Technical and Economic Feasibility of a Nuclear-Integrated, Direct-Air-Capture Power-to-Liquids System for Drop-In Synthetic Fuels

A whole-system assessment of Project Prometheus

Ahmed Elghazali

Founder & Principal Investigator, Project Prometheus (independent research initiative)
City University of New York — Hunter College
ORCID 0009-0002-8317-1421 · aelghazali776@gmail.com

Working paper v1.0 · June 2026 · Preprint — not peer-reviewed · CC BY 4.0

ABSTRACT

Aviation, shipping, defense logistics, and heavy transport require energy-dense liquid hydrocarbons that are difficult to electrify and will remain so for decades. Project Prometheus is a 100,000 barrel-per-day (BPD) power-to-liquids (PtL) concept that synthesizes drop-in fuels — sustainable aviation fuel (SAF), renewable diesel, marine distillate, and naphtha — from atmospheric CO_2, water, and clean firm electricity, using Direct Air Capture (DAC), high-temperature solid-oxide electrolysis (SOEC), the reverse water-gas shift (RWGS), and cobalt low-temperature Fischer-Tropsch (FT) synthesis. This paper presents a first-principles mass-and-energy balance, a chemistry-derived product slate, a well-to-wake lifecycle carbon model, and a Monte-Carlo techno-economic analysis (TEA). We find that **every subsystem is technically feasible and commercially precedented (TRL 6–9)** and that the integrated balance closes at a defensible **52.6% electricity-to-fuel (LHV) efficiency** with **93.1% capture-to-fuel carbon efficiency**. We also find, and state plainly, that **gigascale economics are not yet bankable**: the credit-adjusted P50 levelized cost of fuel (LCOF) is **$13.03/gal** with a near-zero probability of positive net present value under current input ranges. The dominant cost driver is the price of clean firm electricity. We therefore frame gigascale as a *risk-retirement agenda* and identify a **$2.85M, 10 BPD pilot** as the correct, fundable unit of de-risking. The contribution of this work is a transparent, reproducible, end-to-end model — including the assumptions that do not yet close — intended to support honest evaluation by funders, grant programs, and prospective partners.

Keywords: power-to-liquids, e-fuels, direct air capture, solid-oxide electrolysis, Fischer-Tropsch, sustainable aviation fuel, techno-economic analysis, lifecycle carbon, artificial photosynthesis.

HIGHLIGHTS

- Every subsystem (DAC, SOEC, RWGS, Fischer-Tropsch) is technically feasible and commercially precedented (TRL 6–9).
- The integrated mass-and-energy balance closes at 52.6% electricity-to-fuel (LHV) efficiency and 93.1% capture-to-fuel carbon efficiency.
- Gigascale economics are not yet bankable: P50 credit-adjusted LCOF is $13.03/gal with ~0% probability of positive NPV under current ranges.
- The price of clean firm electricity is the single dominant cost driver.
- A $2.85M, 10 BPD pilot is identified as the correct, fundable unit of risk retirement.

NOMENCLATURE

Term	Definition
ASF	Anderson–Schulz–Flory chain-growth distribution
BPD	Barrels per day
CI	Carbon intensity (gCO2e/MJ)
DAC	Direct air capture
FT	Fischer–Tropsch synthesis
LCOF	Levelized cost of fuel ($/gal)
LHV	Lower heating value
MRV	Measurement, reporting & verification
PtL	Power-to-liquids
RWGS	Reverse water-gas shift
SAF	Sustainable aviation fuel
SOEC	Solid-oxide electrolysis cell
TEA	Techno-economic analysis
TRL	Technology readiness level
WtW	Well-to-wake

1. INTRODUCTION

1.1 The hard-to-electrify problem

Roughly 5% of global energy-related CO_2 emissions come from aviation and shipping alone, and these sectors — together with defense logistics and much of heavy transport — are widely classified as *hard to abate* because batteries cannot match the gravimetric and volumetric energy density of liquid hydrocarbons on the relevant duty cycles [2]. Decarbonizing them therefore requires either biofuels (land- and feedstock-constrained) or **synthetic drop-in fuels** manufactured from non-fossil carbon.

