Research Article *Open Access*

Journal of Geoscience and Eco Agricultural Studies

ISSN: 3067-7297

DOI: *doi.org/10.63721/26JGEAS0136*

Thermally Self-Balanced Hydrogen Production from Hydrogen Sulfide via Coupled Combustion and Decomposition

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Citation: *Huseyin Murat Cekirge (2026) Thermally Self-Balanced Hydrogen Production from Hydrogen Sulfide via Coupled Combustion and Decomposition. J. of Geo Eco Agr Studies 3(2): 1-13. WMJ/JGEAS-136*

Abstract

This study proposes a subsea processing architecture for the safe conversion of dissolved hydrogen sulfide into hydrogen and elemental sulfur without surface exposure. Hydrogen sulfide, commonly present in stratified aquatic environments such as the Black Sea, poses severe environmental and operational risks when transported or processed at the surface.

The proposed system operates in a depth-constrained mid-water regime, avoiding both seabed installation and biologically active surface layers. Hydrogen sulfide is locally extracted and subjected to a thermally sustained decomposition process, in which a small controlled fraction is oxidized to provide the energy required for continuous conversion. A simple thermodynamic estimate based on formation enthalpies indicates that only a minor oxidation fraction (on the order of 5–10%) is sufficient to sustain the process.

The system eliminates hazardous gas transport, prevents human exposure, and produces manageable output streams of hydrogen and sulfur. This approach reframes hydrogen sulfide handling from a containment problem into a localized conversion process, offering a potentially safer and more environmentally compatible pathway for resource utilization in anoxic aquatic systems.

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Submitted: 06.04.2026 **Accepted**: 10.04.2026 **Published**: 21.04.2026

Keywords: Hydrogen Production, Hydrogen Sulfide, Thermal Decomposition, Partial Combustion, Solar Thermal Energy, Coastal Processing, Energy Efficiency, Sulfur Recovery, Continuous Processing, Process Intensification

Introduction

Hydrogen is widely regarded as a key energy carrier in future low-carbon energy systems; however, its large-scale deployment remains constrained by production cost, energy intensity, and challenges associated with storage and transportation. Conventional hydrogen production technologies, including steam methane reforming and water electrolysis, rely on either fossil fuels or substantial electrical energy input, resulting in economic and environmental limitations. In particular, the storage and long-distance transport of hydrogen require compression, liquefaction, or chemical carriers, each introducing additional energy penalties, infrastructure complexity, and safety considerations [1-4].

Hydrogen sulfide (H_2S), commonly encountered in sour gas reservoirs, offshore production systems, and natural stratified aquatic environments such as the Black Sea, represents a hydrogen-rich feedstock that is often treated as a hazardous by-product rather than a resource. Existing industrial processes typically focus on the conversion of H_2S into elemental sulfur, such as in the Claus process, while the hydrogen content is not directly utilized. At the same time, the transport of H_2S over long distances poses significant risks due to its toxicity and corrosive nature [5-6].

Alternative approaches have explored the decomposition of H_2S into hydrogen and sulfur through thermal, catalytic, or plasma-based methods. While these methods demonstrate the feasibility of hydrogen recovery, they generally require high external energy input or complex reactor systems, limiting their practical implementation at scale. In particular, thermal decomposition is inherently endothermic and requires sustained high temperatures, posing a challenge for energy efficiency [7-9].

This study considers an alternative framework based on processing at the source, particularly in coastal or offshore environments where continuous H_2S streams are available. Instead of transporting hazardous materials or supplying large amounts of external energy, the proposed system utilizes a fraction of the feedstock itself to generate the required thermal energy through controlled partial combustion. The remaining fraction undergoes thermal decomposition (pyrolysis) to produce hydrogen and elemental sulfur.

The central concept of the proposed approach is the coupling of exothermic and endothermic processes within a single system. Heat generated from partial combustion is transferred to sustain the decomposition reaction, establishing a self-balanced thermal regime. In this configuration, the external energy requirement is significantly reduced, and the process can operate as a thermally sustained system with minimal auxiliary input.

A key parameter governing the system is the combustion fraction (α), which defines the balance between internal heat generation and hydrogen yield. By adjusting this parameter, the process can operate in a regime where thermal self-sufficiency is achieved while maintaining a high conversion of feedstock to hydrogen. Simple thermodynamic estimates based on formation enthalpies indicate that only a small fraction of H_2S needs to be oxidized to sustain the process, providing a practical basis for energy feasibility.

