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Hydrogen Recovery without Bulk Transport: A Dynamic Subsea Capture Approach

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Abstract

This study introduces a dynamic subsea capture framework for hydrogen recovery that departs from conventional production routes based on electrolysis and thermochemical conversion. Instead of generating hydrogen through energy-intensive bond dissociation, the proposed approach recovers hydrogen-bearing fluid through passive, flow-induced capture within a distributed environment. The system consists of a stationary or semi-stationary subsea unit equipped with controllable lateral openings and a sensor-guided control scheme. Relative motion is provided by ambient currents and, when needed, by short-range surface vessel movement over distances on the order of 50–100 meters. During each capture cycle, lateral openings are exposed to the surrounding flow for a short interval, allowing the chamber to fill under natural pressure and velocity conditions. The openings are then sealed and the cycle is repeated. This replaces continuous pumping and long-distance transport with discrete, geometry-driven capture events. First-order analysis indicates that the energy required per kilogram of hydrogen is on the order of 10^6 to 10^7 joules, substantially lower than the approximately 2×10^8 joules per kilogram, typically associated with water electrolysis. The resulting regime is primarily capture-limited, with performance governed by local concentration, flow conditions, and capture efficiency. The framework is particularly relevant in subsea environments where hydrogen-bearing species such as hydrogen sulfide are spatially distributed. Rather than targeting isolated reservoirs, the system performs repeated local sampling and accumulates product over time. By aligning the design with ambient hydrodynamics, the approach minimizes external energy input and simplifies system architecture. While feasibility is site-dependent, the results establish a physically consistent and scalable basis for low-energy subsea hydrogen recovery via dynamic capture.

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Abbreviations

CAPEX	Capital Expenditure
H_2	Hydrogen
H_2S	Hydrogen Sulfide
OPEX	Operational Expenditure
α	Combustion Fraction

Introduction

Hydrogen is widely regarded as a key energy carrier in emerging low-carbon systems; however, its production remains dominated by processes that are intrinsically energy-intensive and infrastructure-dependent. Water electrolysis, one of the most established clean production routes, typically requires on the order of 50-55 kilowatt-hours per kilogram of hydrogen, reflecting the fundamental cost of molecular bond dissociation and associated system losses. Thermochemical pathways, including those involving hydrogen sulfide, offer alternative routes but still rely on significant energy input or complex heat integration strategies. As a result, conventional hydrogen production is inherently energy-limited, with cost scaling directly with supplied energy.

In parallel, large subsea environments contain significant quantities of dissolved and free-phase gases, including hydrogen sulfide, that are naturally present and often spatially distributed over extended regions. In the Black Sea, for example, hydrogen sulfide accumulates in deep anoxic layers, forming one of the largest known natural reservoirs of reduced sulfur compounds. These environments are typically treated as hazardous or environmentally constrained systems, where mitigation rather than utilization is the primary objective. Nevertheless, the presence of hydrogen-bearing species in situ suggests the possibility of resource recovery strategies that do not rely on generating hydrogen from water, but instead on accessing and separating existing chemical potential [1-8].

Conventional subsea processing concepts have generally followed a transport-driven paradigm, in which fluid is pumped, lifted, or transported over significant distances for surface processing. Such approaches introduce substantial energy penalties due to frictional losses, pressure management, and mechanical complexity, particularly in deep or remote environments. Even horizontal transport over moderate distances can dominate the system energy budget, often exceeding the energy required for hydrogen production via electrolysis when evaluated on a comparable basis. These constraints have limited the feasibility of large-scale subsea hydrogen recovery using traditional fluid handling methods.

This work proposes a different formulation of the problem. Instead of transporting fluid to a processing unit, the subsea unit performs repeated localized capture within the ambient environment. A subsea chamber with controllable lateral openings is exposed to the surrounding flow, allowing it to fill passively under natural pressure and velocity conditions. Relative motion is induced either by ambient currents or by short-range surface vessel repositioning, eliminating the need for continuous pumping and long-distance transport. The process operates as a sequence of discrete capture cycles, in which fluid is sampled from a spatially distributed resource field and accumulated over time.

