy, water, environmental, and market boundaries [41–43]. A favorable interpretation would therefore require the integrated route to reduce cradle-to-gate burdens relative to the relevant baseline while using low-remelting-value aluminum fractions, verified product markets, controlled residual streams, and technically compatible heat and water integration.

3. Results

3.1. Verification and Interpretation of the Afşin–Elbistan a Data Basis

The official EÜAŞ plant/mine page reports an installed capacity of 1355 MW for Afşin–Elbistan A and confirms that the Kışlaköy lignite field supplies the plant [44]. Older engineering documents describe the original configuration as four units with a gross-design notation of 4×344 MW, totaling 1376 MW [45]. These values are not interchangeable: 1355 MW is used as the public installed-capacity denominator, whereas 4×344 MW is retained only as a historical design notation. The planned 18 Mt/y coal requirement reported in historical project material [45] corresponds to 49,315 t/d on a 365-day basis; it is a full-design throughput rather than a measured current daily average.

A current, time-matched operator coal assay was not identified in the publicly available sources reviewed. A historical technical compilation describes Kışlaköy lignite as approximately 53% moisture, 19% ash, 20% volatile matter, 7% fixed carbon, about 2 wt% sulfur, and roughly 1150 kcal/kg [46]. Peer-reviewed characterization of 86 Kışlaköy open-pit and borehole samples also demonstrates substantial spatial heterogeneity [47]. Consequently, 1.8 wt% is retained as an illustrative midpoint and 1.0–2.5 wt% as a sensitivity range, not as a verified current average. Any engineering assessment must use time-matched as-received boiler-feed assays and report the year, unit load, sampling frequency, and moisture basis. The status, interpretation, and limitations of these inputs are summarized in Table 7.

Table 7. Status, interpretation, and limitations of the Afşin–Elbistan A input data.

Item	Value/Interpretation	Source Status
Installed capacity/unit notation	Official installed capacity: 1355 MW. Historical engineering notation: 4×344 MW gross design (1376 MW).	Official EÜAŞ [44]; historical technical source [45]. Values are not treated as interchangeable.
Design coal throughput	18 Mt/y = 49,315 t/d at 365 d/y	Historical design requirement [45], not a measured current daily average.
Historical operating evidence	2008: approximately 10.717 Mt coal and 4.198 TWh generation; 2013: average 2497 unit operating hours	Historical evidence [46]; not a current operating report.
Capacity factor/load multiplier	Current value unavailable. λ = actual annual generation/(1355 MW $\times$ 8760 h). 2008 gross-nameplate ratio approximately 35.4%; 2013 calendar-hour ratio 28.5%.	Derived screening ratios; current operator/regulator generation data required.
Coal type and historical composition	Kışlaköy lignite; approximately 53% moisture, 19% ash, 20% volatile matter, 7% fixed carbon, about 1150 kcal/kg	Site-specific historical description [44,46].
Sulfur content	Historical description about 2 wt%; screening midpoint 1.8 wt%, sensitivity 1.0–2.5 wt%	Not a verified current average; time-matched boiler-feed assay required [46,47].
Partial stack SO ₂ record	1 Jul–17 Oct 2020, Units 1–3 mean SO ₂ : 3317; 2613; 2396.15 mg/Nm ³	Partial ministry-shared CEMS evaluation [48]; Unit 4 and complete QA data unavailable.
Annual stack-emission mass	Not calculable from the public partial dataset	O ₂ , flue-gas flow, moisture, complete operating time, and pollutant-specific QA are missing.
Required verification dataset	Annual generation and coal use; hourly unit load; as-received sulfur; ash sulfur; flue-gas flow; O ₂ -corrected SO ₂ /SO ₃ ; FGD/CEMS availability	Must be obtained from operator and regulator before engineering scale-up.

Public operating evidence is sufficient to show that full-design throughput should not be treated as normal operation, but it is insufficient to establish a current capacity factor. Historical reporting gives approximately 10.717 Mt of lignite consumption and 4.198 TWh of generation in 2008; using the official 1355 MW denominator gives an approximate gross-nameplate utilization ratio of 35.4% for that year. A separate 2013 compilation reports an average of 2497 operating hours across four units, equivalent to 28.5% of calendar hours, but this is not a load-weighted capacity factor [46]. For future scaling, the load multiplier is defined as λ = actual annual generation/(1355 MW $\times$ 8760 h). A current plant-specific λ must be obtained from operator or regulator records; until then, the plant-scale flows in Table 8 are reported at $\lambda = 1$ and must be multiplied by the verified value.

The publicly accessible stack record is also incomplete. A detailed evaluation of ministry-shared continuous-emission-monitoring data covers only 1 July–17 October 2020 and only three units. Reported mean SO₂ concentrations were approximately 3317, 2613, and 2396.15 mg/Nm³ for Units 1–3, respectively [48]. The dataset lacks a complete Unit 4 record, oxygen values, flue-gas flow, moisture, and complete operating-time and quality-assurance data. It therefore cannot support a verified annual SO₂ mass or current plant-wide capture basis. The “477 t/y of toxic gases” value is not used because concentration data or aggregated pollutant categories cannot be converted into annual pollutant mass without pollutant-specific flow, oxygen, moisture, operating-time, and quality-assurance information.

Table 8. Central Afşin–Elbistan A full-design-throughput illustration at $\lambda = 1$ (49,300 t coal/d; 1.8 wt% S).