In addition to hydrogen production, the process yields elemental sulfur as a valuable co-product. Sulfur is widely used in chemical manufacturing, materials processing, and emerging energy storage technologies, enhancing the economic viability of the system [10-11]**.** By treating sulfur as an integral component of the value chain rather than a waste stream, the proposed framework operates as a dual-output energy–material platform.

The proposed system therefore integrates three key elements: (i) continuous on-site processing of H_2S streams, (ii) thermal self-balancing through exothermic–endothermic coupling, and (iii) simultaneous production of hydrogen and sulfur. By shifting hydrogen sulfide handling from transport and containment to localized conversion, the approach provides a practical and scalable pathway for hydrogen generation in environments where safety, logistics, and external energy supply present significant constraints.

The process eliminates the need for hazardous material transport by converting hydrogen sulfide locally into stable and manageable products. A rough system-level operational estimate is presented in Section 8 to assess practical energy requirements.

Process Concept and Energy Balance

The proposed system operates as a continuous, thermally coupled process in which hydrogen sulfide (H_2S) is partitioned into two streams: a combustion stream that provides thermal energy and a decomposition stream that produces hydrogen and elemental sulfur. The process is designed to operate at or near the source of H_2S generation, such as coastal or offshore facilities, enabling immediate utilization of the feedstock and eliminating the need for long-distance transport.

Process Configuration

Let the total molar flow rate of incoming hydrogen sulfide be normalized to unity. A fraction α of the feed is directed to controlled combustion, while the remaining fraction $(1 - \alpha)$ is directed to thermal decomposition:

- Combustion fraction: α
- Decomposition fraction: $(1 - \alpha)$

The process flow can be expressed as:
$H_2S \rightarrow \alpha$ (combustion) + $(1 - \alpha)$ (decomposition)

The two sub-processes are defined as follows:
(i) Endothermic decomposition (pyrolysis): $H_2S \rightarrow H_2 + S$
(ii) Exothermic partial combustion: $H_2S + O_2 \rightarrow SO_2 + H_2O$ + heat

The heat released from the combustion stream is transferred to the decomposition reactor, sustaining the endothermic reaction. This establishes a thermally coupled system in which internal energy generation reduces the need for external heat input.

Energy Balance Formulation

The operation of the system is governed by the balance between heat required for decomposition and heat generated by combustion.

Let:

- $\Delta H_d > 0$ denote the molar enthalpy of H_2S decomposition
- $\Delta H_c < 0$ denote the molar enthalpy of H_2S combustion
- $Qs \geq 0$ denote the solar heat input

Define:

- Q_r: required heat for decomposition
- Q_e: external heat requirement
- Qg: heat generated by combustion

Then:
$Q_r = (1 - \alpha) \cdot \Delta Hd$
$Qg = \alpha \cdot |\Delta Hc|$
$Q_e = Q_r - Qg - Qs$

Self-Balancing Condition

A thermally self-sustained regime is achieved when the internally generated heat is sufficient to drive the decomposition process:

$$Qg + Qs \geq Q_r$$

A strictly self-balanced regime corresponds to $Qg + Qs = Q_r$, while practical operation typically satisfies $Qg + Qs \geq Q_r$ due to heat losses and system inefficiencies. This distinction defines the operational margin of the system. In the absence of solar input ($Qs = 0$), the self-balancing condition reduces to:

$\alpha \cdot |\Delta H_c| \geq (1 - \alpha) \cdot \Delta H_d$
Solving for α yields:

$\alpha \geq \Delta H_d / (\Delta H_d + |\Delta H_c|)$

Order-of-Magnitude Estimation

Using representative thermochemical values:

- $\Delta H_d \approx +20$ kJ/mol (H_2S decomposition)
- $|\Delta H_c| \approx 500$ kJ/mol (H_2S combustion)

the minimum combustion fraction required for thermal self-sufficiency becomes:
$\alpha \geq 20 / (20 + 500) \approx 0.15$

This result indicates that, under ideal conditions, approximately 15% of the feedstock is sufficient to sustain the decomposition of the remaining 85%.

Practical Operating Range

In real systems, heat losses, incomplete heat transfer, and reactor inefficiencies must be considered. As a result, the practical operating range of α is expected to be higher than the theoretical minimum:
$\alpha \approx 0.05 – 0.10$

Within this range:

- Internal heat generation compensates for system losses
- Continuous operation is maintained

- A majority fraction of the feedstock is converted into hydrogen

Hydrogen Yield and Trade-Off

The hydrogen production rate is directly proportional to the decomposition fraction:

H_2 yield $\propto (1 - \alpha)$

Thus, increasing α improves thermal self-sufficiency but reduces hydrogen output. Conversely, decreasing α increases hydrogen yield but may require additional external energy input.