This shift from transport-driven extraction to access-driven capture represents a fundamental change in system design. Energy is no longer expended to move large volumes of fluid or to break molecular bonds, but rather to control exposure, actuation, and minimal fluid handling. As a result, the system transitions from an energy-limited regime to a capture-limited regime, where performance depends primarily on local concentration, flow conditions, and capture efficiency.

In the proposed configuration, the dominant operational cost is associated with surface vessel motion. All subsea processes, including capture, actuation, and gas handling, require comparatively minor energy input. This shifts the economic burden from continuous energy consumption to standard marine operation, comparable to routine vessel activities such as survey or fishing operations.

The objective of this study is to establish the physical and energetic basis of this dynamic subsea capture concept. A first-order analysis is presented to quantify the energy requirements, compare them with conventional electrolysis benchmarks, and identify the conditions under which the approach becomes viable. By reframing hydrogen recovery as a problem of controlled access to a distributed resource, the work aims to define a new pathway for low-energy subsea

hydrogen systems [9-11].

Cycle-Based Operation and Energy Scaling

The system functions through repeated capture cycles consisting of approach, filling, separation, and reset. Each cycle processes a finite volume of water, after which the system repositions and repeats. Performance is determined by cycle frequency and captured mass per cycle rather than continuous flow infrastructure.

Energy consumption is dominated by three components: subsea motion, positioning or towing, and auxiliary operations such as gas handling or separation. Unlike conventional systems, there is no persistent energy draw for pumping large volumes. Instead, energy input is discrete and linked to cycle execution.

A key implication is that energy per unit of extracted product depends on how efficiently each cycle converts intercepted mass into usable output. Increasing opening area or relative velocity improves capture per cycle without proportionally increasing system complexity. Similarly, optimizing cycle timing enhances throughput without requiring scale-up of infrastructure.

This leads to a modular scaling behavior. Multiple units can operate independently, each executing the same cycle. Total production increases linearly with the number of units, while each unit remains physically and energetically bounded. This avoids the exponential cost growth associated with centralized processing systems.

In this framework, feasibility is not determined by maximum continuous capacity but by stability, repeatability, and energy cost per cycle. The system behaves as a distributed, motion-driven extractor where efficiency emerges from controlled repetition rather than bulk transport.

Dynamic Capture and Controlled Repositioning

The system operates through relative motion between the subsea unit and the surrounding fluid, enabling passive filling without pumping or bulk transport. Fluid enters the chamber due to velocity difference, with typical seawater density around 1000 kilograms per m^3. For an opening area between 0.5 and 2 m^2 and relative velocity of 0.3 to 1.5 m/s, the resulting inflow ranges from approximately 150-3000 kilograms per second. Capture occurs over short intervals of 10–30 seconds, yielding approximately 1,500–90,000 kilograms of fluid per cycle. Hydrogen yield depends on local concentration and captured volume, making the system primarily capture-limited rather than energy-limited.

Figure 1 presents a subsea chamber connected to a surface vessel via a tether and exposed to ambient flow through lateral inlets. During each cycle, fluid enters the chamber passively under natural pressure and velocity conditions, eliminating the need for pumping or bulk transport. Once filled, the chamber is sealed, and the system undergoes a short-range movement step before repeating the process. This sequence establishes a discrete capture mechanism in which hydrogen-bearing fluid is accumulated through repeated exposure to a spatially distributed resource field. The system therefore operates as a sampling-based extraction process, where performance is governed by local flow conditions, capture volume, and cycle repetition rather than continuous transport.