Quantity	Central Result at $\lambda = 1$	Comment
Sulfur in coal	887.4 t S/d	Full-design 49,300 t/d and 1.8 wt% S; multiply by λ and measured-S/1.8.
Recovered sulfur equivalent	753.2 t S/d	After conversion, SO ₃ , capture, and regeneration losses Molecular SO ₂ basis
Recovered concentrated SO ₂	1506.5 t/d	
H ₂ SO ₄ available	2306.8 t/d	Before downstream conversion
Al feed	423.7 t/d	Feed, not reacted amount
Al reacted	339.0 t/d	80% conversion
Unreacted Al	84.7 t/d	76.3 t/d recycle and 8.5 t/d purge/loss at 90% recycle 415.2 t/d recycle and 46.1 t/d purge/loss
Unreacted H ₂ SO ₄	461.4 t/d	
Al ₂ (SO ₄) ₃ , anhydrous equivalent	2146.7 t/d	Theoretical equivalent at 80% conversion
Al sulfate, 17% Al ₂ O ₃ basis	3763.0 t/d	Commercial reporting basis
H ₂ before purification loss	37.66 t/d	Crude theoretical gas; multiply by λ and measured purification recovery.

3.2. Sulfur Balance and Plant-Scale Material Results

Under the central assumptions, 84.88% of sulfur in coal is recovered as a concentrated-SO₂-equivalent stream. The remaining sulfur is distributed among ash or other retention (5.00%), SO₃/acid mist (0.95%), absorber stack slip (4.70%), and sulfate purge/by-products (4.47%). This separation avoids the simplifying assumption that all sulfur in coal becomes usable SO₂.

At coal sulfur contents of 1.0 and 2.5 wt%, all sulfur-derived flows scale linearly to 55.6% and 138.9% of the 1.8 wt% case, respectively. Actual plant flows are obtained by multiplying Table 8 values by λ and by the ratio of measured sulfur content to 1.8 wt%. Stack-emission concentrations cannot be scaled in the same way because they also depend on flue-gas volume, oxygen, moisture, unit load, control-system operation, and outages.

3.3. Screening Energy Results

Applying Table 5 to 887.4 t S/d gives a base requirement of approximately 2.9–6.4 TJth/d and 160–399 MWhe/d before heat-recovery credits. Hydrogen purification and compression alone require approximately 75–188 MWhe/d for 37.66 t H₂/d. More importantly, if the full acid stream is diluted to the 0.5–1.0 M reaction window and the final material must be concentrated to a 17 wt% Al₂O₃ product, the minimum gross water removal is approximately 19,100–42,200 t/d and the associated latent-heat floor is about 43–96 TJth/d. This conditional duty dominates the screening balance and may make the route impractical unless an alternative reactor/product configuration or exceptionally effective heat integration is demonstrated.

3.4. Material-Value Screening and Break-Even Results

The opportunity-cost boundary uses the non-harmonized screening proxies in Table 6. Per tonne of sulfur in coal, scrap-aluminum feed and sulfuric acid opportunity value total approximately 1115 USD, whereas the 17 wt% Al₂O₃ aluminum sulfate product contributes approximately 824 USD. The remaining pre-process material-value gap is approximately 291 USD before assigning a hydrogen value. With 42.44 kg H₂, the corresponding break-even value is approximately 6.86 USD/kg before energy, labor, maintenance, purification, transport, CAPEX, financing, compliance, and price/quality reconciliation. This result is not a profitability indicator.

Under the internal-acid-production-cost boundary, acid opportunity value is removed, but capture and acid-production costs must be added. Before these costs, the calculated hydrogen balance point is approximately 1.70 USD/kg. The difference between 1.70 and

6.86 USD/kg represents the acid opportunity value foregone, not an economic gain. The scenario results are summarized in Table 9.

Table 9. Scenario material-value results per tonne of sulfur in coal; opportunity-cost boundary, before process costs.

Scenario	Recovered S Fraction	Commercial Al Sulfate (t)	H ₂ (kg)	Material-Value Balance Before Process Costs (USD/t S)	Pre-Process H ₂ Balance Point
Conservative	0.714	2.677	26.8	−656	26.5 USD/kg
Central	0.849	4.240	42.4	−79	6.86 USD/kg
Optimistic	0.936	5.263	52.7	+670	0 USD/kg; Al-sulfate value exceeds material inputs

The optimistic result is driven by simultaneous favorable assumptions for recovery, conversion, low input prices, and high product prices. It is a sensitivity bound, not an expected outcome. A Monte Carlo analysis would require empirically supported probability distributions and correlations derived from experiments, vendor data, and contracts; these data are not yet available.

3.5. Market Capacity, Logistics, and Alternative-Route Results

The scale check in Table 10 shows that neither the ideal case nor the central case can assume unconstrained scrap or product markets. The ideal 499.2 t/d scrap requirement equals 164.7 kt/y at 330 days, corresponding to 49.9% of the 330 kt/y recycled-scrap supply reported for Türkiye and 84.7% of 2024 scrap imports. The ideal 3161.4 t/d anhydrous-equivalent aluminum sulfate result equals 1.043 Mt/y, 8.53 times Türkiye's 2024 aluminum sulfate export quantity, and is not itself a directly priced market product because commercial material is hydrated or sold on an Al₂O₃-concentration basis. The central case requires 139.8 kt/y of Al feed, equivalent to 42.4% of the reported recycled-scrap supply and 71.9% of 2024 scrap imports, while producing 1.242 Mt/y of a 17 wt% Al₂O₃ product, 10.15 times 2024 exports. These are scale comparators rather than evidence of domestic demand. A viable project would require segregated low-remelting-value scrap contracts and multiple verified product offtakers.

