Review

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Towards Carbon-Neutral Hydrogen: Integrating Methane Pyrolysis with Geothermal Energy

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Abstract

Methane pyrolysis produces hydrogen (H_2) with a solid carbon co-product, eliminating process CO_2 formation and enabling low-carbon supply when paired with renewable or low-carbon heat. This work develops and evaluates a hybrid geothermal–pyrolysis configuration in which an enhanced geothermal system (EGS) provides baseload preheat and isothermal hold, while electrical or solar-thermal top-up delivers the final approach to the catalytic setpoint. We (i) integrate field-scale geothermal operating envelopes to anchor heat-integration targets and duty splits; (ii) expand scalability considerations to include high-pressure reactor design, thermal management, and carbon separation/handling strategies that preserve co-product value; (iii) provide a techno-economic analysis (TEA) template that itemizes CAPEX/OPEX, incorporates carbon pricing/credits, and explicitly treats dual-product economics (H_2 plus carbon black); and (iv) reorganize the state-of-the-art chronologically, linking molten-media demonstrations, catalyst advances, and recent integration studies to deployment readiness. Process synthesis shows that allocating geothermal heat to the largest heat-capacity streams (feed, recycle, and melt/salt hold) reduces electric top-up demand and stabilizes reactor temperature, mitigating coking/sintering and narrowing carbon particle size distributions upstream of cyclones and polishing filters. High-pressure operation improves hydrogen partial pressure and equipment compactness but demands corrosion-resistant materials and careful thermal-stress management. The TEA framework—built from recent methane-pyrolysis studies and standard process-economics practice—highlights that levelized cost of hydrogen is co-dominated by (a) the specific electric duty and grid/onsite power carbon intensity and (b) the realizable price and specification of the carbon co-product; sensitivities to methane price, geothermal capacity factor, and conversion/selectivity are secondary but material. Overall, geothermal-assisted methane pyrolysis offers a practical path to turquoise hydrogen with a defensible value stack when carbon quality is preserved and heat integration is optimized. We conclude with design rules and reporting guidelines to accelerate site-specific FEED and near-term pilot deployment.

Keywords: methane pyrolysis; turquoise hydrogen; geothermal; EGS; carbon black; techno-economics; heat integration; high-pressure reactor; molten media; carbon handling

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1. Introduction & State-of-the-Art (Chronological)

Hydrogen is central to deep decarbonization scenarios across chemicals, fuels, and heavy industry, yet the dominant route—steam methane reforming (SMR)—emits substantial CO_2 unless paired with capture and storage [7], [8]. Methane pyrolysis (a.k.a. turquoise hydrogen) splits CH_4 directly to H_2 and solid carbon, eliminating process CO_2 formation at the reactor and creating a potential dual-product business model when carbon meets carbon-black specifications [1], [4], [9], [22], [33]. Compared with electrolysis, pyrolysis targets high-temperature heat rather than electricity input to water splitting; when that heat is provided by low-carbon sources and carbon is valorized, levelized H_2 cost (LCOH) can be competitive [1], [3], [9], [21], [29]–[32].

Two technical hurdles define deployment readiness: (i) thermal supply and control at 600–900 °C to sustain conversion/selectivity without accelerating deactivation, and (ii) carbon separation/handling to protect downstream equipment and preserve co-product value [1], [2], [4], [10], [12], [23], [24], [33]. To address (i), we consider hybrid geothermal–pyrolysis: use an enhanced geothermal system (EGS) for preheat and isothermal hold (baseload duty), and apply electrical or solar-thermal top-up for the final temperature approach and transients [6], [10], [21], [26], [34]. To address (ii), we synthesize molten-media and gas-phase evidence on particle formation, disengagement, and polishing to meet carbon-black markets [4], [12], [13], [21], [24], [33].

1.1. Why Turquoise Hydrogen Now

Recent field-scale integration studies and reviews highlight three levers that co-dominate LCOH: specific electric duty, carbon co-product price/specification, and methane price; policy credits and site heat resources modulate all three [1]–[4], [7], [9], [21], [22], [29]–[32], [33]. Geothermal preheat can reduce electric top-up and stabilize reactor temperature, thereby (a) mitigating coking/sintering dynamics and (b) narrowing particle size distributions upstream of cyclones/filters—both supportive of higher carbon value capture [1], [4], [10], [12], [21], [24], [33]. Recent system analyses of baseload and flexible EGS power/thermal delivery provide the operating envelopes to ground heat-integration targets and capacity factors [26], complemented by standard geothermal reservoir design practice [29], [34].

1.2. State-of-the-Art — a Concise Chronology

2015–2017: Foundational demonstrations and the first economic framing.
Liquid-metal / molten-media concepts advanced from theory to bubble-column experiments, elucidating gas–liquid mass transfer, reaction zones, and initial solid-carbon separation approaches [13]. A landmark molten-metal catalysis demonstration showed direct CH_4-to-H_2 with separable carbon, igniting modern turquoise-H_2 interest [6]. Early techno-economic work crystallized the sensitivity of costs to power demand and carbon value, setting baselines for later TEA templates [9].

