Supplementary Material (S1)
Methodological Positioning and Extended Notes

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S1. Methodological Advances Beyond Existing Frameworks

Traditional hydrogen TEA frameworks prioritize equipment cost-down and efficiency gains. This supplement details methodological contributions beyond existing frameworks under 45V compliance through four contributions [3, 33]. Citation numbering follows the main-manuscript reference list:

S1.1 Dual Fragility Metrics: Capital Intensity (κ) and Credit Dependency (Ψ_{credit})

This supplement formalizes **credit-dependency ratio** $\Psi_{\text{credit}} = C_{\text{credit}}/\text{LCOH}$ as complementary to capital intensity κ, demonstrating that high credit dependency ($\Psi_{\text{credit}} = 0.59$ at baseline) creates policy-induced fragility orthogonal to capital structure. Existing literature identifies electricity price sensitivity and credit magnitude importance but does not frame credit reliance as a distinct, quantifiable risk mode with its own fragility mechanisms [3, 1]:

- **Binary eligibility cliffs:** Credit tiers (Tier 1: \$3/kg, Tier 2: \$1/kg, Tier 3: \$0.60/kg) create discontinuous \$2/kg economic jumps from small emissions exceedances, unrelated to technology or market fundamentals.
- **Temporal expiration risk:** 10-year credit window generates post-subsidy cost cliffs (\$2–3/kg LCOH increase in year 11) that do not exist in capital-intensive-but-unsubsidized technologies like solar PV or wind, which face smooth cost decay rather than step-function increases.
- **Compounding utilization effects:** High Ψ_{credit} amplifies capacity factor fragility because credit per kg is fixed while capital cost per kg scales hyperbolically. A project at $\Psi_{\text{credit}} = 0.59$ and $\phi = 0.50$ experiences $1.8\times$ greater absolute cost escalation from 10-point CF reduction than an unsubsidized project ($\Psi_{\text{credit}} = 0$) with identical κ.

The κ-Ψ_{credit} framework generalizes beyond hydrogen to any subsidy-dependent clean energy technology: sustainable aviation fuels (45Z credit: \$1.25–1.75/gal, $\Psi_{\text{credit}} \approx 0.50$), power-to-liquids (combined ITC/PTC $\Psi_{\text{credit}} \approx 0.40$), and carbon capture (45Q credit: \$85–180/ton, often exceeding facility operating costs). High Ψ_{credit} (> 0.50) systems require distinct risk management strategies (credit insurance, offtake contracts with floor pricing, hybrid revenue models) compared to capital-intensive systems ($\kappa > 0.70$) which prioritize equipment cost reduction and utilization optimization.

S1.2 Feasibility Region Contraction: Quantifying 45V Compliance Penalty

Temporal-matching impact is quantified with the geometric viable-fraction metric, computed over each strategy's achievable operating domain [5, 6]. Transition-window Annual matching (2025–2029) yields $\Gamma_{\text{geom,annual}} = 0.775$ for $\phi \in [0.70, 0.95]$ and $p_e \in [\$20, \$80]$/MWh. Long-run Hourly matching (2030 onward) yields $\Gamma_{\text{geom,hourly}} = 0.672$ for $\phi \in [0.35, 0.65]$.

The contraction ratio $\Gamma_{\text{geom,hourly}}/\Gamma_{\text{geom,annual}} = 0.867$ corresponds to a 13.3% relative reduction (10.3 percentage-point absolute reduction) in geometric viable space. This confirms structural tightening under hourly compliance, especially at mid-tier electricity costs.

Because Γ_{geom} is an area metric, not a probability metric, deployment-risk interpretation should rely on the market-weighted metric Γ_w with region-specific distributions for (p_e, ϕ). Γ_w is retained as a future implementation reference; its omission here reflects data availability, not methodological exclusion.

As an illustrative workflow check (not an empirical claim), a synthetic ERCOT-like Monte Carlo was run with truncated normal inputs over 200,000 draws: Annual window $p_e \sim \mathcal{N}(58, 8)$ clipped to [20,80] and $\phi \sim \mathcal{N}(0.83, 0.05)$ clipped to [0.70,0.95]; Hourly window $p_e \sim \mathcal{N}(67, 9)$ clipped to [20,80] and $\phi \sim \mathcal{N}(0.50, 0.07)$ clipped to [0.35,0.65]. Using baseline Tier 1 assumptions from the main model, the resulting market-weighted viable fractions are $\Gamma_{w,\text{annual}} \approx 0.86$ and $\Gamma_{w,\text{hourly}} \approx 0.26$ (ratio ≈ 0.30), which is directionally consistent with the geometric-contraction result while showing stronger deployment-weighted compression under hourly conditions. These distributions are synthetic and do not represent observed ERCOT hydrogen-project data.

S1.3 Investment Hierarchy Inversion: Electricity Procurement Over Capital Cost Reduction

This study's sensitivity results show that electricity procurement has 3.4× greater leverage than electrolyzer capital-cost reduction: a \$10/MWh delivered-electricity improvement reduces LCOH by about \$0.55/kg, while a 20% electrolyzer capital-cost reduction changes LCOH by about \$0.16/kg. This ranking differs from standard roadmaps that prioritize electrolyzer cost-down as the dominant parity pathway [33].