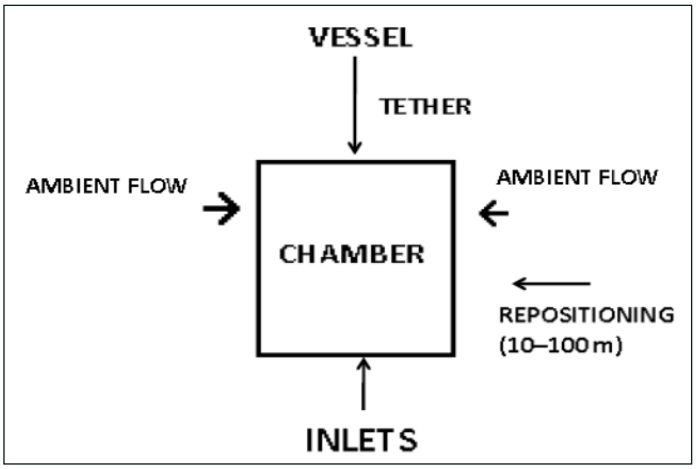

Figure 1: Conceptual representation of the dynamic subsea capture system showing passive filling under ambient flow, lateral inflow through multiple inlets, and short-range repositioning between capture cycles.

Operation is inherently cyclic. Each cycle consists of exposure, filling, sealing, and movement. In stepwise mode, the unit advances through the resource field in discrete steps, performing short-range relocations on the order of tens of meters between cycles. This replaces continuous transport with repeated local sampling.

Ambient currents can provide sufficient flow, allowing operation without active propulsion. When movement is required, a tether-controlled system enables lateral movement within a limited area, typically 10 to 100 meters, allowing the unit to follow higher concentration regions and avoid local depletion.

The system may additionally incorporate low-power subsea thrusters for short-range movement. These operate intermittently and only when needed, providing controlled lateral adjustment without introducing continuous propulsion. This preserves the low-energy, capture-driven nature of the system while improving responsiveness and positioning accuracy.

Two operating modes emerge: fixed mode, where the system remains stationary and relies on ambient flow, and adaptive mode, where controlled movement maintains optimal exposure to the resource field. Ballast-based buoyancy control ensures vertical stability and compensates for mass variation during capture, with negligible energy cost. The generated thrust is limited to short-duration movement and does not contribute to continuous propulsion.

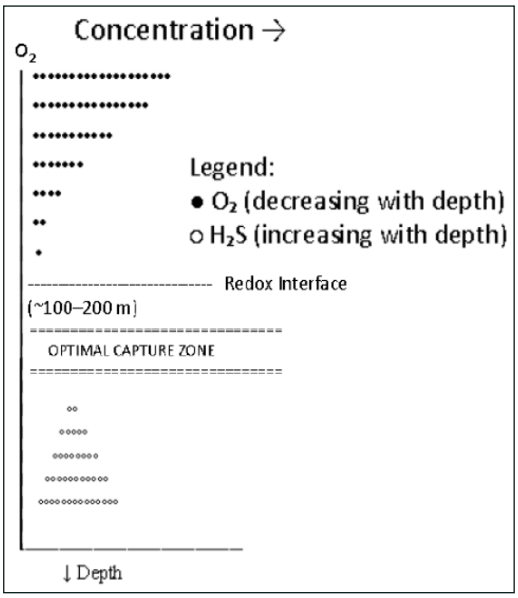

Figure 2: Conceptual vertical distribution of dissolved oxygen (O_2) and hydrogen sulfide (H_2S) in a stratified euxinic basin. Oxygen concentration decreases with depth, while hydrogen sulfide increases sharply below the redox interface (~100–200 m). The highlighted region indicates the optimal depth range for passive capture, where system positioning directly determines accessible hydrogen sulfide concentration.

As illustrated in Figure 2, the vertical separation between oxygenated and sulfide-rich layers defines a sharply bounded chemical interface that directly governs accessible hydrogen sulfide concentration.

The proposed system eliminates active pumping entirely by exploiting hydrostatic pressure and buoyancy-driven motion as the sole driving mechanisms. Fluid intake is achieved passively through the ambient pressure gradient:

$P = \rho g h$

where

ρ: fluid density (kg/m^3),

g: gravitational acceleration (m/s^2),

h: depth below the free surface (m).

Discharge and vertical transport are governed by buoyancy forces:

$F_b = \rho g V$

where

V: displaced volume (m^3).

Through the coupling of these two mechanisms, the system operates as a self-sustained cyclic process of passive filling and buoyancy-driven discharge. No external pumping is required at any stage of operation. This effectively reduces operational energy requirements to near-zero levels and removes one of the primary cost drivers in conventional fluid handling systems. In this configuration, gravity and environmental dynamics replace active pumping, transforming the process from energy-intensive transport into passive capture and release.