Table 10. Feedstock-availability and product-market scale checks for the Afşin–Elbistan illustration.

Metric	Daily Full-Design Value	Annualized at 330 d/y	Türkiye Scale Comparator
Ideal all-sulfur Al feed	499.2 t/d	164.7 kt/y	49.9% of 330 kt/y recycled-scrap supply; 84.7% of 2024 scrap imports
Central Al feed	423.7 t/d	139.8 kt/y	42.4% of reported supply; 71.9% of 2024 scrap imports
Ideal anhydrous-equivalent Al ₂ (SO ₄) ₃	3161.4 t/d	1.043 Mt/y	8.53 × 2024 exports; not a directly marketable hydrate/solution basis
Central 17 wt% Al ₂ O ₃ product	3763.0 t/d	1.242 Mt/y	10.15 × 2024 exports; requires multiple offtakers and logistics

Table 11 confirms that clean, sorted scrap should normally be remelted because remelting preserves metallic value and uses far less energy than primary aluminum production [40]. The proposed route is therefore evaluated only as a possible outlet for low-remelting-value fractions. Wet-limestone FGD remains the established emission-control

benchmark, whereas regenerable FGD with acid sale avoids consuming aluminum. Steam-methane reforming is the mature incumbent hydrogen route, and water electrolysis is the principal electricity-based benchmark [23]. The proposed pathway produces hydrogen only as a by-product and cannot be classified as competitive, low-carbon, or fuel-cell grade without complete energy, carbon, purity, and cost evidence.

Table 11. Screening comparison of the proposed route with principal alternatives.

Route	Main Product/Function	Resource Implication	Key Decision Criterion
Scrap-aluminum remelting	Secondary aluminum	Preserves metal value; recycled Al about 8.3 GJ/t and 95.5% below primary-energy demand [40]	Preferred for clean sorted scrap; alloy and contamination control
Conventional Al-sulfate manufacture	Al sulfate from $\text{Al}(\text{OH})_3$ /bauxite + acid	Uses standardized feed; established product quality	Benchmark cost, impurity limits, and market demand
Wet limestone FGD	SO_2 control + gypsum	Established high-volume emission control	Gypsum quality, water/sludge, retrofit status
Wellman–Lord + acid sale	SO_2 recovery + H_2SO_4	Avoids consuming valuable Al scrap	Acid market, regeneration energy, corrosion
Proposed acid + scrap-Al route	Al sulfate + by-product H_2	Consumes metallic Al; base duty approximately 6.9–15.1 GJth/t Al plus electricity; much larger if reconcentration is required	Only plausible for segregated low-remelting-value scrap with proven purity, energy balance, and offtake
Steam-methane reforming	Industrial H_2	Mature, high-volume incumbent; fossil carbon unless coupled with effective CCS	Hydrogen cost, carbon intensity, gas supply, purification [23]
Water electrolysis	H_2 and O_2	Electricity- and water-dependent; can be low-carbon with qualifying power	Electricity price/carbon intensity, electrolyzer efficiency, utilization [23]

3.6. Integrated Sustainability Screening Results

The combined material, energy, material-value, and market results identify both potential resource-recovery benefits and countervailing sustainability burdens. Table 12 summarizes the principal outcomes using an ISO-consistent life-cycle interpretation framework and an industrial-symbiosis perspective [41–43]. These results are screening indicators rather than an aggregate sustainability score.

Table 12. Integrated sustainability screening outcomes for the central case.

Sustainability Dimension	Central Screening Result	Interpretation
Sulfur control and resource recovery	84.88% of sulfur in coal is recovered for acid production; 15.12% remains as ash/other retention (5.00%), SO_3 /acid mist (0.95%), absorber slip (4.70%), and sulfate purge/by-products (4.47%).	The route has pollutant-to-resource potential, but the residual emissions, purge, wastewater, and waste-treatment burdens must be lower than those of the selected FGD baseline [8,9,15].
Energy and carbon implications	Base demand: 3.3–7.2 GJth and 0.18–0.45 MWh per tonne of sulfur in coal. If dilute reaction liquor is reconcentrated to a 17 wt% Al_2O_3 product, the latent-heat floor adds approximately 49–108 GJth/t S.	No low-carbon or net-energy benefit is demonstrated. Product reconcentration may dominate the energy balance unless an alternative product form, water recycle, or validated heat integration is available [9,13,15,41,42].

Table 12. Cont.