The inversion stems from electricity-dominated cost structure ($\kappa = 0.22$): at \$67/MWh effective delivered pricing and 55 kWh/kg consumption, electricity contributes 73% of gross LCOH (\$3.69/kg of \$5.04/kg), while capital recovery contributes only 16% (\$0.81/kg). A 20% capital cost reduction (\$800 → \$640/kW) therefore reduces total LCOH by only 3.2%, whereas a comparable 15% electricity price reduction (\$67 $\rightarrow$ \$57/MWh) reduces LCOH by 10.9%, a 3.4$\times$ greater impact despite similar percentage changes in input parameters.

This has profound implications for public R&D strategy and policy design:

- **R&D prioritization:** Continued investment in electrolyzer stack materials, catalyst loading reduction, and membrane durability yields diminishing returns in electricity-dominated regimes. Greater impact comes from renewable integration research (firming strategies, hybrid wind-solar optimization, transmission loss minimization) that reduces effective delivered electricity price.

- **Policy mechanism alignment:** Production tax credits (\$3/kg for 10 years) are better aligned with electricity-dominated economics than investment tax credits (30% of capital cost), because PTC value scales with operating intensity while ITC is insensitive to utilization and electricity costs. A shift toward electricity cost subsidies (renewable energy zones, transmission infrastructure grants, PPA guarantees) would provide 2–3$\times$ greater economic impact than capital grants.

- **Site selection dominance:** Project developers create more value through renewable resource site optimization (\$10–20/MWh electricity price variation from resource quality) than through equipment vendor selection (\$100–200/kW capital cost variation from technology choice). This explains observed industry behavior: major hydrogen project announcements cluster in exceptional renewable corridors (Patagonia, Western Australia, Morocco) despite higher infrastructure costs, rather than in low-capital-cost manufacturing regions.

The electricity-over-capital priority holds even under optimistic 2030 projections (\$500/kW capital cost, 50 kWh/kg efficiency): at \$60/MWh electricity (achievable with excellent renewables), $\kappa = 0.18$, maintaining electricity dominance and rendering further capital cost reduction economically insignificant relative to electricity procurement optimization.

S1.4 Threshold Nonlinearity: Identifying Parity Cliff Dynamics

Linear sensitivity frameworks in existing literature obscure threshold effects where small parameter perturbations produce qualitative viability shifts. A critical nonlinearity is identified at baseline effective electricity price (\$67/MWh): this cost level eliminates *all* hourly-compliant parity scenarios (no viable combinations of ϕ and renewable technology achieve Net LCOH $<$ \$1.70/kg) while barely preserving annual matching viability (only $\phi \geq 0.87$ achieves parity, an 8-point window within the 0.70–0.95 annual range).

This cliff dynamic manifests as:

$$\left.\frac{\partial \Gamma}{\partial p_e}\right|_{p_e=67} \approx \begin{cases} -0.13 \text{ per \$/MWh} & \text{(annual, steep but continuous)} \\ -\infty & \text{(hourly, discontinuous at \$65–67/MWh)} \end{cases} \tag{1}$$

The hourly-annual divergence at mid-range electricity costs creates investment decision asymmetry: annual matching projects tolerate moderate electricity price forecast errors ($5–10/MWh variance maintains parity), while hourly projects exhibit option-like payoff structures where $5/MWh forecast errors determine total project viability (go/no-go rather than merely affecting returns). As seen in Figure 1 of the main manuscript (right panel), the hourly-compliant viability region collapses rapidly near this mid-range electricity band.

This nonlinearity has three practical consequences:

1. **Forecasting burden:** Hourly projects require higher-precision electricity cost modeling (including time-of-day variation, seasonal patterns, congestion pricing) because small errors compound through both utilization constraints and credit eligibility thresholds. Annual projects tolerate cruder estimates since viability persists across broader electricity cost ranges.

2. **First-mover advantage erosion:** In capital-intensive technologies (solar PV: $\kappa \approx$ 3–5), early adopters benefit from learning curves despite higher initial costs. In electricity-dominated, high-Ψ_{credit} systems, first movers face higher effective electricity prices (less developed renewable markets, fewer PPA options, nascent firming infrastructure) that can prevent parity entirely rather than merely reducing margins.

3. **Policy timing criticality:** The 2030 transition from annual to hourly matching creates a binary shift rather than continuous tightening. Projects achieving financial close in 2027 (annual matching grandfathered) face fundamentally different economics than 2030+ projects (hourly required), independent of technology progress. This administrative threshold may dominate technology learning curves in determining deployment timing.

Identifying and quantifying such cliffs is essential for decision-grade analysis: simplified linear models project smooth parity convergence as technology improves, while the threshold-aware framework reveals that certain parameter combinations produce discrete viability jumps where marginal technology improvements provide zero value until crossing discontinuous boundaries.

S1.5 Policy-Context Portability Under Statutory Change

Policy context note: Public Law 119-21 (One Big Beautiful Bill Act, July 2025) modifies the U.S. clean-hydrogen credit landscape, including 45V implementation timing and adjacent credit interactions. The analytical framework developed here remains applicable to any tiered production-credit design with temporal-matching requirements; numerical thresholds should be updated to current statutory and regulatory language when applying results to post-2025 project decisions [31, 37].

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