1.2 Artificial photosynthesis as an engineering target

Photosynthesis fixes atmospheric CO_2 into hydrocarbons using sunlight, water, and enzymatic catalysis. Project Prometheus pursues the same net transformation by industrial means: clean electricity replaces sunlight, electrolysis replaces the light reactions, and engineered heterogeneous catalysis (RWGS + FT) replaces the Calvin cycle. The result is a **closed atmospheric-carbon loop for liquid fuel** — carbon is captured from air, built into fuel, and returned to air on combustion — rather than the open loop of extracting and burning fossil carbon. We treat "artificial photosynthesis" as a framing and a long-horizon research direction (biomimetic catalysis, §5.5), not as the bankable design basis, which is conventional catalysis.

1.3 Contribution and scope

This paper assesses feasibility along two independent axes that the literature too often conflates: 1. **Technical feasibility** — does the chemistry work, does the mass/energy balance close, and are the subsystems buildable at scale? (§3–§6) 2. **Economic feasibility** — can the fuel be produced at a financeable cost? (§7)

Our central, deliberately unembellished finding is that the answer to (1) is *yes* and the answer to (2) is *not yet, and here is exactly why and by how much*. All figures derive from an open model (`src/prometheus/`, `scripts/`, `data/generated/`); the screening tier is a fast CH_2-equivalent balance and the detailed tier adds NIST-Shomate RWGS equilibrium, Anderson-Schulz-Flory (ASF) product distribution with wax hydrocracking, SOEC degradation, and explicit heat integration [17].

2. SYSTEM ARCHITECTURE AND METHODS

2.1 Process configuration

```
Air ──▶ DAC ──▶ CO₂ ┐
                    ├─▶ RWGS ─▶ syngas ─▶ Fischer-Tropsch ─▶ upgrading/distillation ─▶ SAF · diesel ·
Water ─▶ SOEC ─▶ H₂ ┘                                  └─▶ FT exotherm ─▶ (heat) ─▶ DAC sorbent rege
```

Clean firm power (grid clean-firm contracts, with containerized nuclear modeled as a supplemental option) drives SOEC and DAC. The FT reaction exotherm is recovered to offset DAC regeneration heat.

Figure 1. Reference process configuration. Atmospheric CO_2 (DAC) and electrolytic H_2 (SOEC) are combined via the reverse water-gas shift and cobalt Fischer-Tropsch synthesis, then upgraded and distilled into drop-in fuels; recovered FT heat offsets DAC sorbent regeneration.

2.2 Modeling approach

- **Thermodynamics:** RWGS equilibrium constant K(T) and reaction enthalpies are computed from NIST Shomate coefficients [17]; FT enthalpy is evaluated at 503 K (161.5 kJ/mol CO).
- **Product distribution:** ASF statistics with chain-growth probability $\alpha = 0.90$, a CH_4 override of 7% (cobalt LTFT runs above the ASF methane prediction), and hydrocracking of the C21+ wax fraction into diesel/jet/naphtha [8, 9].
- **Electrolysis:** an SOEC submodel with area-specific-resistance (ASR) degradation, thermoneutral-voltage crossover, a 1.45 V end-of-life replacement limit, rectifier/BOP overheads, and multi-stage isentropic H_2 compression.
- **Lifecycle carbon:** a well-to-wake (WtW) carbon-intensity model parameterized by grid carbon intensity, with an atmospheric-CO_2 credit (§6).
- **Economics:** a Monte-Carlo TEA sampling capital cost, clean-power price, SOEC energy, DAC cost, capacity factor, policy credit, and slate price (§7).