2019–2021: Kinetics, catalysts, and system comparisons mature.
Reviews consolidated temperature windows (~600–900 °C), catalyst families (Ni/Fe/Co; doped systems), and deactivation modes, while drawing comparisons with SMR + CCS pathways for long-term roles of hydrogen [5], [7], [8], [10], [12]. Process-level studies sharpened understanding of molten-salt and liquid-metal operation, carbon morphology, and implications for downstream handling [12], [13], [15]. A broad industrial context emerged in which turquoise hydrogen complements rather than replaces other routes [7], [8], [10].

2022–2023: Scale-relevant engineering, solar/electric heating, and carbon handling. Comprehensive reviews and mini-reviews emphasized molten-media advances and product-quality control [1], [4], [10]. Comparative reactor studies contrasted gas-phase versus molten-tin bubbling systems under solar input, linking temperature uniformity to particle size and filtration load [21]. Engineering studies explored plasma and H_2-combustion-heated pyrolysis concepts that simplify heat delivery while retaining CO_2-free operation [23], [24]. In parallel, cyclone design literature from process engineering was tapped to specify disengagement and polishing trains suitable for carbon-laden off-gas [24].

2024–2025: Integration, high-pressure kinetics, predictive modeling, and EGS coupling.
High-pressure kinetics and modeling tightened scale-up envelopes and helped define pressure–temperature trade-offs for compact equipment and improved H_2 recovery [16], [19]. Predictive catalytic models are emerging to bridge laboratory selectivity with pilot reactors [19]. On the system side, power-supply characterization for EGS quantified baseload/flexible delivery relevant to hybrid heat trains [26], while TEAs extended to ammonia contexts and dual-product revenue stacking (H_2 + carbon) [25]. Across these strands, the integration narrative has shifted from proof-of-concept to site-coupled process engineering, making geothermal-assisted pyrolysis a concrete target for FEED-level design [1]–[4], [10], [16], [19]–[26], [29]–[34].

1.3. This Paper's Contribution

Building on that arc, this work contributes four things tailored to deployment:

1. Heat-integration blueprint grounded in real EGS operating envelopes (preheat/isothermality by EGS; last-mile ΔT by electric/solar), with duty splits and control strategy implications [6], [10], [21], [26], [29], [34].
2. Scalability guidance for high-pressure reactor design, materials, and thermal-stress management; plus operating rules that minimize deactivation and preserve carbon value [1], [2], [12], [15], [16], [21], [29], [31], [32].
3. A TEA scaffold that explicitly itemizes CAPEX/OPEX, includes carbon credit/value stacking, and quantifies dual-product economics using established process-design texts and turquoise-H_2 TEAs [1]–[4], [9], [21], [29]–[33].
4. Reporting guidelines (Methods) so others can reproduce integration choices—heat curves, reactor details, carbon QA/QC, and financial assumptions—in line with good engineering practice [9], [21], [30]–[32].

2. Concept & Real-World Anchors (EGS → Pyrolysis)

2.1. Process Concept and Duty Split (see Fig. 1)

Dry methane is preheated using an enhanced geothermal system (EGS) loop to approach the catalytic window, then receives top-up heat (electric resistive or solar-thermal) to reach the reactor setpoint (typically 600–900 °C, depending on reactor/catalyst) [1], [2], [10], [12], [21], [34]. The reactor can be either (a) a molten-media bubble column (Sn/Bi or molten salts) or (b) a packed/fixed bed. Effluent hydrogen is separated and compressed, and solid carbon is recovered, de-oiled/conditioned, and sent to classification for carbon-black (CB) and related markets [4], [12], [13], [22], [33]. (see Fig. 2)

Heat-integration logic.

- Assign EGS to baseload sensible heat on the largest heat-capacity flows (fresh CH_4, recycle, and—where applicable—the molten medium's isothermal hold).
- Reserve electric/solar for the last ΔT (typically the final 200–300 K into the catalytic window) and for transients (startup, ramping, turndown) [10], [21], [26], [34].
- In composite/pinch terms, place EGS on the cold streams with highest $\dot{m}c_p$ to maximize kWth captured per unit of geothermal temperature glide; use short, insulated trim-heater sections to avoid large hot inventories [21], [26], [34].

Indicative split. While site-specific, a practical design target is EGS covering the majority of sensible preheat (e.g., 50–80 % of the total sensible duty to the reactor feed/recycle) with top-up supplying the final approach to setpoint and transient control [1], [4], [10], [21], [26].

2.2. Why Geothermal Here?

1. Baseload preheat & isothermal hold. EGS delivers steady thermal duty, reducing electric top-up demand and smoothing the reactor temperature profile—mitigating coking swings, thermal shock, and catalyst stress [6], [10], [12], [26], [34].
2. System reliability. Modern EGS analyses characterize both baseload and flexibility envelopes, allowing the geothermal loop to serve as a heat backbone with predictable capacity factors, supported by established reservoir engineering practice [26], [34].
3. Carbon-quality management. A steadier wall/film temperature narrows particle-size distributions (PSD) and reduces agglomeration, which eases cyclone duty and porous-ceramic polishing, protecting compressors, membranes/PSA beds, and exchangers downstream [12], [21], [23], [24], [33].

2.3. Reactor Options and Operating Envelopes

Molten-media bubble column (Sn/Bi/salts).