By eliminating pumping as an operational requirement, the system fundamentally shifts the cost structure from energy consumption to structural design.

Gas–Liquid Behavior During Discharge

Following gas extraction, the internal pressure of the chamber decreases, altering the equilibrium between dissolved and free gas phases. Upon opening, the pressure differential primarily drives the discharge of the degassed liquid phase, while portions of gas-rich fluid—particularly hydrogen sulfide-bearing fractions—may remain within the chamber. As a result, discharge is not purely volumetric but phase-selective discharge. To maintain effective removal of

gas-containing fluid and avoid stratification or retention, controlled motion or induced mixing is required. This introduces a mild hydrodynamic requirement within the cycle, ensuring that gas-bearing fractions are continuously exposed and recovered.

Phase-selective discharge simplifies subsea charge and discharge operations and further reduces external energy demand, reinforcing the fundamental advantage over electrolysis-based systems.

A passive discharge mechanism can be implemented through controlled geometric tilting of the chamber. By introducing a small inclination, the captured fluid is released under gravity without requiring active pumping or continuous motion. In this configuration, discharge is governed by hydrostatic imbalance and vessel orientation rather than mechanical energy input.

This approach maintains the fully passive nature of the cycle. Filling is achieved through ambient flow, while emptying is achieved through gravity-assisted release. As a result, the capture cycle becomes entirely geometry-driven, with energy input limited to state and control.

The tilting mechanism therefore completes the transition from transport-based fluid handling to passive capture and release, eliminating one of the remaining active energy components in the system.

Sensor integration enables adaptive operation by providing real-time information on local hydrogen sulfide concentration, flow conditions, and phase behavior. Distributed sensing elements, including chemical concentration sensors and flow detectors, allow the system to identify regions of higher yield within the surrounding environment.

Based on sensor input, the subsea unit can adjust its lateral position through tether control or short-range actuation, maintaining exposure to regions of elevated concentration. This establishes a feedback-driven capture strategy in which system positioning is continuously refined without requiring large-scale motion.

Such sensor-guided operation increases effective capture efficiency per cycle and reduces unnecessary movement, thereby preserving the low-energy character of the system while improving overall production rate. The system operates through local concentration tracking rather than global search. This physical behavior establishes the basis for the thermodynamic interpretation of the system.

Thermodynamic Basis and Cost Structure

Hydrogen production from hydrogen sulfide follows a direct stoichiometric relation, where each mole of hydrogen sulfide yields one mole of hydrogen. Although the theoretical decomposition energy is relatively modest per mole, practical operation does not rely on direct external energy input.

Instead, the system relies on partial oxidation of a small fraction of hydrogen sulfide to provide the required thermal energy. Only about 4-10% of the feed needs to be oxidized to sustain the process, while the remaining fraction is converted to hydrogen. This establishes an internally sustained thermochemical regime.

As a result, external energy demand is no longer dominated by chemical processing. Thermochemical energy is largely self-supplied, and external energy demand shifts to mechanical and operational components, including subsea motion, short-range movement, and gas handling. Total energy per cycle remains on the order of 10^6 to 10^7 joules, significantly below conventional electrolysis on a per-cycle basis.

However, system feasibility is not determined by energy consumption alone. The dominant factor is cost structure. In electrolysis, cost is driven by electricity and capital equipment. In the proposed system, cost is driven primarily by vessel operation and amortized subsea infrastructure.

Unit cost depends inversely on production rate. Because operating costs are largely fixed on an hourly basis, cost per kilogram decreases as hydrogen production rate increases. At low production rates, the system is not competitive due to underutilization. As production increases, cost decreases rapidly and approaches conventional benchmarks.

This creates a clear operational threshold. Below approximately 50 kilograms per hour, the system

remains non-competitive. Around 100 kilograms per hour, it approaches viability. Beyond 150-200 kilograms per hour, it becomes competitive with conventional methods.

The key conclusion is that the system does not compete on energy efficiency, but on cost structure. Energy for chemical conversion is largely self-supplied, while economic performance depends on maintaining sufficiently high production rates through effective capture, concentration tracking, and cycle repetition. This behavior is illustrated in Figure 3.