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3. PROCESS CHEMISTRY AND THERMODYNAMICS

3.1 Net stoichiometry

On a CH_2-equivalent basis the controlling balance is:

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CO₂ + 3 H₂ → CH₂ + 2 H₂O           (RWGS + FT, net)
H₂O → H₂ + ½ O₂                      (electrolysis)
```

An octane-specific illustration, useful for intuition, is `8 CO₂ + 25 H₂ → C₈H₁₈ + 16 H₂O`. Per barrel of liquid product the screening balance requires ≈367.5 kg CO_2 and ≈52.6 kg H_2.

3.2 RWGS

The endothermic RWGS (`CO₂ + H₂ ⇌ CO + H₂O`, $\Delta H \approx +33$ kJ/mol at 1173 K) is supplied electrically (≈379 MW at plant scale). The Shomate-based equilibrium yields ≈78% single-pass CO_2 conversion at 900 °C and $H_2:CO_2 = 3$, with the unconverted fraction handled by recycle and a purge that is explicitly debited as carbon loss.

3.3 Fischer-Tropsch

Cobalt LTFT (200–240 °C, ~20–25 bar) is the bankable basis. The product spectrum is fundamentally bounded by ASF statistics, which is unselective toward any single cut — a well-documented limitation of conventional FT catalysts [8, 9]. At $\alpha = 0.90$ with a 7% CH_4 override the model returns **C5+ selectivity of 86.3%** and a chemistry-derived raw slate of approximately 30.4% naphtha, 33.8% jet/SAF, 23.3% diesel, and 12.5% marine after wax hydrocracking. The FT exotherm (161.5 kJ/mol CO; ≈2.04 GWth at plant scale) is recovered for heat integration. FT-derived synthetic paraffinic kerosene (FT-SPK) is an approved aviation-fuel pathway under ASTM D7566 [16], which materially de-risks certification.

> **Note on the slate.** The *chemistry-derived* ASF slate above differs from the *economic/target* slate used for revenue (42% SAF, 26% diesel, 13% marine, 14% naphtha, 5% wax/LPG). Reconciling the two — via α-tuning, cut points, recycle, and hydrocracker severity — is an explicit design task, not a solved result.

4. Mass and energy balance (detailed reference case)

Quantity	Value	Notes
Nameplate liquid output	100,000 BPD (4.2 MMgal/day)	—
CO_2 captured	42,231 t/day	DAC
H_2 (net / design)	5,816 / 6,107 t/day	20% design margin retired toward net
Capture-to-fuel carbon efficiency	93.1%	after RWGS purge loss
SOEC system energy	38.1 kWh/kg H_2	32.8 initial DC; lifetime-avg incl. BOP
+ H_2 compression (1→25 bar)	+1.78 kWh/kg → **39.9**	3-stage isentropic, $\eta = 0.75$
SOEC electric load	9,693 MW	—
H_2 compression load	452 MW	—
DAC electric load (350 kWh/t)	616 MW	see §5.2 caveat
RWGS heating (900 °C)	379 MW	electric
DAC regen heat pumps (COP 3)	156 MW	covers FT-heat deficit
Balance of plant	650 MW	—
Net process electric load	**11,947 MW**	≈ 11.9 GWe
Fuel LHV output	6.29 GW	—
Electricity-to-fuel efficiency (LHV)	**52.6%**	screening tier gives 58.2%
FT exotherm / recovered	2.04 / 1.73 GWth	85% recovery
DAC thermal demand (4.5 GJ/t)	2.20 GWth	recovered FT heat covers ~79%
Raw water intake (85% FT-water reuse)	30.0 MGD	—
SOEC stack life (1%/1000 h to 1.45 V)	≈9.8 years	—

The 52.6% electricity-to-fuel efficiency is consistent with the upper range of literature PtL-FT studies once compression, degradation, and RWGS heat are charged honestly (many published values report 25–50% depending on system boundary) [10, 11]. The heat-integration result is important and non-obvious: recovered FT heat offsets the majority — but **not all** — of DAC regeneration demand, leaving a ~0.47 GWth deficit that must be served by high-temperature heat pumps. DAC heat is therefore explicitly *not free* in this model, a correction over earlier drafts.