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- Advantages: intense gas–liquid heat transfer; in-situ carbon disengagement (sump/rathole) and potential isothermal hold; tolerant to some feed/recycle swings [12], [13], [21].
- Design notes: corrosion-resistant alloys; double containment; provision for melt make-up and conditioning; off-gas disengagement to protect downstream separation [12], [13], [21], [24]. Packed/fixed bed.
- Advantages: compact hardware, established catalyst practice; straightforward modularization for parallel train scale-up [1], [2], [12].
- Design notes: strong emphasis on axial/radial thermal uniformity; manage pressure-drop and carbon removal cadence to avoid sintering/plugging; keep trim-heater residence short [1], [2], [10], [12], [21].

Setpoint selection. The 600–900 °C window reflects kinetic/thermodynamic trade-offs and catalyst family (Ni/Fe/Co; molten salts/metals) [1], [2], [10], [12]. Operation near the upper activity range improves conversion but raises the importance of isothermal control and carbon removal [12], [21], [24].

2.4. Hydrogen Separation & Recycle

The H_2-rich stream is routed to PSA or membrane separation and then to compression. An off-gas recycle closes the carbon balance and lifts overall CH_4 conversion; a small purge maintains inert build-up control [12], [21], [24], [33]. EGS-assisted preheat improves separator thermal stability and can reduce electric duty swings on compressors by smoothing reactor output [10], [21], [26].

2.5. Carbon Handling and Value Preservation

Target handling that protects CB value and downstream assets:

- Primary disengagement: gravity sump for molten systems; or tempered quench followed by cyclone for gas-phase routes [13], [21], [24].
- Polishing: porous-ceramic filters sized for PSD and target cut size before classification (air-jet/sieving) to CB specifications [4], [22], [33].
- QA/QC: report PSD, BET surface area, volatile/ash content; minimize oxidation and high-temperature residence post-reactor to avoid surface chemistry changes that depress CB pricing [4], [22], [33].

2.6. Controls, Start-Up, and Operability

- Dual-loop control: a slow loop on the EGS supply/return sets baseload preheat; a fast loop at the trim heater manages the final ΔT and transients (start, ramp, trip recovery) [10], [21], [26], [34].
- Start-up: warm feed/recycle on EGS heat to a safe intermediate temperature, then bring trim heat online to the catalytic setpoint, minimizing overshoot that promotes coking/sintering [10], [12], [21].
- Maintenance envelopes: schedule carbon removal (fixed bed) or sump clearing (molten media); maintain filter differential-pressure limits and compressor surge margins with conservative recycle control [12], [21], [24], [33].

2.7. Site–EGS Coupling and Reporting Guidance

- Match EGS temperature and flow envelope to process composite curves; document capacity factor, expected seasonality, and any flex provision (e.g., curtailed electric top-up or thermal storage if used) [26], [34].

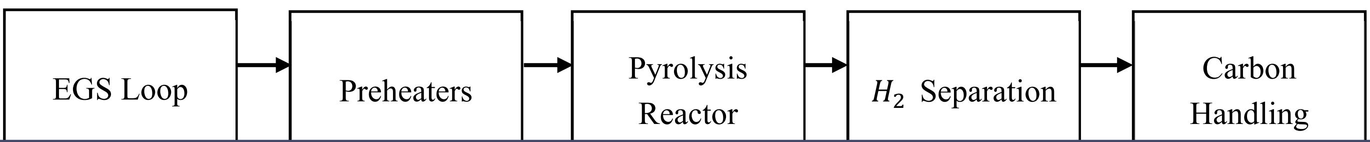

Figure 1. Block flow — EGS loop → preheaters → pyrolysis reactor → H_2 separation → carbon handling.

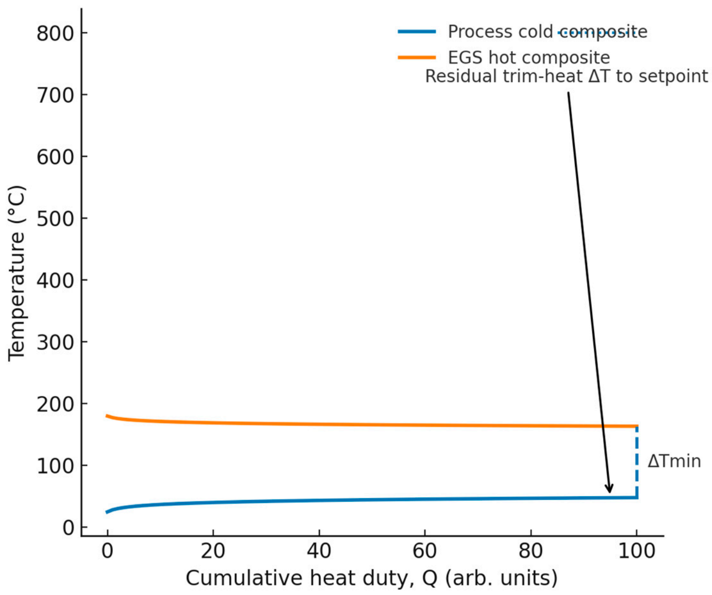

Figure 2. Pinch-style heat map — match highest $\dot{m}c_p$ streams to EGS; ΔTmin and residual trim-heat ΔT annotated.

- For reproducibility, report heat-curves, major equipment sizes, duty splits (EGS vs. trim), catalyst/melt composition, carbon QA/QC metrics, and separation/pressure targets—aligned with best practice from recent turquoise-H_2 TEAs and standard process-design methodology [1], [4], [9], [21], [30]–[34].