Sustainability Dimension	Central Screening Result	Interpretation
Water, purge, and residual streams	The selected 0.5–1.0 M reaction window creates a minimum 21.6–47.6 t water-removal/recycle burden per tonne of sulfur in coal, in addition to Na ₂ SO ₄ purge, wash water, wastewater, filter cake, and purification rejects.	Water and residual management are central sustainability constraints rather than secondary utilities [9,15,41,42].
Aluminum circularity	The central balance requires 0.4775 t Al feed per tonne of sulfur in coal. Clean recycled aluminum requires approximately 8.3 GJ/t and preserves metallic value through remelting [40].	Clean, sorted scrap should normally remain in the metallic recycling loop. Chemical conversion is potentially defensible only for segregated low-remelting-value or off-spec fractions [38,40–43].
Market and logistics scale	At 330 full-load-equivalent days, the central illustration requires about 140 kt/y Al feed and produces about 1.24 Mt/y of 17 wt% Al ₂ O ₃ aluminum sulfate product and 12.4 kt/y H ₂ .	The flows are market-transforming rather than marginal. Named suppliers, multiple product offtakers, storage, transport, and buyer-specific product specifications are prerequisites [34–36,43].
Material-value robustness	The central sulfuric acid opportunity-cost case requires an H ₂ value of approximately 6.86 USD/kg merely to balance material values before process energy, labor, maintenance, purification, transport, CAPEX, and compliance costs.	The current results do not demonstrate profitability or economic sustainability [34–37,49].
Environmental and public health relevance	SO ₂ control is environmentally and socially relevant [3,4], but the study does not quantify avoided stack emissions, pollutant dispersion, population exposure, disease burden, healthcare costs, or ecosystem effects.	Environmental and public health co-benefits remain hypotheses and cannot be attributed to the proposed route without a measured baseline and impact assessment [3,4].

Note: Quantitative values are derived from Tables 4–11. The interpretation is informed by the FGD and acid-process literature [8,9,15], aluminum-sector and recycling sources [38,40], market data [34–36], hydrogen benchmarks [23,37,49], ISO life-cycle-assessment standards [41,42], and the industrial-symbiosis literature [43].

Taken together, the integrated indicators do not demonstrate a net sustainability advantage. The route could support industrial symbiosis only if recovered sulfur substitutes a more burdensome product route, aluminum is sourced from fractions unsuitable for efficient remelting, heat and water integration are technically matched, residual streams are controlled, and the aluminum sulfate and hydrogen outputs displace existing production rather than creating additional oversupply or waste [40–43].

4. Discussion

4.1. Implications of the Complete Sulfur Balance and Selected Capture Route

Separating sulfur conversion, capture, and recovery materially reduces the acid available relative to a 100% sulfur-recovery assumption. Even the central recovered fraction of 0.849 may be optimistic for a retrofit unless particulate, halogen, metal, and SO₃ control are demonstrated. Selecting the Wellman–Lord route closes the conceptual gap between dilute flue gas and a usable SO₂ feed, but it introduces absorbent oxidation, sodium sulfate purge, evaporation duty, wastewater, and corrosion. These streams must be included in any environmental comparison with wet-limestone FGD [8,9,15].

The selected route is not the only possible configuration. Direct wet-gas sulfuric acid or SNOX-type systems may be attractive for sufficiently sulfur-rich, well-cleaned gases with compatible heat integration, whereas limestone FGD may remain preferable when emission control rather than sulfur recovery is the primary objective. Plant-specific flue-

gas composition, existing controls, available space, materials of construction, and retrofit constraints determine the appropriate route [9,13,15].

4.2. Aluminum Chemistry, Feed Quality, and Product Specification

The selected reaction window removes the implicit assumption that concentrated acid maximizes hydrogen production. The 96–98 wt% acid leaving the upstream acid section is not fed directly to the Al reactor in the reference case; it is cooled and diluted to 0.5–1.0 M at 40–60 °C. The cited dilute-acid studies do not validate concentrated-acid hydrogen production. The standard-electrode calculation gives $\Delta G^\circ \approx -970.8$ kJ for $2\text{Al} + 6\text{H}^+ \rightarrow 2\text{Al}^{3+} + 3\text{H}_2$ under standard ionic conditions [28], not a practical Gibbs-energy value for concentrated H_2SO_4 or mixed scrap. Even within the dilute window, hydrogen yield cannot be validated without reporting alloy assay, exposed surface area, oxide removal and repassivation, temperature profile, agitation, residence time, gas composition, and residual free acid.

Product form is equally important. Pricing an anhydrous formula against hydrated or liquid commercial material overvalues water and creates an inconsistent mass basis. The 17 wt% Al_2O_3 basis links the stoichiometric calculation to a recognized commercial specification [27], but compliance still requires testing for insolubles, free acid, iron, other metals, concentration, and physical form. Off-specification material may have substantially lower value or may require treatment and disposal.

4.3. Energy, Material-Value Boundaries, and Uncertainty

The energy screening shows that sulfur recovery is not a negligible auxiliary step. The upstream base range of 3.3–7.2 GJth/t S is dominated by regeneration and acid finishing, and the electrical demand becomes significant at plant scale. The dilute-acid aluminum reaction introduces a more severe conditional burden: producing a 17 wt% Al_2O_3 material from a 5–10 wt% acid reaction liquor creates a latent-heat floor of approximately 49–108 GJth/t S before sensible heat and process inefficiency. Waste-heat integration may reduce purchased energy, but it cannot be credited without matching temperature levels, duties, operating availability, corrosion constraints, and lost electricity sales. A future TEA must therefore compare alternative acid concentrations and product forms before scale-up.

The two material-value boundaries answer different questions. The internal-acid-production-cost boundary asks whether the integrated plant can cover capture, acid, aluminum, utility, and capital costs. The opportunity-cost boundary asks whether converting recovered acid into aluminum sulfate and hydrogen is preferable to selling the acid. Combining these boundaries double counts acid value. The central 6.86 USD/kg hydrogen balance point only closes the pre-process material-value gap and is not a profitability indicator.

Scenario values remain uncertain because no integrated pilot data are available. The ranges are anchored to published capture performance, laboratory aluminum-conversion behavior, and customs unit values, but they are not probability distributions. A defensible Monte Carlo model should be developed only after correlations among sulfur content, unit load, capture performance, regeneration energy, aluminum composition, conversion, product grade, and contract prices can be estimated.