Table 2. Screening vs. detailed model reconciliation. The detailed tier removes earlier simplifications; the deltas show exactly where and why.

Metric	Screening	Detailed	Basis for change
CO_2 captured (t/day)	42,800	42,231	explicit capture loss + loop purge vs flat 10%
H_2 design (t/day)	6,416	6,107	exact paraffin stoichiometry + purge; margin 20%→5%
SOEC energy (kWh/kg)	36.0	38.1	lifetime degradation average + rectifier/BOP
DAC electric (MW)	330	616	intensity raised to literature 350 kWh/t
RWGS heat (MW)	0	379	endotherm previously ignored
Heat-pump load (MW)	0	156	DAC deficit not covered by FT heat
Net electric load (MW)	10,604	11,947	—
Electricity-to-fuel (%)	58.2	52.6	—
Raw water (MGD)	47.7	30.0	85% FT-water reuse credited

Table 3. Reference stream table (screening basis, 100,000 BPD).

ID	Stream	Value	Unit
S-101	Atmospheric CO_2 to DAC	42,800	t/day
S-102	Ambient air through contactors	125.9	billion m^3/day
S-201	SOEC hydrogen to syngas island	6,416	t/day
S-202	SOEC pure-water feed	57,339	t/day
S-203	SOEC oxygen byproduct	50,921	t/day
S-301	Fischer-Tropsch liquids	12,401	t/day
S-302	FT reaction water (recovered)	31,855	t/day
E-101	SOEC electric load	9,624	MW
E-201	DAC electric load	330	MW
Q-301	FT heat release	1.69	GWth
Q-401	DAC thermal regeneration	0.82	GWth

5. Subsystem feasibility and technology readiness

5.1 Solid-oxide electrolysis (SOEC) — TRL 6–7

SOEC is the largest load and the principal scale-up risk. The model's **38.1 kWh/kg (system) / 39.9 kWh/kg (with compression)** is corroborated by independent data: Idaho National Laboratory tested a Bloom Energy 100 kW SOEC for >7,100 h with **~37 kWh/kg-H_2 DC and no measurable degradation** [4], and the ISPT consortium reports ~40 kWh/kg system-level for steam electrolysis [7]. Degradation — the project assumes 1%/1000 h — sits between the 2030 target of 0.5%/kh and demonstrated best-cases of 0.1%/kh [5, 6]. The genuine open risk is **simultaneous module count and dynamic operation**: no >100 MW SOEC system yet exists, and SOEC turn-down under variable power is harder than for PEM [5, 19]. This is a scale-and-integration risk, not a physics risk.

5.2 Direct air capture (DAC) — TRL 7–8

DAC is commercially demonstrated at the ~10^4–10^5 t/yr scale (e.g., Climeworks Mammoth [20]). The seminal engineering-cost study by Keith et al. (2018) reports a levelized **\$94–232/t-CO_2** for an aqueous design, with ~366 kWh/t electric plus thermal input [1]; the IEA tracks a broadly similar status and a declining cost trajectory [2]. **Caveat (stated for honesty):** the project's solid-sorbent assumption of **350 kWh/t electric + 4.5 GJ/t thermal** is at the optimistic end of the electric range — several solid-sorbent reports cite 1,500–2,000 kWh/t electric. DAC cost and energy are accordingly treated as top-tier sensitivities (§7), and a vendor-specific DAC data package is a required pre-FEED action.

5.3 Reverse water-gas shift (RWGS) — TRL 6–7

RWGS at 900 °C is thermodynamically well-understood [17] but high-temperature catalyst durability at gigascale requires a dedicated demonstration. It is the least de-risked of the chemical steps.

5.4 Fischer-Tropsch and upgrading — TRL 8–9

Cobalt LTFT and wax hydrocracking are fully commercial (GTL precedents at 10^4–10^5 BPD). FT in a PtL (CO_2-sourced) context, rather than from fossil syngas, is the only novel element, and it is modest. FT-SPK certification under ASTM D7566 is established [16].