This establishes a fundamental trade-off between:

- Energy self-sufficiency (higher α)
- Hydrogen production efficiency (lower α)

An optimal operating point α* can therefore be defined based on system design, energy availability, and economic considerations.

Process Interpretation

The resulting process can be interpreted as a thermally coupled system in which internal energy redistribution replaces external energy supply. By allocating a controlled fraction of the feedstock to combustion, the system establishes a stable operating regime that sustains continuous hydrogen production with minimal external input.

This formulation provides a simple yet scalable framework for hydrogen generation from H_2S, particularly in environments where energy supply and transport infrastructure are constrained.

The proposed system does not operate as a heat engine and is therefore not constrained by classical thermodynamic efficiency limits such as those associated with Carnot cycles. Instead, the process relies on direct thermochemical coupling, in which heat generated from partial oxidation is immediately utilized to sustain the decomposition reaction.

In practical subsea operation, heat losses to the surrounding environment are unavoidable. These losses do not invalidate the process, but require an increase in the oxidation fraction (α) to maintain thermal balance. As a result, α is expected to exceed its theoretical minimum and typically lie in the range of 5–10% under realistic conditions.

This adjustment corresponds to a modest increase in oxygen supply, which can be delivered through a controlled feed line from the surface. The required oxygen flow remains small relative to the processed hydrogen sulfide, ensuring that the system retains its simplicity while compensating for environmental heat dissipation.

Parametric Analysis of the Combustion Fraction (A)

The performance of the proposed system is governed by the combustion fraction α, which determines both the internal heat generation and the hydrogen production yield. This section examines the influence of α on thermal balance and process efficiency, identifying the operational trade-offs and optimal regimes.

Dimensionless Energy Balance

To generalize the analysis, a dimensionless energy ratio is defined:

$$\text{Energy ratio} = Qg / Q_r$$

Using the expressions from Section 2:

$$\text{Energy ratio} = (\alpha \cdot |\Delta H_c|) / ((1 - \alpha) \cdot \Delta H_d)$$

Interpretation:

- Energy ratio < 1 → external energy required
- Energy ratio = 1 → thermally self-sustained
- Energy ratio > 1 → excess heat available

Representative Values

Using:

- $\Delta H_d \approx 20$ kJ/mol
- $|\Delta H\_c| \approx 500$ kJ/mol

the energy ratio becomes:

$$\text{Energy ratio} \approx (\alpha \cdot 500) / ((1 - \alpha) \cdot 20)$$

Parametric Evaluation

The system behavior can be evaluated across a range of α values:

Table 1: Parametric evaluation of combustion fraction (α) showing hydrogen yield and energy ratio.

α (combustion fraction)	H_2 production fraction (1 − α)	Energy ratio
0.1	0.9	0.62
0.15	0.85	0.98
0.2	0.8	1.39
0.25	0.75	1.85
0.3	0.7	2.38

The table illustrates the transition from externally driven operation to thermally self-sustained regimes as α increases.

Thermal Balance Formulation

$Qr = (1 - \alpha) \cdot \Delta Hd$

$Qg = \alpha \cdot |\Delta Hc|$

$Qe = Qr - Qg - Qs$

A self-sustained regime is achieved when

$$Qg + Qs \geq Q_r .$$

Key Observations

Self-sustaining threshold

The transition from externally driven to self-sustained operation occurs near:

$\alpha \approx 0.15$

Below this value, additional external energy is required to maintain the decomposition process.

Practical operating window

Considering heat losses and inefficiencies, the practical operating range is:

$\alpha \approx 0.05 – 0.10$

Within this range:

- Energy ratio > 1 → sufficient internal heat
- Stable continuous operation
- Reduced dependence on external energy

Hydrogen yield trade-off

Hydrogen production decreases linearly with increasing α:

H_2 yield = (1 − α)

Thus:

- α = 0.20 → 80% conversion to hydrogen
- α = 0.30 → 70% conversion to hydrogen

This establishes a trade-off between:

- maximizing hydrogen output
- ensuring thermal self-sufficiency

Optimal Operating Point

An optimal combustion fraction α* can be defined as the minimum value that ensures thermal self-sufficiency under realistic conditions:

$\alpha^* \approx 0.05 – 0.10$

This range provides:

- sufficient internal heat generation
- high hydrogen yield (75–80%)
- robustness against heat losses

Graphical Interpretation

The system behavior can be visualized using two curves:

- Energy ratio vs α (increasing nonlinear curve)
- Hydrogen yield vs α (linear decreasing curve)

The intersection of operational constraints defines the feasible region of operation. The optimal regime lies where:

- Energy ratio ≥ 1
- Hydrogen yield remains high

Process Insight

The parametric analysis demonstrates that a relatively small fraction of the feedstock can sustain the entire process thermally, enabling the majority of the feed to be converted into hydrogen. This internal energy redistribution mechanism is the key factor that enables low external energy operation.

Coastal Processing, Transport Reduction, and Environmental Considerations

Transport Constraints and Risk Reduction

Conventional hydrogen production and utilization pathways are strongly influenced by the challenges associated with storage and transportation. Hydrogen requires compression, liquefaction, or chemical carriers, all of which introduce energy penalties, infrastructure complexity, and safety considerations. Similarly, hydrogen sulfide (H_2S), while abundant in certain environments, is highly toxic and presents significant risks during long-distance transport.

The proposed system addresses these limitations by processing H_2S directly at or near its source, such

as coastal terminals receiving offshore production streams. Instead of transporting hazardous or energy-dense materials, the system converts H_2S into hydrogen and elemental sulfur at the point of arrival.

This approach provides several advantages:

- Elimination of long-distance H_2S transport
- Reduction of hydrogen storage and transport requirements
- Lower infrastructure complexity
- Enhanced operational safety

As a result, the process shifts from a transport-dependent model to a localized conversion model, improving both feasibility and reliability.

Continuous Coastal Processing Concept

The system is designed for continuous operation, receiving a steady flow of H_2S from offshore sources, such as subsea extraction systems or transport vessels.

A representative operational scenario is as follows:

- A vessel transports H_2S-rich gas from offshore production
- The gas is delivered to a coastal processing unit
- The feed is immediately partitioned into combustion and decomposition streams
- Hydrogen is produced on-site and can be used locally or fed into distribution systems
- Elemental sulfur is collected as a stable solid product

This configuration avoids intermediate storage of hazardous gases and enables real-time processing, reducing both environmental and safety risks.

Environmental Considerations

Hydrogen sulfide is a toxic and environmentally hazardous compound. Uncontrolled release can lead to severe ecological and health impacts. Conventional handling methods often involve flaring or chemical conversion, which may result in emissions such as sulfur dioxide (SO_2).

In the proposed system:

- H_2S is consumed continuously, minimizing accumulation
- Controlled combustion is limited to a fraction of the feed (α)
- The majority of sulfur is recovered as elemental sulfur, a stable and non-volatile form

This reduces:

- toxic emissions
- environmental exposure
- waste generation

Additionally, by coupling internal combustion with decomposition, the system reduces reliance on external fossil-based energy sources, further lowering its environmental footprint.

Process Flow Representation

The overall process can be summarized as a coupled flow system integrating transport, thermal conversion, and product separation. Figure 1 illustrates the overall process configuration, including feed splitting, thermal coupling, and product separation.

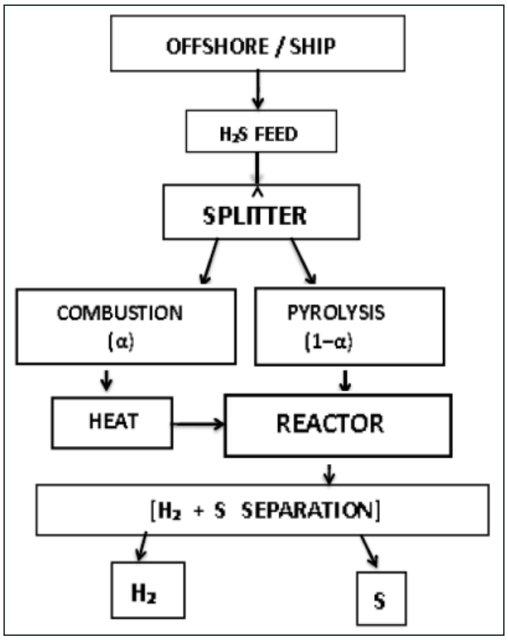

Figure 1: Process-level representation of H_2S conversion with combustion–decomposition coupling

A continuous H_2S feed is partitioned into combustion (α) and decomposition ($1 - \alpha$) streams. Heat generated from combustion sustains the decomposition reactor, enabling thermally self-balanced operation. The parameter α represents the fraction of the feedstock allocated to internal energy generation.