4.4. Market Absorption and Circularity Trade-Off

The plant-scale output is market-transforming rather than marginal. The ideal all-sulfur/complete-conversion case would consume approximately half of Türkiye's reported annual recycled-scrap supply and produce an anhydrous-equivalent aluminum sulfate quantity more than eight times 2024 exports. The central flows remain material: approximately 140 kt/y of Al feed and 1.24 Mt/y of a 17 wt% Al_2O_3 product at 330 full-load-equivalent days. These comparisons do not establish domestic demand because customs

exports are not total consumption and product grades differ. Named customers, buyer specifications, seasonal demand, inventory limits, export infrastructure, shelf life, transport mode, and alternative product concentrations are therefore primary design constraints rather than secondary considerations.

From a circular-economy perspective, clean scrap should normally remain in metallic cycles. Recycled aluminum has a reported primary-energy demand of approximately 8.3 GJ/t, 95.5% below primary production [40]. Diverting clean scrap to aluminum sulfate sacrifices future remelting value and may create a substantially larger hydrated-product and transport burden. The proposed route may have a role only for segregated fractions that are technically or economically unsuitable for remelting, and only if the sulfate product substitutes an existing product without creating a new waste burden. A comparative LCA must include avoided remelting, primary-aluminum substitution, conventional FGD-gypsum, acid sale, established hydrogen routes, waste treatment, product transport, and hydrogen purification/compression [41,42].

4.5. Integrated Sustainability and Public Health Interpretation

From an industrial-symbiosis perspective, linking sulfur recovery, conditional heat recovery, low-remelting-value aluminum, and chemical-product manufacture can reframe selected emission and waste streams as potential resources [43]. However, resource recovery is not automatically equivalent to sustainability. The benefit of sulfur capture must be weighed against regeneration and acid-finishing energy, the conditional water-removal duty, sodium sulfate purge and wastewater, hydrogen purification, product transport, and the loss of future metallic-recycling value [9,15,40–42].

Potential public health benefits depend on a measured reduction in SO_2 , SO_3 /acid mist, and particulate exposure relative to the plant-specific control baseline [3,4]. The present assessment does not calculate avoided emissions, atmospheric dispersion, exposure, dose–response relationships, avoided mortality or disease, healthcare savings, or distributional effects on nearby communities. Public health relevance is therefore part of the environmental motivation, not a demonstrated outcome of the proposed valorization route.

A comparative cradle-to-gate LCA should follow ISO 14040 and ISO 14044 and include conventional wet FGD and gypsum management, regenerable sulfur recovery with direct acid sale, conventional aluminum sulfate production, avoided or displaced scrap remelting, primary-aluminum substitution, electricity and heat sources, water scarcity, wastewater and purge treatment, hydrogen purification/compression, product transport, and market displacement [41,42].

5. Conclusions

The assessment distinguishes sulfur in coal from gaseous SO_x formation, absorber-inlet SO_2 , captured sulfur, regenerated/recoverable SO_2 , stack slip, SO_3 /acid mist, ash retention, and sulfate purge. Under the central assumptions, 84.88% of coal sulfur is recovered for acid production rather than 100%. Per tonne of sulfur in coal, this yields 2.599 t H_2SO_4 , 0.477 t aluminum feed, 2.419 t anhydrous-equivalent aluminum sulfate, 4.240 t of a commercial product containing 17 wt% Al_2O_3 , and 42.4 kg H_2 at 80% aluminum conversion.

A specific regenerable Wellman–Lord route and preliminary operating window are defined. The aluminum reaction is restricted to dilute acid and controlled temperature; concentrated-acid passivation and SO_2 -forming side reactions are recognized; and scrap composition and pretreatment requirements are specified. The material balance includes unreacted acid and aluminum, recycle, purge, oxygen, process water, SO_3 /acid mist, stack emissions, wastewater, and solid residues. The upstream base energy demand is 3.3–7.2 GJth and 0.18–0.45 MWh per tonne of sulfur in coal before heat recovery. If dilute

reaction liquor must be reconcentrated to a 17 wt% Al_2O_3 product, an additional latent-heat floor of approximately 49–108 GJth/t S applies.

The Afşin–Elbistan A data basis is explicitly qualified. Official public information gives 1355 MW installed capacity [44], whereas 4×344 MW is retained only as a historical gross-design notation [45]. The 49,300 t coal/d value is the daily equivalent of an historical 18 Mt/y design requirement, not a verified current average. Historical data indicate lower utilization in specific years, but a current capacity factor is not publicly established. The 1.8 wt% sulfur value is an illustrative midpoint tested over 1.0–2.5 wt%, not a time-matched plant assay. Partial 2020 CEMS data cover only three units and lack the oxygen and flue-gas-flow information required for annual mass calculation [48]. Accordingly, no current plant-wide SO_2 mass, recovery quantity, or “477 t/y toxic gases” value is claimed.

At 330 full-load-equivalent days, the central plant-scale illustration would consume approximately 140 kt/y of scrap aluminum and produce approximately 1.24 Mt/y of commercial aluminum sulfate and 12.4 kt/y of H_2 . These quantities create major feedstock, offtake, storage, transport, and product-concentration risks and compete directly with scrap remelting. The route should therefore be treated as a possible niche option for low-remelting-value scrap, not as a default use of recyclable aluminum. Comparison with remelting, wet FGD-gypsum, regenerable acid sale, steam-methane reforming, and electrolysis does not demonstrate an advantage over established alternatives.