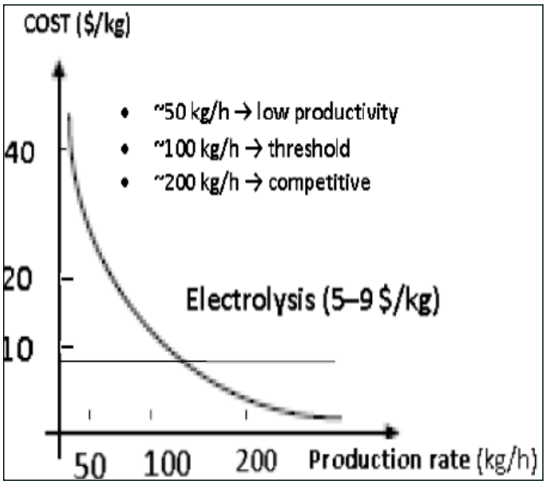

Figure 3: Hydrogen production cost as a function of production rate. Because system costs are dominated by fixed hourly vessel and infrastructure expenses, unit cost decreases inversely with production rate, resulting in a nonlinear transition from low-productivity to competitive operating regimes. The horizontal line indicates the typical cost range of conventional electrolysis.

The economic behavior of the system is governed by production rate rather than process energy. Because operational costs are largely fixed on an hourly basis, cost per unit hydrogen decreases as production increases. This results in a nonlinear transition from high-cost, non-viable operation at low production rates to competitive cost levels at higher throughput.

Thermodynamic and Comparative Energy Analysis

This section establishes the thermodynamic basis of hydrogen production from hydrogen sulfide, introduces electrolysis as a reference, and defines the role of partial oxidation in reducing external energy demand. Building on the thermodynamic framework introduced in the previous section, a comparative energy perspective is developed below.

The primary decomposition reaction produces one mole of hydrogen from one mole of hydrogen sulfide. Based on molar mass, hydrogen production is directly proportional to hydrogen sulfide input. The enthalpy of decomposition is approximately 20 kilojoules per mole, which corresponds to about 1.0×10^{10} joules per kilogram of hydrogen.

For comparison, water electrolysis typically requires about 50-55 kilowatt-hours per kilogram of hydrogen, corresponding to approximately 1.8×10^{8} to 2.0×10^{8} joules per kilogram. This difference indicates that direct decomposition is not intended to be driven by external energy alone, but must rely on internal energy sources.

To achieve this, a fraction of hydrogen sulfide is oxidized to generate heat. This partial oxidation releases approximately 400 – 500 kilojoules per mole, providing sufficient thermal energy to sustain the decomposition process. Energy balance shows that only a small fraction of the feed is required for this purpose, typically on the order of 4 to 10 percent.

This result implies that most of the hydrogen sulfide is converted into hydrogen, while a small portion supplies the necessary thermal energy. As a consequence, external energy input is substantially reduced, and the system operates in a self-sustained thermochemical regime.

In conventional systems, external energy is used directly for chemical production. In the present approach, chemical energy is internally recycled, and external energy demand is shifted toward mechanical and operational functions. Hydrogen production from hydrogen sulfide therefore does not eliminate energy requirements, but redistributes them.

To provide a quantitative perspective, consider a representative case of hydrogen production from hydrogen sulfide at the scale of hundreds of moles. For example, for 500 moles of hydrogen production, the required decomposition energy is approximately 10 megajoules. In a conventional electrolysis-based process, this energy would be supplied externally in the form of electricity, directly contributing to

operational cost.

In the present system, however, this energy demand is largely supplied internally through partial oxidation. For a typical oxidation fraction of approximately 5 percent, a small portion of the hydrogen sulfide feed provides sufficient thermal energy to sustain the process. As a result, external electrical energy input is substantially reduced for the chemical conversion stage.

This shift has direct economic implications. In conventional systems, energy cost is a primary contributor to hydrogen production cost. In contrast, the proposed approach avoids this cost component by utilizing internal chemical energy, allowing the corresponding expenditure to be retained within the system. Consequently, the economic burden shifts away from energy supply and toward operational factors such as capture rate and system deployment.