System-Level Insight

The integration of transport minimization, thermal coupling, and continuous processing defines a unified system in which:

- energy is internally redistributed
- hazardous materials are immediately converted
- valuable outputs are directly generated

This configuration transforms the overall process from a **transport-limited and risk-sensitive system** into a **localized, controlled, and value-generating platform.**

Feasibility and Economic Considerations

Energy Efficiency and External Input Reduction

The feasibility of the proposed system is primarily determined by its ability to minimize external energy requirements through internal thermal coupling. As demonstrated in Sections 2 and 3, a relatively small fraction of the feedstock ($\alpha \approx 0.05–0.10$) can supply sufficient heat to sustain the decomposition of the remaining fraction.

This leads to a substantial reduction in external energy demand compared to conventional hydrogen production methods. In particular:

- No electrical input for electrolysis is required
- No reforming of hydrocarbons is needed
- Thermal demand is largely satisfied internally

Any remaining energy requirement can be supplemented by low-cost thermal sources, such as solar concentrators, particularly in coastal environments.

Thus, the system does not eliminate energy input, but **restructures it,** shifting from externally supplied energy to internally generated heat.

Capital Expenditure (CAPEX) Considerations

A key advantage of the proposed framework lies in its relatively simple infrastructure requirements. The system avoids several high-cost components associated with conventional hydrogen production technologies.

The primary system elements include:

- Thermal reactor (high-temperature resistant design)
- Gas splitting and flow control unit
- Combustion chamber
- Heat transfer interface between combustion and decomposition zones
- Product separation unit (H_2 and sulfur)
- Optional solar thermal input system

Compared to electrolysis-based systems, the proposed configuration:

- avoids expensive electrical infrastructure
- reduces dependence on high-purity water
- minimizes the need for complex catalysts (depending on implementation)

As a result, the overall capital investment is expected to be **moderate and scalable,** particularly for modular coastal installations.

Operational Simplicity and Continuous Processing

The system is inherently designed for continuous operation, which enhances both efficiency and economic viability. The absence of batch processing, iterative optimization, or complex control requirements simplifies operation.

Key operational advantages include:

- Continuous feed utilization
- Direct conversion without intermediate storage
- Reduced downtime
- Simplified control based on the combustion fraction α

This contributes to lower operational expenditure (OPEX) and improved system reliability.

Value of Sulfur Co-Product

In addition to hydrogen production, the process yields elemental sulfur as a co-product. Unlike conventional systems where sulfur is treated as a secondary output, the present framework considers sulfur as an integral component of the value chain.

Elemental sulfur is widely used in:

- chemical manufacturing (e.g., sulfuric acid production)
- materials processing
- industrial applications
- emerging energy storage systems (e.g., sulfur-based batteries)

The recovery of sulfur in stable solid form provides:

- additional revenue stream
- reduction in waste handling costs
- improved overall process economics

Thus, the system operates as a **dual-output platform,** producing both energy (hydrogen) and a marketable material (sulfur).

Transport and Infrastructure Savings

A major economic advantage arises from the elimination of long-distance transport of hazardous or energy-intensive materials. By processing H_2S at the source:

- transportation costs are reduced
- storage requirements are minimized
- safety-related infrastructure is simplified

Furthermore, hydrogen can be utilized locally or distributed in smaller, controlled networks, avoiding large-scale transport challenges.

This shift from centralized processing to **localized conversion** significantly improves economic feasibility, particularly in offshore and remote production environments.

Overall Feasibility Perspective

The proposed system combines:

- reduced external energy demand
- moderate capital requirements
- continuous operation
- dual-product output
- minimized transport and safety costs

These factors collectively contribute to a favorable feasibility profile.

Rather than competing directly with established hydrogen production methods, the system defines a **complementary operational regime,** particularly suited for environments where:

- hydrogen sulfide is readily available
- transport is costly or risky
- external energy supply is limited

Economic Interpretation

From a system-level perspective, the process transforms hydrogen production from an energy-intensive operation into a **resource-coupled conversion system,** in which part of the feedstock is strategically used to sustain the process itself.

This internalization of energy demand, combined with co-product generation and transport reduction, provides a pathway toward economically viable hydrogen production under constrained conditions.