The integrated sustainability result is conditional rather than uniformly positive. Potential advantages include improved sulfur control, recovery of a concentrated sulfur stream, and possible substitution of conventional chemical products. Potential burdens include substantial heat and electricity demand, a large water-management load, purge and wastewater generation, diversion of recyclable aluminum from closed-loop remelting, hydrogen-purification requirements, and product-market saturation [9,15,40–43]. None of these trade-offs can be resolved by stoichiometry alone.

5.1. Limitations

Calculated results include the stoichiometric sulfur/material flows, scenario outputs, the water-separation lower bound, and arithmetic material-value balances. The literature-supported inputs include the AP-42 sulfur conversion default, published SO_3 and Wellman–Lord ranges, dilute-acid aluminum studies, and customs unit values. Author-defined assumptions include η_{recycle} and selected sensitivity bounds. Unverified plant inputs include current capacity factor, time-matched coal sulfur, complete stack flow and oxygen data, integrated reaction performance, product quality, and vendor energy duties.

The unresolved process items are flue-gas impurity control, catalyst life, corrosion, sodium sulfate purge, circulating water closure, hydrogen purification recovery, aluminum sulfate compliance, waste classification, and life-cycle impacts. The conditional evaporation duty is a thermodynamic lower bound rather than an evaporator design [33,41,42].

5.2. Validation Roadmap

Stage 1 should obtain operator and regulator records for annual generation, unit-level load, coal consumption, as-received sulfur assays, ash sulfur, flue-gas flow, oxygen-corrected SO_2/SO_3 , control-device operation, and CEMS quality assurance, and should close a measured sulfur balance across multiple loads. Stage 2 should perform controlled experiments with certified reference alloys and characterized low-remelting-value scrap using 0.5–1.0 M H_2SO_4 at 40–60 °C; 96–98 wt% acid should be examined only in separate passivation and side-reaction tests. Kinetics, induction period, surface treatment, gas composition and purification recovery, impurity transfer, filtration, and product quality must be measured. Stage 3 should develop a process model for the selected Wellman–Lord/contact-acid

route, including dilution, heat integration, water, purge, corrosion, product concentration, and hydrogen compression. Stage 4 should obtain vendor quotations, scrap-supply agreements, named product offtakes, and complete TEA, ISO-consistent comparative LCA, HAZOP, and market/logistics comparisons with remelting, wet FGD-gypsum, acid sale, steam-methane reforming, and electrolysis [41,42].

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References

1. U.S. Environmental Protection Agency. *AP-42, Chapter 1.1: Bituminous and Subbituminous Coal Combustion*; U.S. EPA: Research Triangle Park, NC, USA, 1998. Available online: https://www.epa.gov/sites/default/files/2020-09/documents/1.1_bituminous_and_subbituminous_coal_combustion.pdf (accessed on 25 July 2026).
2. U.S. Environmental Protection Agency. TENORM: Coal Combustion Residuals. Available online: <https://www.epa.gov/radiation/tenorm-coal-combustion-residuals> (accessed on 25 July 2026).
3. World Health Organization. *WHO Global Air Quality Guidelines: Particulate Matter (PM_{2.5} and PM₁₀), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*; World Health Organization: Geneva, Switzerland, 2021.
4. Jacimovski, S.; Miladinovic, S.; Radovanovic, R. Analysis of the emission of SO₂, NO_x, and suspended particles from the thermal power plants Kostolac (Serbia). *Hum. Ecol. Risk Assess.* **2016**, *22*, 1208–1223. [CrossRef]
5. Tong, D.; Zhang, Q.; Liu, F.; Geng, G.; Zheng, Y.; Xue, T.; Hong, C.; Wu, R.; Qin, Y.; Zhao, H.; et al. Current emissions and future mitigation pathways of coal-fired power plants in China from 2010 to 2030. *Environ. Sci. Technol.* **2018**, *52*, 12905–12914. [CrossRef] [PubMed]
6. Filonchik, M.; Peterson, M.P. An integrated analysis of air pollution from U.S. coal-fired power plants. *Geosci. Front.* **2023**, *14*, 101498. [CrossRef]
7. Tomas, A.F. A new perspective about recovering SO₂ offgas in coal power plants: Energy saving. Part I. Regenerable wet methods. *Energy Sources* **2005**, *27*, 1035–1041. [CrossRef]
8. Koralegedara, N.H.; Pinto, P.X.; Dionysiou, D.D.; Al-Abed, S.R. Recent advances in flue gas desulfurization gypsum processes and applications—A review. *J. Environ. Manag.* **2019**, *251*, 109572. [CrossRef] [PubMed]
9. Poullikkas, A. Review of design, operating, and financial considerations in flue gas desulfurization systems. *Energy Technol. Policy* **2015**, *2*, 92–103. [CrossRef]
10. Hardman, R.; Stacy, R.; Dismukes, E. Estimating sulfuric acid aerosol emissions from coal-fired power plants. In Proceedings of the DOE-FETC Conference on Formation, Distribution, Impact, and Fate of Sulfur Trioxide in Utility Flue Gas Streams, Pittsburgh, PA, USA, March 1998.
11. Zheng, C.; Wang, Y.; Liu, Y.; Yang, Z.; Qu, R.; Ye, D.; Liang, C.; Liu, S.; Gao, X. Formation, transformation, measurement, and control of SO₃ in coal-fired power plants. *Fuel* **2019**, *241*, 327–346. [CrossRef]
12. Dunn, J.P.; Koppula, P.R.; Stenger, H.G.; Wachs, I.E. Oxidation of sulfur dioxide to sulfur trioxide over supported vanadia catalysts. *Appl. Catal. B Environ.* **1998**, *19*, 103–117. [CrossRef]
13. Sørensen, P.A.; Møllerhøj, M.; Christensen, K.A. New dynamic models for simulation of industrial SO₂ oxidation reactors and wet gas sulfuric acid plants. *Chem. Eng. J.* **2015**, *278*, 421–429. [CrossRef]
14. Brachert, L.; Kochenburger, T.; Schaber, K. Facing the sulfuric acid aerosol problem in flue gas cleaning: Pilot-plant experiments and simulation. *Aerosol Sci. Technol.* **2013**, *47*, 1083–1091. [CrossRef]
15. U.S. Environmental Protection Agency. *Summary Report: Sulfur Oxides Control Technology Series—Flue Gas Desulfurization, Wellman–Lord Process*; U.S. EPA: Washington, DC, USA, 1979. Available online: <https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=30004EB1.TXT> (accessed on 28 July 2026).