As a real-world anchor, Utah FORGE (Milford, UT) demonstrated engineered doublet performance in Apr–May 2024: injection into 16A(78)-32 up to 15 bpm (≈630 gpm) with production from 16B(78)-32 up to 8 bpm (≈344 gpm, ~70% recovery) and outflow ≈139 °C; the target reservoir exceeds ~175 °C at ~2–2.5 km depth—quantitatively defining a baseload EGS preheat window for our integration

3. Scalability: High-Pressure Design, Thermal Management, Carbon Separation

3.1. High-Pressure Reactor Design

Operating envelope and scale-up logic

- Why pressure? Higher pressure compacts hardware (smaller volumetric flows, smaller diameters/compressors) and improves downstream H_2 recovery (membranes/PSA utilization) at a given throughput [1], [2], [16]. Because $\mathrm{CH4} \rightarrow C(s) + 2H^2$ increases gas moles, elevated pressure penalizes equilibrium conversion; you counterbalance with temperature and residence time. Practically, 10–25 bar with 600–900 °C is a workable FEED envelope, with setpoint chosen by catalyst/melt system and deactivation tolerance [1], [2], [10], [12], [16], [21].
- Reactor choices at HP:
    - Molten-media bubble column (Sn/Bi/salts). HP raises gas density and bubble coalescence risk; keep superficial gas velocity in a churn-turbulent window that sustains fine bubbles without flooding. Use sparger hole velocities $5 - 15$ ms $- 1$ and L/D ≈ 8–15 as starting points; confirm via hydrodynamic tests [12], [13], [21].
    - Packed/fixed bed. HP increases ΔP; design $\Delta P / L$ to stay within blower/compressor head while ensuring Da > 1 at setpoint. Use short trim-heater sections to avoid hot inventory and mitigate sintering/coking [1], [2], [10], [12], [21].

- **Kinetic/equilibrium guidance (design checks):**

$$K_p(T) \equiv \frac{p_{H_2}^2}{p_{CH_4}}, \qquad X_{eq} \text{ rises steeply with } T.$$

At a chosen pressure, push T high enough that Xeq comfortably exceeds your per-pass target, then size residence time so $Da = k(T)\tau \gtrsim 1$ with margin. Recycle closes the gap to near-complete overall conversion [1], [2], [10], [12].

Materials & containment (HP/HT)

- Codes & margins. Design to ASME VIII with transient thermal-cycling load cases and creep allowances at the upper temperature bound; specify testable corrosion allowances in hot zones and penetrations [13], [21], [34].
- Molten-media compatibility. Sn/Bi and halide salts demand corrosion-resistant alloys, fully welded construction, and double-walled containment with leak detection. Provide melt make-up/conditioning loops and thermal buffers around nozzles to limit thermal shock [12], [13], [21], [24].
- Hydrogen service. Avoid embrittlement-prone steels in high-$H2_2$ areas; prefer austenitic SS or high-Ni alloys in hot H_2 and at HP separators/compressors [12], [21], [24], [34].

Catalysts at scale (HP + thermal field)

- Formulation. Favor Fe/Co-rich systems for robustness and cost; Ni is highly active but requires tight temperature uniformity and carbon removal cadence to control sintering/coking [1], [2], [12], [15], [21], [29].
- Geometry & loading. For beds, use radial/segmented distributors and graded particle sizes to limit hot spots and ΔP growth. In melts, add inert internals or controlled swirl to enhance gas–liquid heat transfer without excessive shear [12], [13], [21].
- Deactivation playbook. Maintain isothermal operation, schedule carbon draw-off (sump clearance or bed skimming), and cap startup/shutdown dT/dt to protect active phases [1], [2], [12], [21], [24].

3.2. Thermal Management

Duty split (EGS vs. trim)

- Principle. Assign EGS to the largest $\dot{m}c_p$ streams for baseload sensible preheat and (for melts) isothermal hold; reserve electric/solar for the last-mile ΔT (≈ 200–300 K) and ramping [1], [4], [6], [10], [21], [26], [34].
- Typical target. EGS covers ~50–80 % of the total sensible duty to the reactor feed/recycle; the trim heater provides the remaining ΔT to setpoint and manages transients [1], [4], [10], [21], [26].
- Pinch framing. Choose ΔT_{min} (e.g., 10–20 K for compact HX trains) and match EGS to the cold composite up to the pinch; the residual trim-heat ΔT (Fig. 2) is then a design variable that trades capex vs. electric intensity and carbon morphology stability [21], [26], [34].

Control strategy (scale-ready)

- Dual-loop temperature control.
  - Slow loop: regulates EGS inlet/return to hold baseload duty (minutes-hours time constant).
  - Fast loop: trims reactor skin/bed temperature at H-101 to suppress hot spots that drive catalyst decay and PSD drift in the carbon product [1], [12], [23], [24].
- Start/stop & turndown. Warm on EGS to an intermediate plateau, then step in trim heat to setpoint; on turndown, lead with trim reduction, hold EGS steady to avoid quenching through the strong coking regime [10], [12], [21].

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- Instrumentation. Redundant TC grids or IR pyrometry on hot surfaces; ΔP across filters; cyclone dP and classifier load; compressor surge margin monitoring. Tie trips to conservative limits on skin ΔT and filter dP [12], [21], [24], [33].