To illustrate the energy scale, the decomposition energy can be expressed as proportional to the number of moles, with approximately 20 kilojoules per mole. For example, for 500 moles, the required energy is on the order of 10^7 joules.

In contrast, the heat released by partial oxidation is approximately 400 to 500 kilojoules per mole. Using an oxidation fraction $\alpha \approx 0.05$, the internally generated energy can be estimated as $\alpha \times 500 \times 450$ kilojoules, which yields a value on the order of 10^7 joules.

This comparison shows that the internally generated energy is of the same order of magnitude as the decomposition requirement, confirming that the process can be thermally sustained without external electrical input for the chemical conversion stage.

System Scaling and Performance Envelope

The performance of the proposed system is governed by the interaction between capture volume, local concentration, and cycle frequency. Unlike conventional systems, where throughput is determined by continuous flow capacity, the present framework operates through discrete accumulation over repeated cycles.

Let the hydrogen production rate be expressed as proportional to the product of captured volume per cycle, local concentration, and cycle frequency. This implies that system performance can be improved through three independent mechanisms: increasing capture volume, operating in higher concentration regions, and increasing cycle repetition rate.

Because the system operates without bulk transport, scaling does not require proportional increases in infrastructure. Instead, multiple units can be deployed in parallel, each operating independently within a local region. This leads to a distributed scaling model in which total production increases linearly with the number of units, while each unit remains physically and energetically bounded.

A key constraint emerges from the trade-off between cycle duration and movement efficiency. Short cycles increase sampling frequency but may reduce capture volume per cycle, while longer cycles increase volume but reduce responsiveness to spatial variations in concentration. Optimal operation therefore depends on balancing these competing effects.

The system also exhibits sensitivity to environmental conditions. In regions with strong ambient flow, passive filling dominates and energy requirements are minimized. In low-flow environments, controlled movement becomes more important, and system performance depends on the ability to maintain exposure to fresh fluid.

This defines a performance envelope in which system viability is determined not by maximum theoretical throughput, but by the ability to sustain consistent capture under variable conditions. Within this envelope, production rate becomes the primary control parameter, directly linking physical operation to economic performance.

Limitations and Practical Considerations

The proposed framework relies on several assumptions that define its domain of applicability. First, the presence of sufficiently high concentrations of hydrogen-bearing species is required for viable operation. In environments with low concentration, the capture-limited nature of the system may result in insufficient production rates.

Second, the system assumes the availability of ambient

flow or the ability to achieve effective movement within a limited spatial range. In stagnant conditions, performance may degrade unless additional mechanical input is introduced.

Third, while the thermochemical process is internally sustained, practical implementation requires control of reaction pathways, heat distribution, and gas separation. These factors introduce engineering challenges that are not explicitly addressed in the present analysis.

Environmental and operational constraints must also be considered. Subsea deployment introduces issues related to corrosion, fouling, and long-term stability. In addition, vessel operation cost remains a dominant factor, and economic viability depends on maintaining sufficient production rates over time.

Despite these limitations, the framework provides a physically consistent basis for evaluating subsea hydrogen recovery under conditions where conventional transport-based systems are not feasible.

Discussion

The proposed system reframes hydrogen production as a problem of access rather than synthesis. Instead of relying on external energy to break molecular bonds, the system leverages naturally occurring hydrogen-bearing species and converts the challenge into one of capture efficiency and spatial positioning. This shift introduces a different set of governing parameters, where local concentration, flow conditions, and cycle execution dominate performance. Unlike conventional approaches, which scale with energy input and infrastructure, the present framework scales with repetition, positioning accuracy, and resource accessibility. As a result, optimization is no longer directed toward minimizing process energy, but toward maximizing capture per cycle and sustaining high production rates under variable environmental conditions.