16. Funk, J.E. Thermochemical hydrogen production: Past and present. *Int. J. Hydrogen Energy* **2001**, *26*, 185–190. [CrossRef]
17. Brown, L.C.; Besenbruch, G.E.; Lentsch, R.D.; Schultz, K.R.; Funk, J.F.; Pickard, P.S.; Marshall, A.C.; Showalter, S.K. *High Efficiency Generation of Hydrogen Fuels Using Nuclear Power*; General Atomics Report GA-A24285; General Atomics: San Diego, CA, USA, 2003. [CrossRef] [PubMed]
18. Gorenssek, M.B.; Summers, W.A. The hybrid sulfur cycle. In *Nuclear Hydrogen Production Handbook*; Yan, X.L., Hino, R., Eds.; CRC Press: Boca Raton, FL, USA, 2011; pp. 499–545. [CrossRef]
19. Zhu, Z.; Ma, Y.; Qu, Z.; Fang, L.; Zhang, W.; Yan, N. Study on a new wet flue gas desulfurization method based on the Bunsen reaction of the sulfur–iodine thermochemical cycle. *Fuel* **2017**, *195*, 33–37. [CrossRef]
20. Steimke, J.L.; Steeper, T.J.; Colón-Mercado, H.R.; Gorenssek, M.B. Development and testing of a PEM SO₂-depolarized electrolyzer and an operating method that prevents sulfur accumulation. *Int. J. Hydrogen Energy* **2015**, *40*, 13281–13294. [CrossRef]
21. Colón-Mercado, H.R.; Mauger, S.A.; Gorenssek, M.B.; Fujimoto, C.H.; Lando, A.A.; Ganesan, P.; Meekins, B.H.; Meeks, N.D. Electrode optimization for efficient hydrogen production using an SO₂-depolarized electrolysis cell. *Int. J. Hydrogen Energy* **2022**, *47*, 14180–14185. [CrossRef]
22. U.S. Department of Energy. Hydrogen Fuel Basics. Available online: <https://www.energy.gov/cmei/fuels/hydrogen-fuel-basics> (accessed on 25 July 2026).
23. U.S. Department of Energy. Hydrogen Production and Distribution. Available online: <https://afdc.energy.gov/fuels/hydrogen-production> (accessed on 25 July 2026).
24. Abdel-Gaber, A.M.; Abd-El Nabey, B.A.; Sid Ahmed, I.M.; El-Zayady, A.M.; Saadawy, M. Kinetics and thermodynamics of aluminum dissolution in 1.0 M sulphuric acid containing chloride ions. *Mater. Chem. Phys.* **2006**, *98*, 291–297. [CrossRef]
25. Arellanes-Lozada, P.; Olivares-Xometl, O.; Guzmán-Lucero, D.; Likhanova, N.V.; Domínguez-Aguilar, M.A.; Lijanov, I.V.; Arce-Estrada, E. The inhibition of aluminum corrosion in sulfuric acid by poly(1-vinyl-3-alkyl-imidazolium hexafluorophosphate). *Materials* **2014**, *7*, 5711–5734. [CrossRef] [PubMed]
26. El-Meligi, A.A. Hydrogen production by aluminum alloy in sulphuric acid solutions. *Recent Pat. Mater. Sci.* **2017**, *10*, 75–81. [CrossRef]
27. American Water Works Association. *ANSI/AWWA B403-24: Aluminum Sulfate—Liquid, Ground, or Lump*; AWWA: Denver, CO, USA, 2024.
28. Bratsch, S.G. Standard electrode potentials and temperature coefficients in water at 298.15 K. *J. Phys. Chem. Ref. Data* **1989**, *18*, 1–21. [CrossRef]
29. The Aluminum Association. *International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys (Teal Sheets)*; The Aluminum Association: Arlington, VA, USA, 2018. Available online: <https://www.aluminum.org/teal-sheets> (accessed on 28 July 2026).
30. ISO 14687:2025; Hydrogen Fuel Quality—Product Specification. ISO: Geneva, Switzerland, 2025.
31. SAE J2719_202604; Hydrogen Fuel Quality for Fuel Cell Vehicles. SAE International: Warrendale, PA, USA, 2026. [CrossRef] [PubMed]
32. Rockward, T.; Brosha, E.; Garzon, F.; Quesada, C.; Rau, K.; Mukundan, R. Hydrogen fuel quality. In *U.S. Department of Energy Hydrogen and Fuel Cells Program Annual Progress Report*. Available online: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/progress13/viii_5_rockward_2013.pdf (accessed on 25 July 2026).
33. National Institute of Standards and Technology. NIST Chemistry WebBook, SRD 69: Water, Phase-Change and Thermochemical Data, NIST, Gaithersburg, MD, USA. Available online: <https://webbook.nist.gov/cgi/cbook.cgi?ID=C7732185&Mask=4> (accessed on 28 July 2026).
34. World Bank. World Integrated Trade Solution (WITS), Based on UN Comtrade. Türkiye Exports of Sulfuric Acid and Oleum, HS 280700, 2024. Available online: <https://wits.worldbank.org/trade/comtrade/en/country/TUR/year/2024/tradeflow/Exports/partner/ALL/product/280700> (accessed on 25 July 2026).
35. World Bank. World Integrated Trade Solution (WITS), Based on UN Comtrade. Türkiye Exports of Aluminum Sulfates, HS 283322, 2024. Available online: <https://wits.worldbank.org/trade/comtrade/en/country/TUR/year/2024/tradeflow/Exports/partner/ALL/product/283322> (accessed on 25 July 2026).
36. World Bank. World Integrated Trade Solution (WITS), Based on UN Comtrade. Türkiye Imports of Aluminum Waste and Scrap, HS 760200, 2024. Available online: <https://wits.worldbank.org/trade/comtrade/en/country/TUR/year/2024/tradeflow/Imports/partner/ALL/product/760200> (accessed on 25 July 2026).
37. Hubert, M.; Peterson, D.; Miller, E.; Vickers, J.; Mow, R.; Howe, C. *Clean Hydrogen Production Cost Scenarios with PEM Electrolyzer Technology*; DOE Hydrogen Program Record 24005; U.S. Department of Energy: Washington, DC, USA, 2024. Available online: <https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/24005-clean-hydrogen-production-cost-pem-electrolyzer.pdf> (accessed on 28 July 2026).