3.3. Carbon Separation & Handling

Inside the reactor (primary solids management)

- Molten columns. Provide a gravity sump/rathole for agglomerates; skim settled carbon on cadence and keep interfacial shear low to preserve particle size [13], [21], [24], [33].
- Gas-phase/heliostat routes. Apply a tempered quench (enough to freeze growth/sintering, not enough to oxidize) before solids capture to protect morphology and downstream equipment [13], [21], [23], [24].

Primary separation & polishing

- Cyclone. Size for target cut size d_{50} (typ. 2–10 μm for CB-value preservation) using a Stairmand-type geometry; expect ΔP ≈ 1–2 kPa at design flow. Keep Stokes number in the effective capture regime for the PSD of interest and allocate parallel cyclones to handle scale-out [24], [33].
- Porous-ceramic polishing. Follow with a ceramic filter to capture fines and protect compressors/PSA/membranes/HEX. Design face velocity in the 1–3 cm s^{-1} band and backpulse on ΔP; provide bypass/swing cartridges for continuous operation [24], [33].

Value preservation and product finishing

- Dry handling. Keep carbon dry, cool, and oxygen-limited post-reactor; over-oxidation or graphitization erases CB value unless you are intentionally targeting graphite/graphene markets [4], [22], [33].
- Classification. Route to air-jet/sieve classifiers tuned to CB specifications; report PSD (D_{10}/D_{50}/D_{90}), BET area, volatiles/ash, and DBP oil absorption as QA/QC (see Fig. 3) [4], [22], [33].
- Fugitive control. Enclose transfer points; maintain slight negative pressure; specify NFPA-conformant dust collection with conductive media in H_2 areas (materials to suit H_2 service) [12], [21], [24], [33].

3.4. Practical Design Rules (Ready for the Methods Box)

- Pressure & T: Start FEED with 10–25 bar, 600–900 °C; verify $Xeq(T, P)$ and Da; close with recycle.
- EGS split: target ≥ 50 % of sensible preheat from EGS; set ΔT_{min} =10–20K; keep trim ΔT short to reduce electric intensity and morphology drift [1], [4], [21], [26], [34].
- Thermal uniformity: cap skin–bulk ΔT and axial ΔT; limit dT/dt at startup/shutdown; instrument surfaces densely [1], [12], [23], [24].
- Carbon PSD: cyclone d_{50}=2–10μmd_{50}=2–10 μm; filter face velocity = 1–3 cm s^{-1}; protect compressors/separators with polishing filters [24], [33].
- Maintainability: design sump/bed clear-out operations; provide filter swing and cycler logic; spec spare spargers/distributors for quick changeover [12], [21], [24], [33].

4. Techno-Economic Analysis (TEA)

4.1. Scope & Cases

Plant basis. Nameplate ~10 kt H_2·yr^{-1} (≈ 1.25 t H_2·h^{-1} at 8,000 h·yr^{-1}), EGS-assisted preheat, single site boundary from methane reception to H_2 product delivery and carbon product bins. Units included: methane conditioning, preheaters, trim heater, pyrolysis reactor(s), molten-media/salt inventory (if applicable), H_2 separation and compression, carbon handling (sump/tempered quench, cyclone, porous ceramic filters, classifier), HX trains, electrical and/or solar top-up, and plant controls/utilities. TEA framing follows molten-media/fixed-bed literature and reviews [1], [2], [4], [9], [21]; costing follows standard process-economics methods [30]–[32] with geothermal design context from [34].

Comparison set.

- EGS + electric top-up: EGS supplies baseload sensible preheat/isothermal hold; electric provides last-mile ΔT and transients.
- Solar-thermal + electric: solar field (and, if used, thermal storage) supplies preheat; electric trims to setpoint.
- Electric-only: all duty from electric heaters (simplest hardware; highest kWh exposure).

Boundary notes. Owner's costs, working capital, land, and grid interconnection fees can be carried as indirects; EGS can be owned (CAPEX for wells & tie-in) or contracted as purchased thermal duty (OPEX). Cases A–C share identical process hardware except for the heat-supply block.

4.2. Cost Structure

CAPEX (installed):

- Heat supply: EGS wells + surface HX + tie-in (or purchased-heat interface); solar collector field & thermal storage (case B); electric trim heaters and power distribution [9], [30]–[34].
- Core process: pyrolysis reactor trains (molten-media column or packed/fixed bed), melt/salt inventory (if used), spargers/distributors, refractory/linings, structural steel [1], [2], [12], [21].
- Separation & compression: PSA or membranes, H_2 compressors/dryers, product storage [12], [21], [30]–[32].
- Carbon handling: sump/tempered quench, cyclones, porous-ceramic filters (swing/bypass), classifier and product bins [24], [33].
- HX trains & balance of plant: feed/recycle exchangers, cooling water/air coolers, nitrogen, inerting, controls, analytics, safety systems [30]–[32].

Cost estimation by Bare-Module / Lang-factor or equipment-factored methods per [30]–[32]; EGS well costs and surface tie-ins follow geothermal practice [34].