5.5 Biomimetic catalysis — research track, not basis

Copper-ruthenium nanoclusters and crystallite-size engineering can, in principle, bend the ASF distribution toward target cuts [8]; we carry this as upside R&D only. **The economics in this paper assume none of it.**

5.6 Power: clean firm electricity — the binding constraint

The plant needs ~11.9 GWe of *clean firm* power. Containerized nuclear (5 MWe/15 MWth reference module) is modeled as a supplemental option — a 5% share needs ~107 modules; 100% would need ~2,121 and is not treated as practical. Microreactors are TRL 5–6 (regulatory and HALEU-supply gated). Power, not chemistry, is the feasibility fulcrum (§7).

Subsystem	TRL	Principal risk
FT / hydrocracking	8–9	Scale in PtL context
DAC (solid sorbent)	7–8	Energy intensity & cost trajectory
SOEC	6–7	>100 MW scale-up, dynamic duty
RWGS	6–7	High-T catalyst durability
Containerized nuclear	5–6	Licensing, HALEU supply

6. Lifecycle carbon and policy eligibility

Well-to-wake carbon intensity (CI) is dominated by the carbon intensity of the input electricity. Using atmospheric CO_2 (which carries an embedded removal credit on the fuel's combustion carbon), the model returns:

Power scenario	Grid CI (gCO$_2$e/kWh)	WtW CI (gCO$_2$e/MJ)	vs. petroleum jet (~89)
Zero-carbon (nuclear/geo)	0	**−64.8**	strongly negative
Dedicated renewable	15	**−56.3**	strongly negative
US clean grid (2030, IRA)	80	**−19.8**	>50% reduction
US average grid (2026)	380	**+149**	**worse than fossil**

The decisive insight: **clean power is a hard eligibility gate, not an optimization.** A 11.9 GW plant on the average grid would emit more per MJ than the petroleum fuel it replaces. Dedicated, additional clean power is the minimum bar. Under clean power the FT-SPK product is positioned to qualify for the U.S. §45Z Clean Fuel Production Credit (certified via 45ZCF-GREET) [14, 15]; however, §45Z eligibility, emissions-factor method, and the credit's legislated horizon (currently through 2029, subject to legislative change) are modeled as *conditional expected value*, not guaranteed revenue.

7. Techno-economic analysis

7.1 Method

A Monte-Carlo TEA (`scripts/technoeconomic_uncertainty.py`) samples the dominant uncertain inputs and propagates them to LCOF, EBITDA, and 20-year NPV. Headline deterministic inputs: CAPEX ≈ $28B (pre-FEED, Class 4–5), fixed OPEX ≈ $2.25B/yr, net load 11.9 GWe, weighted product price $4.46/gal, 8% WACC.

7.2 Results

Metric	P05	P50	P95
Credit-adjusted LCOF ($/gal)	9.98	**13.03**	16.57
LCOF before credit ($/gal)	10.07	13.12	16.67
Annual EBITDA ($B/yr)	−11.35	−6.98	−3.33
NPV_{20} (mean)	—	**−$129.8B**	—
Probability of positive NPV	—	**~0%**	—

The P50 LCOF of **$13.03/gal** sits at the upper end of the published PtL-SAF range (single-point literature estimates commonly cluster $8–15/gal; ORNL's 2025 CO_2-to-jet TEA reports ~$8.50–11/gal) [10, 11, 12, 13]. Our higher central value reflects deliberately conservative, fuller-boundary accounting — including a containerized-nuclear power premium and honest DAC/SOEC ranges — rather than a more optimistic single-point estimate.

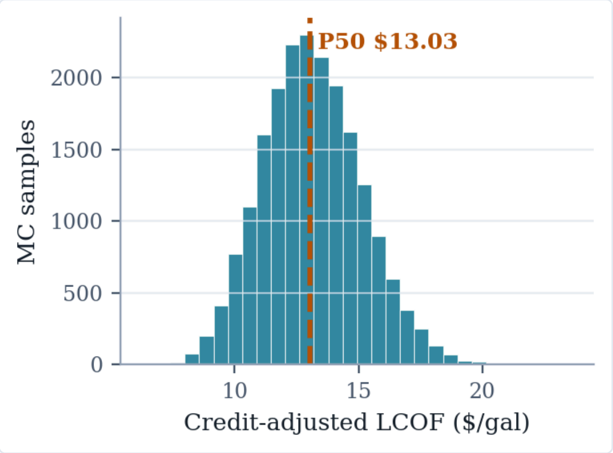

Figure 2. Monte-Carlo distribution of credit-adjusted LCOF (P50 ≈ $13.03/gal; P05–P95 ≈ $9.98–$16.57).

7.3 Sensitivity

Spearman rank correlation of LCOF against sampled inputs (`data/generated/tea_sensitivity_rank.csv`):

Rank	Driver	ρ