38. European Bank for Reconstruction and Development; Republic of Türkiye Ministry of Industry and Technology. *A Low Carbon Pathway for the Aluminium Sector in the Republic of Türkiye*; EBRD: London, UK, 2023. Available online: https://www.ebrd.com/content/dam/ebrd_dxp/assets/pdfs/green-economy-transition/Aluminum%20LCP.pdf (accessed on 25 July 2026).
39. Republic of Türkiye Ministry of Energy and Natural Resources. *Türkiye Hydrogen Technologies Strategy and Roadmap*; Republic of Türkiye Ministry of Energy and Natural Resources: Ankara, Türkiye, 2023. Available online: https://enerji.gov.tr/Media/Dizin/SGB/en/HSP_en/ETKB_Hydrogen_T_Strategies.pdf (accessed on 25 July 2026).
40. International Aluminium Institute. Aluminium Recycling Saves 95% of the Energy Needed for Primary Aluminium Production. Available online: <https://international-aluminium.org/landing/aluminium-recycling-saves-95-of-the-energy-needed-for-primary-aluminium-production/> (accessed on 25 July 2026).
41. ISO 14040:2006; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006.
42. ISO 14044:2006; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO: Geneva, Switzerland, 2006.
43. Chertow, M.R. Industrial symbiosis: Literature and taxonomy. *Annu. Rev. Energy Environ.* **2000**, *25*, 313–337. [CrossRef]
44. Elektrik Mühendisleri Odası. *Afşin–Elbistan Havzasında Yeni Yatırım İmkânları ve Mevcut Santrallerin Teknik Verileri*; EMO: Ankara, Türkiye, 2009. Available online: https://www.emo.org.tr/ekler/9bd638cf0b19174_ek.pdf (accessed on 25 July 2026).
45. Elektrik Üretim, A.Ş. Afşin–Elbistan Lignite Field. Official Plant/Mine Information. Available online: <https://www.euas.gov.tr/en-US/power-plants/afsin-elbistan-lignite-field> (accessed on 25 July 2026).
46. Algedik, Ö. Afşin–Elbistan Coal Power Plants: Historical Compilation Based on Public EÜAŞ and Court of Accounts Records. 2019. Available online: <https://onderalgedik.com/wp-content/uploads/2019/03/AfsinElbistanCoalReport.pdf> (accessed on 25 July 2026).
47. Cicioğlu Sütçü, E.; Karayığit, A.I. Mineral matter, major and trace element content of the Afşin–Elbistan coals, Kahramanmaraş, Turkey. *Int. J. Coal Geol.* **2015**, *144–145*, 111–129. [CrossRef]
48. Greenpeace Türkiye. *Afşin–Elbistan A Termik Santrali SEÖS Verileri Detaylı Değerlendirme Raporu*; Greenpeace Türkiye: İstanbul, Türkiye, 2024. Available online: <https://www.greenpeace.org/static/planet4-turkey-stateless/2024/12/43245b34-afsin-elbistan-a-termik-santrali-seos-verileri-detayli-degerlendirme-raporu-greenpeace.pdf> (accessed on 25 July 2026).
49. U.S. Department of Energy. *The Department of Energy Hydrogen Program Plan*; U.S. DOE: Washington, DC, USA, 2024. Available online: <https://www.hydrogen.energy.gov/library/roadmaps-vision/program-plan> (accessed on 28 July 2026).

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