Partial phase retention and incomplete discharge introduce a cumulative concentration effect within the capture cycle. As gas-rich fractions are preferentially retained, subsequent cycles begin from an elevated baseline concentration, leading to a progressive increase such that $C_{n+1} > C_n$. This cumulative behavior enhances local concentration over time and suggests a natural tendency toward enrichment of heavier components, including deuterium-bearing species, within the captured fluid. During thermochemical processing, particularly under oxidation conditions, both hydrogen and heavier isotopic fractions are released together, indicating that enrichment may potentially arise within the cyclic capture and processing sequence without requiring additional separation energy [12-15].

Unlike conventional heavy hydrogen or heavy water production methods that rely on pressure, thermal input, or chemical equilibrium shifts to induce isotopic separation, the present system suggests a passive accumulation pathway driven by cyclic capture and phase retention. While not a primary objective, this behavior may provide a secondary pathway toward higher-value isotopic products, including deuterium-enriched hydrogen streams relevant to specialized medical or research-grade applications.

The present framework does not eliminate or replace isotope exchange mechanisms such as the Girdler–Sulfide process. Instead, it shifts the location at which these mechanisms are considered. In conventional systems, isotope exchange is enforced through engineered multi-stage cascades operating under controlled temperature and flow conditions. In contrast, the current approach considers whether comparable exchange interactions may already occur within naturally structured environments, where pressure, phase contact, and residence time are inherently present. Under this interpretation, the system does not reproduce the Girdler process; it attempts to access its effects in situ. Thus, no fundamental mechanism is lost. The difference lies in implementation: industrial systems impose the interaction, whereas the present system seeks to access it. The distinction is not in the physics, but in where the physics is realized.

Ballast-controlled vertical motion can be used to lower and raise the subsea unit, enabling operation at depths where hydrogen sulfide concentration is highest. By selectively positioning the system within these high-concentration layers, capture efficiency per cycle is increased. This approach allows depth optimization without continuous propulsion, while towing requirements remain limited to short-range movement and do not constitute a dominant operational

constraint. As a result, overall operational energy demand is reduced.

Sensor-guided operation enables adaptive positioning of the subsea unit to maintain exposure to regions of higher hydrogen sulfide concentration. By integrating underwater robotic or submarine-like control, the system can respond to spatial variations in the resource field and optimize capture conditions in real time. This improves effective hydrogen production by increasing capture efficiency per cycle while avoiding unnecessary motion and associated energy expenditure.

In addition to hydrogen recovery, the process generates sulfur-bearing species whose management has both environmental and economic implications. Rather than allowing uncontrolled release into the water column, the system can be configured to favor controlled conversion and collection pathways, thereby limiting local ecological impact. This is particularly relevant for sensitive marine environments, where elevated sulfur concentrations may affect biological systems. At the same time, recovered sulfur represents a valuable industrial material, enabling an additional value stream without altering the primary operating principle of the system. This dual consideration—environmental compatibility and material recovery—can be addressed through design choices related to residence time, phase separation, and controlled extraction.

Any residual gas phase released during operation is expected to interact rapidly with the surrounding water column during ascent. Due to dissolution and chemical conversion processes, such gas phases are unlikely to persist as discrete bubbles over extended vertical distances and instead transition into dissolved forms within the ambient fluid. In oxygenated layers, these dissolved species are further stabilized through naturally occurring reactions, reducing the likelihood of concentrated gas accumulation. As a result, the system operates within a regime where gas-phase persistence is inherently limited by the physicochemical properties of the environment, favoring dispersion and dilution over localized accumulation.

While lightweight AI-based optimization techniques can be employed for parameter tuning and adaptive operation, this does not constitute the primary decision mechanism of the system. Instead, the operational behavior may be interpreted within a deterministic structural elimination framework. In this perspective, candidate operational states—defined by local chemical conditions, flow characteristics, and cycle configurations—are not continuously optimized but progressively reduced by eliminating infeasible or inefficient configurations. Sensor-based chemical state recognition (e.g., O_2, H_2S levels) provides the filtering criteria, enabling selective operation under favorable conditions. The remaining admissible states define the feasible operational regime without requiring iterative convergence. This perspective does not replace optimization but complements it by offering an alternative interpretation in which decision-making emerges through structured elimination and filtering rather than iterative search, consistent with the Çekirge method [16]. As a result, the system maintains robustness, low computational overhead, and reduced sensitivity to initialization.