In-Situ Separation and Phase Management

A thermodynamic estimate based on formation enthalpies shows that oxidizing approximately 4% of the hydrogen sulfide feed is sufficient to sustain the decomposition reaction. In practical operation, a slightly higher fraction (5–10%) is expected to compensate for heat losses in the subsea environment.

General Concept

The proposed system performs separation directly within the subsea processing unit, eliminating the need for transporting mixed or hazardous streams to the surface. Following the thermally sustained conversion of hydrogen sulfide into hydrogen and elemental sulfur, the reaction products are handled as distinct phases and separated in situ.

The separation strategy relies on intrinsic physical differences between the products: hydrogen remains in the gaseous phase, while sulfur transitions into a condensed phase depending on local temperature conditions. This phase contrast enables passive and low-complexity separation without reliance on large-scale external processing facilities.

Hydrogen Phase Separation

Hydrogen produced in the reaction chamber forms a low-density gas phase that naturally rises within the separation volume. A dedicated gas collection zone is positioned above the reaction region, allowing hydrogen to accumulate and be extracted through a controlled outlet.

Depending on system design, two approaches may be employed:

- **Direct gas collection**, in which hydrogen is guided to a riser or storage line
- **Membrane-assisted separation**, used to enhance purity if required

In its simplest implementation, the system operates without complex purification, treating the hydrogen

stream as a primary energy carrier to be handled at the surface under controlled conditions.

Sulfur Phase Management

Elemental sulfur is produced as a condensed phase, typically forming liquid droplets at elevated temperatures and solidifying upon cooling. Due to its significantly higher density relative to hydrogen and surrounding fluids, sulfur is directed downward and collected in a designated storage compartment.

The system may operate in one of two regimes:

- **Molten sulfur collection**, where temperature is maintained above the sulfur melting point
- **Solid or slurry collection,** where sulfur is allowed to solidify and accumulate

This passive gravitational separation eliminates the need for mechanical filtration or complex solid-handling systems.

Phase Stability and Flow Control

To ensure reliable separation, the system maintains a controlled internal flow structure:

- Upward flow region for hydrogen transport
- Downward or quiescent zone for sulfur accumulation
- Minimal turbulence to prevent phase mixing

Thermal gradients are also managed to stabilize phase behavior, ensuring that hydrogen remains in the gas phase while sulfur remains condensed.

Integration with System Architecture

The separation unit is integrated directly downstream of the reaction chamber, forming a continuous processing pathway from extraction to product handling. This configuration avoids intermediate storage of reactive mixtures and minimizes the system footprint.

By performing separation in situ, the system ensures that only stable and manageable products—hydrogen and sulfur—are transported beyond the processing unit. This approach significantly reduces safety risks and simplifies downstream handling requirements.

In-situ separation transforms the system from a reactive processing unit into a controlled product-generation platform, where only stable and manageable phases leave the reactor.

Industrial Feasibility

The feasibility of the proposed system is governed by feedstock concentration, volumetric processing rate, and energy self-sufficiency.

The primary reactions governing the process are:

$\Delta H \approx +20$ kJ/mol $\quad H_2S \rightarrow H_2 + S$

$\Delta H \approx -518$ kJ/mol $\quad H_2S + 3/2\ O_2 \rightarrow SO_2 + H_2O$

The ratio $518/40 \approx 12.95$ indicates that the energy released by oxidation is approximately 13 times larger than the energy required for decomposition. As a consequence, only a small fraction of hydrogen sulfide needs to be oxidized to sustain the process, yielding an approximate balance $\alpha \approx 1/13 \approx 0.077$. In practical subsea operation, accounting for thermal losses, the oxidation fraction is expected to lie within the range $\alpha \approx 5–10\%$.

This energy imbalance enables a thermally self-sustained regime in which heat generated by partial oxidation directly supports the decomposition reaction. The process is therefore not dependent on large external energy input, but on internal thermochemical coupling.

A representative concentration of dissolved hydrogen sulfide in stratified aquatic environments is on the order of 10 mg/L. At this concentration, approximately 100,000 tons of water must be processed to recover one ton of hydrogen sulfide. While this value appears large, it is consistent with continuous-flow marine systems, where high volumetric throughput can be achieved without bulk transport of hazardous materials.

The proposed system operates through direct in-situ conversion within the water column, eliminating the need for collection, compression, or transportation of hydrogen sulfide. This significantly reduces safety risks and infrastructure requirements.

The corresponding oxygen demand remains modest. For example, at an oxidation fraction of 5%, the required oxygen input is approximately 0.075 mol O_2 per mol of H_2S processed, enabling simple and controlled oxygen supply from the surface.