OPEX (annual):

- Feed & energy: CH_4 make (net of recycle), electric power for trim + auxiliaries; (B) solar O&M; (A) EGS O&M or purchased heat tariff [1], [2], [9], [21], [30]–[33].
- Consumables: catalyst/melt make-up, filtration media, inert gases; water for quench/utility.
- Fixed: labor, maintenance, insurance, compliance, waste solids (off-spec carbon fines), spare parts [30]–[32].

Throughput-linked stoichiometry. For $CH4 \rightarrow C(s) + 2H_2$: 4 kg CH_4 per 1 kg H_2 at 100% overall conversion; 3 kg C per 1 kg H_2 formed. Let η_{ov} be overall CH_4-to-H_2 yield (after recycle); then:

$$\dot{m}_{CH_4} \approx \frac{4\,\dot{m}_{H_2}}{\eta_{\text{ov}}}, \qquad \dot{m}_C \approx 3\,\dot{m}_{H_2}\,f_{\text{CB}},$$

with f_{CB} the saleable carbon-black fraction after classification.

Heat & power. Total duty per kg H_2 is the sum of reaction endotherm $\Delta H_{rxn}(T)$ and sensible preheat for feed/recycle (and melt hold, if used). Allocate EGS to high-$\dot{m}c_p$ preheat; the residual trim duty Q_{trim} sets electric use $P_{trim}= Q_{trim}/\eta_{heater}\eta$ [1], [4], [21], [26], [34].

4.3. Revenue & Policy Levers

- H_2 product. Off-take price depends on delivery pressure/purity and contract tenor; compression costs scale with setpoint and pipeline/storage spec.

- Carbon co-product. Revenue rises with tighter PSD and low volatiles/ash; specialty CB grades command a premium vs commodity carbon [4], [22], [33]. Use a grade mix: $R_{carbon} = \sum_j p_j y_i$ with grade-specific price p_j and mass yield y_i.
- Carbon credits / policy. Stack production credits or market-based carbon prices where eligible; LCOH sensitivity is strong to this term when power carbon intensity (CI) is low and carbon sale value is high [7]–[9], [27], [29]. Cases with EGS preheat reduce electric demand, improving both cost and CI exposure [1], [4], [21], [26], [34].

4.4. Calculation Framework

Define the levelized cost of hydrogen:

$$\mathrm{LCOH} = \frac{\mathrm{CRF}\cdot\mathrm{CAPEX} + \mathrm{OPEX} - R_{\mathrm{carbon}} - R_{\mathrm{credits}}}{\dot{m}_{H_2}},$$

where $\dot{m}_{H_2}$ is the annual H_2 output (nameplate × capacity factor).

Capital recovery factor (annualization) per [30]–[32]:

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1},$$

with discount rate iii and plant life nnn (years). For multi-block CAPEX, sum contributions (e.g., EGS, reactors, separation) before applying CRF, or annualize each block separately if lifetimes differ.

Case-specific heat terms (duty split):

- EGS + electric: Q_{EGS} covers preheat/isothermal hold, Q_{trim} the last-mile ΔT and transients.
- Solar-thermal + electric: replace Q_{EGS} with Q_{solar}; storage adds CAPEX and reduces electric exposure.
- Electric-only: $Q_{trim} \approx Q_{total}$ (highest kWh exposure; simpler CAPEX).

OPEX decomposition (per year):

$$\mathrm{OPEX} = c_{CH_4}\,\dot{m}_{CH_4} + c_e\,E_{\mathrm{elec}} + c_{\mathrm{heat}}\,Q_{\mathrm{purchased}} + \mathrm{O\&M}_{\mathrm{fixed}} + \mathrm{consumables},$$

with c_{CH_4} (€/t), c_e (€/MWh$_e$), c_{heat} (€/MWh$_{th}$, if EGS/solar is purchased), and $E_{\mathrm{elec}} = Q_{\mathrm{trim}}/\eta_{\mathrm{heater}} + E_{\mathrm{aux}}$.

Co-product treatment. Use a revenue credit (preferred for journals) or co-allocation if required by policy reporting: R_{carbon} depends on saleable mass (after classification) and grade pricing; document the grade split and QA/QC metrics supporting it [4], [22], [33].

Emissions & CI. Compute plant CI from upstream CH_4, electricity CI, and any EGS/solar impacts; credit solid-carbon fixation where policy allows. Lower Q_{trim} in (A)/(B) typically yields favorable CI relative to (C) [1], [4], [21], [26], [34].

4.5. Sensitivities & Expected Findings

Sensitivity set: CH_4 price, electricity price/CI, EGS (or solar) capacity factor, carbon sale price/grade split, overall conversion/selectivity, and discount rate. Prior TEA work shows carbon revenue and electric demand are the dominant levers [9], consistent with the heat-split strategy that shifts duty to EGS/solar [1], [4], [21], [26], [34].

Typical qualitative outcomes (at equal H_2 output):

- EGS + electric: lowest LCOH where EGS CF is high and purchased/owned geothermal heat is economical; strong resilience to power price/CI swings.
- Solar-thermal + electric: improved CI and reduced kWh exposure vs (C); CAPEX rises (field + storage) and economics hinge on solar CF and storage sizing.