Tether-Controlled Movement and System Evolution

The subsea capture unit is connected to the surface vessel via a controllable tether, enabling short-range lateral movement without full system transport. By adjusting tether length and vessel heading, the subsea unit can be moved within a local area to access regions of higher concentration.

This enables a concentration-following mode of operation in which local concentration is monitored, the unit is repositioned over distances on the order of 10 to 100 meters, and capture cycles are preferentially executed in regions of higher yield.

Two operating modes can be defined. In fixed mode, the subsea unit remains stationary and relies on ambient currents for fluid renewal. In adaptive mode, tether adjustment and small vessel movements are used to reposition the unit within the local concentration field.

This approach eliminates the need for large-scale horizontal transport. Instead, the system performs controlled micro-movement within a limited spatial envelope, maintaining access to fresh fluid while minimizing energy expenditure.

Movement over short distances introduces only a

minor additional energy requirement, on the order of 10^6 joules per adjustment, with no continuous towing or bulk transport. As a result, total energy per cycle remains on the order of 10^6 to 10^7 joules.

In conventional subsea systems, fluid is actively pumped or transported, and energy scales with distance and volume. In the proposed configuration, the system is repositioned instead of the fluid, and energy scales with displacement rather than throughput.

Because the resource is spatially distributed, even small lateral displacements can restore effective concentration. Local depletion is avoided, fresh fluid is accessed through movement, and repeated cycles maintain yield.

Initial system configurations relied on fluid transport and pumping. First-order energy and cost evaluation showed these approaches to be economically uncompetitive with conventional hydrogen supply. This led to a reformulation of the system design in which pumping was eliminated entirely.

The final configuration leverages ambient flow and controlled exposure to achieve passive filling. The system is not an optimization of a transport-based design, but a departure from it.
The pumping paradigm was not improved; it was abandoned.

This framework also introduces a conceptual shift in how hydrogen systems are evaluated. Conventional approaches emphasize efficiency in energy conversion, whereas the present approach emphasizes efficiency in resource access. This distinction alters the criteria for system optimization, moving the focus from minimizing energy input to maximizing effective interaction with a distributed resource field.

Conclusion

This study demonstrates that hydrogen recovery without bulk transport is physically and energetically feasible within a dynamic subsea capture framework. By combining passive filling, cycle-based operation, and internally sustained thermochemical processes, the system reduces reliance on external energy and shifts the primary constraint from energy consumption to capture efficiency and operational cost. The results indicate that the viability of the approach is governed by production rate and environmental conditions rather than intrinsic process energy, establishing a new paradigm in which hydrogen recovery is driven by controlled access to distributed resources rather than energy-intensive conversion.

By eliminating external energy input for chemical conversion, the associated cost component is effectively removed from the production pathway. Beyond hydrogen recovery, the observed cumulative capture behavior may also indicate a broader potential for passive enrichment of higher-value components within naturally distributed resource fields.

The proposed system departs fundamentally from conventional hydrogen production paradigms by adopting a harvesting-based operational logic rather than a synthesis-driven approach. In this configuration, hydrogen is not actively produced through energy-intensive chemical transformation, but instead passively recovered from naturally occurring subsea chemical distributions, analogous to a fishing process that has not been previously considered in this context. The primary cost structure is therefore not governed by reaction energy, but by equipment and deployment logistics. Capital expenditure is limited to the subsea platform, capture chambers, and structural components, while operational expenditure resembles that of marine harvesting systems, including vessel operation, towing, and periodic deployment cycles. Energy consumption is minimal and restricted to auxiliary functions such as winch operation, control systems, and limited pumping where required. As a result, the system reframes hydrogen acquisition as a low-energy, location-dependent capture process, in which economic performance is determined by access, state, and repetition, rather than continuous energy input.

Hydrogen acquisition in this system is governed by access and positioning, not by energy input. Discharge is achieved passively through geometric tilting, as established in Section 3.

With passive capture, gravity-assisted cycling, and tilt-induced discharge, the system approaches a fully geometry-governed regime with minimal active energy input. The system does not transport fluid; it

positions itself within it.

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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