1	Effective electricity price	+0.59
2	Clean firm power price	(high)
3	DAC non-power cost	(high)
4	Capital expenditure	(moderate)
5	Containerized-nuclear share	(moderate)

Electricity price is the single dominant lever, consistent with the entire PtL TEA literature, which repeatedly identifies the cost of electricity as the controlling variable for e-fuels [10, 11]. This is the most important quantitative result in the paper: it tells us precisely where de-risking effort and capital should be aimed.

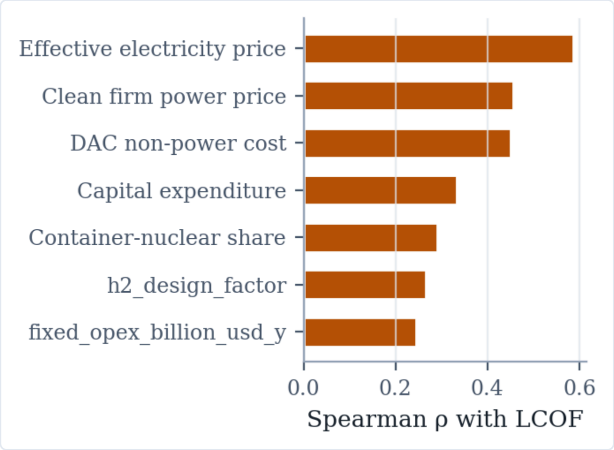

Figure 3. Rank-correlation (Spearman ρ) sensitivity of LCOF to sampled inputs; electricity price dominates.

8. Discussion — the path to economic feasibility, and an author's assessment

8.1 What "feasibility" honestly means here

Technically, Prometheus is feasible: each subsystem exists, the chemistry is bounded by well-known physics, the integrated balance closes, and the product is certifiable. Economically, at gigascale and today's input ranges, it is not — and the model says so with a near-zero positive-NPV probability. These are not contradictory statements; they describe a technology whose **physics is solved and whose cost curve is not yet retired.**

8.2 The cost-down path

Because LCOF is dominated by electricity price, the path to viability is concrete and measurable: 1. **Clean firm power toward ~$0.02/kWh** — the largest single lever. 2. **SOEC capital and durability** — toward <$200/kW installed and >0.5%/kh degradation, lowering both CAPEX and replacement OPEX. 3. **DAC energy and cost** — validating the solid-sorbent energy assumption (§5.2) and moving toward the IEA/Climeworks <$200/t trajectory [2, 20]. 4. **Policy** — §45Z as a tailwind, never the thesis; the model must close without maximal credits.

8.3 Why a 10 BPD pilot is the right next unit

A gigascale plant cannot be the first financing case, and a benchtop cannot retire commercial risk. A **$2.85M, 10 BPD containerized pilot** — sized to a DOE/USDA Fast-Track grant — produces exactly the data the model currently has to assume: catalyst selectivity and deactivation, SOEC durability under real duty cycles, the true DAC energy intensity (§5.2), heat-integration performance, and ASTM-track fuel certification. Each datum collapses a distribution in §7 into a point. This is the correct, capital-efficient ordering.

8.4 Author's independent commentary

The following is my own analytical view rather than a model output. - **Honesty is a strategic asset, not a liability.** Most pre-pilot ventures present a single optimistic LCOF; publishing a Monte-Carlo P50 with a 0% positive-NPV probability is unusual and, I argue, more credible to sophisticated reviewers. It converts the pitch from "trust our number" to "stress-test our model." - **The real moat is power procurement and heat integration, not the chemistry.** The chemistry is largely commodity; the defensible engineering is the clean-firm-power strategy and the FT→DAC thermal network that others under-account for. - **Right-size the ambition.** The 100,000 BPD reference is best treated as a *design north star* that disciplines the engineering, while the company's near-term identity should be a focused pilot-and-data enterprise. The most common failure mode for this class of venture is raising gigascale capital before the unit economics are earned. - **Sequencing beats scale.** Prometheus's strongest claim is not "cheap fuel today" but "a transparent, staged, data-gated route from a fundable pilot to a defined gigascale architecture." That is a fundable thesis.