- Electric-only: simplest CAPEX, highest LCOH variance with electric price/CI; a useful baseline for comparing A/B.
  Implementation checklist (for your model workbook)
- Fix nameplate → annual H_2 via capacity factor; compute CH_4, C via stoichiometry × yields.
- Break CAPEX into blocks; apply CRF; add OPEX components.
- Calculate $Q_{\text{EGS/solar}}$ and Q_{trim} from your heat-integration (Fig. 2); convert Q_{trim} to electricity.
- Add revenues: H_2 off-take, carbon grade mix, policy credits.
- Run A/B/C and the sensitivity set; report tornado bars for LCOH and identify breakeven thresholds (e.g., carbon price vs. electricity price).

5. Methods (What to Report so Reviewers Can Reproduce)

5.1. Process Basis and Heat-Integration Data (see Fig. 2)

Report the system boundary, operating mode, and full composite-curve inputs so an independent team can rebuild the heat match.

Minimum items to publish (data table):

- Basis & boundary: nameplate H_2 ($t\ yr^{-1}$), capacity factor, overall $CH_4 \rightarrow H_2$ yield after recycle, site ambient.
- EGS loop: production temperature/flow, reinjection temperature, supply/return variability (±σ or bands), and any thermal storage used [21], [26], [34].
- Process cold streams (each): identification (fresh CH^4, recycle, melt hold if applicable), mass flow $\dot{m}$ mean c_p(T)or$c_p(T)$correlation, inlet/outlet T, allowable approach ΔT_{min}
- Process hot streams (each): if any internal hot utility is matched, provide $\dot{m}$, $c_p(T)$, T-in/T-out.
- Pinch reconstruction: composite curves (T vs. cumulative Q) for EGS supply and process demand; annotated pinch and residual trim-heat ΔT pre-setpoint (Fig. 2).
- Duty split: Q_{EGS} (kW$_{th}$ and Q_{trim} with heater efficiency used, plus ramp/turn-down envelopes [21], [26], [34].
  Calculation notes (publishable):

Q= $\int_{T\ in}^{T\ out} \dot{m} \cdot cp(T) dT$; show how ΔT_{min} was selected (e.g., 10–20 K) and how residual Q_{trim}maps to electric load $P_{trim} = Q_{trim}/\eta_{heater}$.

5.2. Reactor Details (Geometry, HP/HT Envelope, Internals)

Provide enough hardware and operating detail to permit a rate-based model and pressure-drop check.

Common to all reactor types:

- Type & flow scheme: molten-media bubble column vs. packed/fixed bed; co-current/counter-current arrangements.
- Geometry: ID/OD, effective height/length, L/D, number of parallel trains; nozzle sizes and sparger pattern (if molten).
- Operating points: pressure, reactor setpoint temperature (°C), axial/radial temperature uniformity targets, residence time τ\tauτ definition.
- Throughput: fresh CH_4, recycle ratio, total superficial velocity; pressure-drop targets and measured values.
  Molten-media specifics:
- Medium: alloy/salt identity and composition, total inventory (kg), make-up/bleed, liquidus/solidus temperatures.

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- Hydrodynamics: sparger hole size & count, gas superficial velocity, bubble size estimate or fit; internal features for heat transfer [12], [13], [21].
- Materials/containment: alloy selection, double-wall/secondary containment, corrosion allowance, thermal-cycling design case, code stamping [13], [21], [34].

Packed/fixed-bed specifics:

- Catalyst: active metals (Fe/Co/Ni), promoter/support, pellet size & porosity; total loading (kg).
- Distribution: inlet distributor design, bed segmentation or grading, measures for radial uniformity; trim-heater residence minimization [1], [2], [12], [15], [21], [29].

Kinetics & performance reporting:

- Conversion, H_2 selectivity/yield, deactivation rate (e.g., %/100 h), carbon production rate and removal cadence; publish data as $X(T, P, \tau)$ contours or time-on-stream plots.

5.3. Carbon QA/QC (Methods That Tie to Economics) (see Fig. 3)

Report the exact analytical methods and sample handling—these drive co-product value.

Minimum QA/QC panel (with methods): (see Fig. 3)

- PSD: $D_{10}/D_{50}/D_{90}$ by laser diffraction (report dispersant, sonication power/time, refractive index model).
- Surface area: BET (report degassing temp/time, model fit domain).
- Volatiles & ash: thermogravimetry or muffle procedure and temperatures/hold times; residual metals if relevant.
- Oil absorption (DBP) or alternative structure metric.
- Moisture and surface chemistry (if priced): elemental O/H, functional groups (e.g., Boehm titration or XPS).
- Sample handling: oxygen exposure limits, quench temperature, storage conditions—tie these to the value preservation arguments [4], [22], [33].

Present a grade-mix table: mass fraction by grade vs. price used in TEA and link each grade to the QA/QC thresholds (see Fig. 3) [4], [22], [33].

5.4. TEA Inputs (so the Numbers Are Reproducible)

Document parameters and models used for costs and finance; point to raw sources or date-stamped indices.