In addition to hydrogen production, the process

generates elemental sulfur as a valuable co-product with established industrial applications. This dual-output structure improves the overall economic potential of the system.

Overall, the feasibility of the system is defined not by high feedstock concentration or external energy supply, but by continuous processing of large water volumes combined with localized thermochemical conversion. This shift from transport-based handling to in-situ processing establishes a scalable and industrially relevant pathway for hydrogen production from hydrogen sulfide.

The reactor operates at ambient subsea pressure, allowing hydrogen to be produced in a naturally compressed state, thereby simplifying transport to the surface.

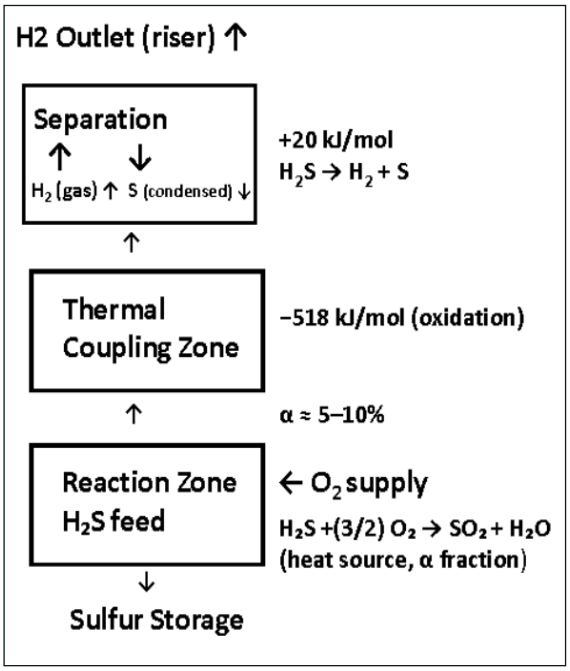

Figure 2: Conceptual subsea reactor implementing the coupled process

Combustion and Oxygen Supply Configuration

Oxygen is supplied from the surface through a dedicated high-pressure line and injected directly into the lower reaction chamber. The reactor operates at ambient subsea pressure, and the oxygen supply pressure is maintained slightly above this level to ensure controlled flow into the system.

Hydrogen sulfide is continuously fed into the reaction chamber, where a small fraction is subjected to oxygen-limited combustion. This localized reaction acts as a heat source and initiates the thermochemical process.

The combustion region is confined to the lower section of the reactor, forming a stabilized reaction zone rather than an open flame. Heat generated in this region is transferred upward into the main reactor volume, where it sustains the decomposition of hydrogen sulfide into hydrogen and elemental sulfur.

Ignition is achieved through a short-duration startup mechanism, such as electrical heating or a localized ignition source. Once initiated, the process becomes thermally self-sustained and no longer requires continuous external heating.

The upper section of the reactor functions as a separation chamber. Hydrogen, as a low-density gas, rises and is collected at the top outlet, while sulfur condenses and settles toward the bottom storage zone. This configuration enables continuous operation with simultaneous reaction and phase separation.

The oxygen supply remains limited to a small fraction of the total feed, corresponding to the required oxidation fraction. As a result, oxygen demand is low and can be delivered through a simple surface-fed system without significant infrastructure.

Overall Energy Estimate Per 1m³ of Hydrogen

This section provides a system-level estimate of the operational energy required to produce 1 m³ of hydrogen under representative subsea conditions. Rather than focusing solely on thermochemical feasibility, the analysis considers the practical contributions of oxygen delivery, product transport, water handling, and system logistics. The objective is to assess whether the proposed process remains energetically viable when real operational factors are included.

A rough order-of-magnitude estimate is performed to evaluate the total operational energy required to produce 1 m³ of hydrogen under representative conditions.

At a typical dissolved hydrogen sulfide concentration of 10 mg/L, approximately 150 m³ of water must be processed to produce 1 m³ of hydrogen. The total operational energy consists of oxygen delivery, product

transport, water handling, and system logistics.

The energy required for oxygen compression to subsea depth (~200 m, ~20 bar) is small. For the required oxidation fraction ($\alpha \approx 0.05–0.10$), this contribution is on the order of 0.01 kWh per m^3 of hydrogen and can be considered negligible.

Hydrogen transport to the surface is assisted by buoyancy and ambient pressure conditions. As a result, the associated energy requirement is minimal and limited to flow losses.