9. Limitations and threats to validity

1. **CAPEX is pre-FEED** (Class 4–5, Monte-Carlo modal ~$28B); a Class 3 estimate is required before financing.
2. **DAC electric intensity (350 kWh/t)** is optimistic versus some solid-sorbent reports and must be vendor-validated (§5.2).
3. **Steady-state model**; renewable variability, H_2 buffer dynamics, and SOEC turn-down need time-series simulation.
4. **RWGS recycle/purge** is modeled at single-pass equilibrium with a purge debit; full loop closure is

pending.

5. **Policy risk** (§45Z scope and horizon) is material and exogenous.
6. **No biomimetic credit** is taken; conversely, no learning-curve cost reductions are assumed in the headline LCOF, so the figure is conservative in that respect.

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10. Conclusion

Project Prometheus is **technically feasible and commercially precedented at the subsystem level**, with an integrated mass-and-energy balance that closes at 52.6% electricity-to-fuel efficiency and 93.1% carbon efficiency, producing ASTM-certifiable drop-in fuels from atmospheric CO_2 and water. It is **not yet economically feasible at gigascale**: the P50 credit-adjusted LCOF is $13.03/gal with ~0% probability of positive NPV under current ranges, gated overwhelmingly by the price of clean firm electricity. The appropriate response is neither to overstate the economics nor to abandon the architecture, but to **retire the dominant uncertainties through a 10 BPD pilot** whose data convert modeled assumptions into measured facts. The value of this paper is its transparency: it publishes the parts of the model that work and the parts that do not, which is the necessary foundation for credible public funding and partnership.

Acknowledgments

Modeling, simulation, figures, and this manuscript were prepared with AI assistance (Anthropic Claude and OpenAI Codex) under the author's direction; all technical assumptions, the engineering model, and final claims are the author's responsibility. The intellectual-honesty framing — publishing negative results — is intentional.

Competing interests

The author is the founder of Project Prometheus and holds a financial interest in its commercialization. The paper deliberately publishes negative results (a non-bankable gigascale NPV) to mitigate optimism bias.

Funding

This work received no external funding to date. The project is seeking non-dilutive grant support (e.g., NSF SBIR/STTR, DOE/USDA) for a pilot-scale demonstration.

Author contributions

A. Elghazali conceived the project, developed the engineering and techno-economic models, performed the analysis, generated the figures, and wrote the manuscript.

Data and code availability

The screening and detailed models, simulation scripts, generated datasets, and figures are maintained in the project repository (`src/prometheus/`, `scripts/`, `data/generated/`, `outputs/`). An interactive subset (scaling calculator, sensitivity charts, and a "path to bankability" tool) is published at https://space-kitty.com.

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Suggested citation: Elghazali, A. (2026). *Technical and Economic Feasibility of a Nuclear-Integrated, Direct-Air-Capture Power-to-Liquids System for Drop-In Synthetic Fuels: A Whole-System Assessment of Project Prometheus*. Working paper v1.0. https://space-kitty.com