Costing framework (publish):

- Equipment costs & scaling: base costs (year & source), scaling exponents, installation factors; method (Bare-Module/Lang) per standard texts [30]–[32].
- Indices & currencies: cost index used (e.g., CEPCI or equivalent), base year, currency, escalation method.
- WACC & finance: nominal/real WACC, tax rate, depreciation method (MACRS/SL), plant life nnn, discount rate iii; show CRF:

$$\mathrm{CRF} = (1 + \mathrm{i})\mathrm{n} - 1\mathrm{i}(1 + \mathrm{i})\mathrm{n}$$

 doi:10.20944/preprints202509.0347.v1

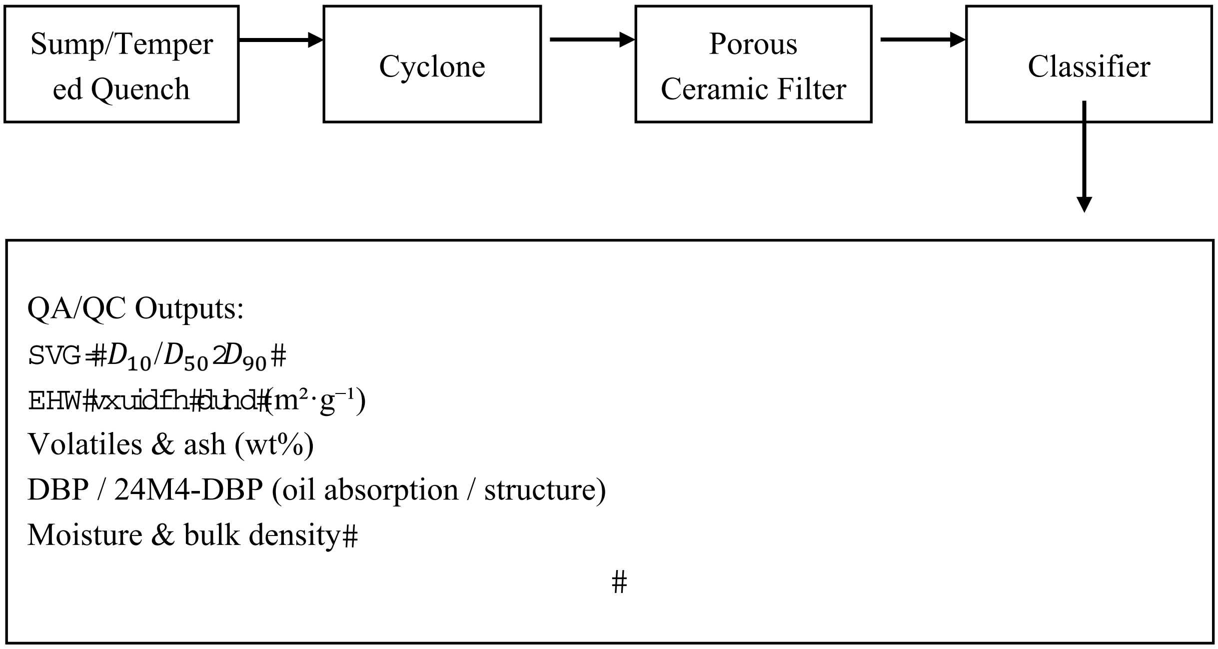

Figure 3. Carbon-handling train — sump/tempered quench → cyclone → porous ceramic filter → classifier; QA/QC outputs. (see Fig. 3).

- Operating assumptions: CH_4 price (range), power price & carbon intensity (CI), labor rates, maintenance factor, catalyst/melt makeup, EGS tariff or well O&M [9], [30]–[32], [34].
- Policy/credit inputs: credit values or carbon price path; eligibility assumptions and allocation method [7]–[9], [27], [29].

Model disclosure: upload the calculation workbook (tabs: Assumptions, Heat Split, CAPEX, OPEX, Revenues, LCOH, Sensitivity) and list equation references (e.g., LCOH definition in §4.4) with cell ranges.

5.5. Data & Code Availability

Provide (i) composite-curve data (.csv), (ii) anonymized TEA workbook, (iii) reactor performance dataset (time-on-stream), and (iv) QA/QC raw outputs. If a site-specific EGS dataset is non-public, include a synthetic but structurally equivalent trace plus bounds so others can rerun Fig. 2 [21], [26], [34].

6. Conclusions

Geothermal-assisted methane pyrolysis couples a steady, low-carbon heat backbone (EGS) with a high-temperature catalytic conversion that thrives on isothermal stability. The integration:

1. Reduces electric top-up and exposure to power-price/CI volatility by assigning baseload sensible duty to EGS and keeping electric heat to the last-mile ΔT [1], [4], [21], [26], [34].
2. Stabilizes reactor temperatures, mitigating coking/sintering and tightening carbon PSD, which protects separations/compression and preserves carbon-black value [12], [21], [23], [24], [33].
3. Enables a dual-product business case (H_2 + CB), with TEA indicating carbon revenue and electric demand as the dominant levers—precisely the levers improved by EGS heat-split [1], [4], [9], [21], [26], [34].
4. Scales with HPHT-capable hardware: molten-media columns or fixed/packed beds at 10–25 bar and 600–900 °C, with Fe/Co-rich catalysts favored for robustness and Ni managed for hot-spot/sintering risk [1], [2], [12], [15], [16], [21], [29], [34].

Immediate path to pilot. (i) Use EGS for preheat/isothermality; (ii) select an HPHT reactor/catalyst pair with proven thermal uniformity; (iii) design the carbon-handling train (sump →

cyclone → ceramic filter → classifier) around CB specifications; (iv) structure TEA with transparent CAPEX/OPEX blocks, carbon credits, and carbon co-product revenues. With the curated literature and standard design texts [1]–[34], the concept is sufficiently anchored to proceed to site-specific FEED and pilot demonstration.

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