The dominant operational energy term is associated with water handling. Under active pumping conditions, this contribution may reach several kWh per m^3 of hydrogen. However, in stratified aquatic environments, passive intake and natural flow mechanisms can significantly reduce this requirement.

Additional energy is associated with system logistics, including deployment, retrieval, and towing of subsea units. When amortized over continuous operation, this contribution is estimated to be on the order of a few kWh per m^3 of hydrogen.

Combining these contributions, the total operational energy requirement is estimated to lie in the range:

3–10 kWh per m^3 of hydrogen

For comparison, the energy content of hydrogen is approximately 10.8 kWh per m^3. This indicates that the process operates near energy parity under conservative assumptions and can achieve a favorable balance under optimized passive-flow and stationary configurations.

Table 2: Rough Operational Energy Estimate per 1 m^3 of Hydrogen

Item	Description	Energy (kWh per m^3 H_2)	Justification
Towing / logistics	Deployment and 150–300 km transport (amortized)	1 – 5	Energy dominated by hydrodynamic drag and mission duration, reduced by amortization over continuous operation
Lowering / hoisting	Subsea deployment and retrieval (ballast-controlled)	< 0.5	Net energy is small due to buoyancy-assisted ballast control and limited vertical travel
Oxygen supply	Compression to ~20 bar and injection	~0.01	Required O_2 amount is small ($\alpha \approx 0.05–0.10$), making compression energy negligible
Product lifting (H_2)	Buoyancy-driven, minor flow losses	~0	Hydrogen rises naturally due to buoyancy and is already at elevated pressure
Water handling	Flow intake / circulation (design-dependent)	1 – 5	Dominant term; depends strongly on whether passive flow or active pumping is used

The table highlights that water handling and system logistics dominate operational energy, while oxygen supply and product transport contribute negligibly. The estimates in Table 2 provide a system-level interpretation of the operational energy requirements. While multiple components contribute to the overall expenditure, the results indicate a clear hierarchy among them. Oxygen delivery and hydrogen transport are energetically negligible due to the small oxidation fraction and buoyancy-driven flow, respectively. In contrast, water handling and system logistics dominate the operational energy budget.

This distinction highlights a key design principle of the proposed system: its feasibility is governed more by fluid handling and deployment strategy than by reaction thermodynamics. In particular, minimizing active pumping and reducing towing frequency are critical for maintaining a favorable energy balance. Under passive-flow or stationary configurations, the system can operate near or below energy parity, whereas excessive mechanical handling may offset the thermodynamic advantage.

Overall, the analysis indicates that the process operates near energy parity under conservative assumptions and can achieve a favorable balance under optimized conditions. The results emphasize that operational feasibility is governed primarily by fluid handling and system logistics rather than reaction energetics. Consequently, design strategies that minimize active pumping and transport requirements are essential for realizing the full potential of the proposed subsea hydrogen production system.

The estimates are intentionally conservative and indicate that the system operates near feasibility limits, with performance strongly dependent on flow management and system design.

Conclusion

This study presented a subsea process architecture for the direct conversion of hydrogen sulfide into hydrogen and elemental sulfur through thermochemically coupled reactions. By combining partial oxidation with thermal decomposition, the system operates in a self-sustained regime in which a small fraction of the feed provides the energy required for continuous conversion. The analysis shows that only a limited oxidation fraction, on the order of 5–10%, is sufficient to maintain thermal balance, eliminating the need for large external energy input.

The proposed approach shifts hydrogen sulfide handling from transport and containment to localized transformation within the water column. This eliminates hazardous gas transport, reduces environmental exposure, and enables continuous processing of large water volumes under ambient subsea pressure. The integrated reaction–separation configuration produces hydrogen and sulfur as stable, manageable outputs, providing a scalable and industrially relevant pathway for resource utilization in hydrogen sulfide-rich environments. Rough operational estimates indicate that the process can operate near energy parity under realistic conditions. The process therefore represents a physically grounded and operationally viable pathway for hydrogen production under constrained subsea conditions.

Abbreviations

CAPEX	Capital Expenditure
H_2	Hydrogen
H_2S	Hydrogen Sulfide
MAS	Multi-Agent System
OPEX	Operational Expenditure
Qe	External Heat Requirement
Qg	Generated Heat
Qr	Required Heat
Qs	Solar Heat Input
S	Elemental Sulfur
α	Combustion Fraction
ΔHc	Enthalpy of Combustion
ΔHd	Enthalpy of Decomposition

Author Contributions

Huseyin Murat Cekirge is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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