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Private Fusion's Net-Energy Race

Who reaches net electric first — and what the physics, funding, and engineering gates really allow

Star Power — Research Desk

Coverage: Star Power

ABSTRACT

Which private-fusion approach reaches net energy first, and does a credible path to net electricity by the mid-2030s exist? This report compares the leading programs on the physics that actually gates them — the fusion triple product (n·T·τ), energy gain Q, and field/temperature regime — against verified funding and timelines, then prices the engineering risks. The cumulative private fusion total reached roughly \$9.8 billion across 53 companies by mid-2025, with Commonwealth Fusion Systems (~\$3 billion raised) building SPARC to target $Q \approx 11$ at 12.2 T, and Helion and Focused Energy claiming the most aggressive net-electric dates (2028, 2037). The headline finding: net fusion energy ($Q > 1$ in a magnetically confined plasma) is now a near-term, 2027-class milestone, but net electric to the grid at credible cost is an engineering — not physics — problem dominated by HTS magnets, tritium, materials lifetime, and rep-rate, pushing realistic first net-electric to the 2031–2035 window. The fastest-moving capital is hyperscaler offtake; the cleanest public exposure remains advanced fission (OKLO, SMR, NNE, GEV, BWXT).

Keywords: fusion, triple product, tokamak, SPARC, Helion, inertial fusion, HTS magnets, net energy, Q, FRC, data center power, SMR

Executive Summary

The private-fusion field has crossed from "can the physics work" to "can the machine be built and paid for." Net fusion energy — gain Q > 1 in a confined plasma — is now a near-term, demonstrably engineerable milestone: Commonwealth Fusion Systems (CFS) is assembling SPARC to demonstrate Q ≈ 11 at 140 MW of fusion power, with first plasma targeted for 2026 and net energy in 2027 [1][8][12]. That is a physics result, not a power plant.

Capital has followed conviction. Cumulative private and public funding across 53 surveyed fusion companies reached roughly **$9.766 billion by mid-2025**, a five-fold increase since 2021, with $2.64 billion raised in the trailing twelve months — the second-highest annual figure on record [3]. CFS alone has raised about **$3 billion** — roughly one-third of the field — including an $863 million Series B2 in August 2025 backed by Nvidia, Google and Breakthrough Energy [2][4].

The leaders split into three physics camps. Magnetic confinement built on high-temperature superconducting (HTS) magnets is the most mature route (CFS, Tokamak Energy). Pulsed/field-reversed-configuration (FRC) approaches that skip a steam cycle by harvesting electricity directly (Helion) claim the most aggressive net-electric date — Microsoft offtake by 2028 [5][6]. Inertial routes — laser (Focused Energy) and pulser-driven (Pacific Fusion) — ride the 2022–2025 NIF ignition results but face the steepest rep-rate gap [9][10][11].

The honest read: the gating risks are no longer ignition-physics but engineering — HTS magnet manufacturing at scale, tritium breeding and supply, plasma-facing materials lifetime under 14 MeV neutron flux, and (for pulsed/inertial) repetition rate. Each is a years-not-months problem.

> **BOTTOM LINE:**
> Expect at least one credible **net-energy (Q > 1)** demonstration in 2027; treat **net-electric-to-grid before ~2031 as optimistic** and a defensible first-of-a-kind window of **2031–2035 (Star Power estimate)**. The cleanest public-market exposure to the "firm-power-for-data-centers" thesis that fusion rides is still advanced fission (OKLO, SMR, NNE, GEV, BWXT) — the pure fusion plays remain private.

1. Context and Scope

This report addresses a single question with two parts: which private-fusion approach reaches **net energy** first, and is there a credible path to **net electricity** delivered to a grid at a defensible cost by the mid-2030s? It spans two coverage domains — net-energy milestones, the triple product and Q (the physics spine) and private fusion programs, funding and timelines (the capital and execution spine) — and touches a third, advanced fission/SMR, as the public-market and demand context.

The system boundary matters. "Net energy" in this report means scientific gain at the plasma ($Q_{plasma} > 1$) or, for inertial schemes, target gain > 1. "Net electric" is a far higher bar: electricity onto wires after subtracting the entire facility's recirculating power (magnets, lasers, cryogenics, pumps, controls). NIF's December 2022 shot produced 3.15 MJ of fusion output from 2.05 MJ of laser light delivered to the target — a target gain of ~1.5 — but the lasers themselves drew roughly 300 MJ from the wall [9]. That gap is the whole game.

In scope: the physics basis (triple product, Q, field/temperature) of the leading approaches; verified funding and timelines; the four engineering gates (magnets, tritium, materials, rep-rate); a transparent path-to-plant economics view with scenarios; and public-market implications. Out of scope: public-sector megaprojects (ITER, DEMO) except as physics reference points, and any non-public technical claims.

2. Technology Landscape and State of the Art

2.1 The physics that gates everything: the triple product

Fusion power density scales with the **fusion triple product**, n·T·τ_E — the product of plasma density (n, particles/m³), ion temperature (T, in keV or equivalent °C), and energy confinement time (τ_E, seconds). For a deuterium–tritium (D-T) plasma, sustained net energy requires a triple product of order **10^{21} keV·s·m⁻³** (the Lawson criterion regime). Every approach in this report is, at bottom, a different bet on how to buy that product cheaply: tokamaks buy confinement with magnetic field; FRCs and Z-pinches buy density and self-organization; inertial schemes buy enormous n·T for a vanishingly short τ.

The public-science state of the art frames the private race. ITER-class and national devices have pushed the triple product and its sustainment: Wendelstein 7-X (stellarator) maintained a record triple product for **43 seconds** on 22 May 2025, surpassing prior long-duration tokamak results and pulling level with unpublished JET data [7]. EAST sustained high-confinement plasma for **1,066 seconds** in 2025, up from its 403-second 2023 record [7]. Tokamak Energy's ST40 reached an ion temperature of **100 million °C** (the oft-cited commercial threshold) in a compact spherical tokamak in 2022, and closed 2025 with its highest-ever plasma current, stored energy and triple product [2 (Tokamak Energy)][12]. These are the physics tailwinds the private programs are riding.

2.2 Why HTS magnets changed the economics

The single most important enabler is high-temperature superconducting (REBCO) tape. Magnetic confinement scales steeply with field — fusion power density rises roughly as B^4 — so a magnet that reaches 12–20 T instead of ITER's ~12 T (with low-temperature superconductor at far larger scale) lets a tokamak shrink by an order of magnitude in volume for the same performance. CFS demonstrated a full-scale toroidal-field coil at **20 T** in 2021 (DOE-validated performance test, $8 million milestone award) and SPARC's 18 REBCO coils target a **12.2 T** on-axis field at a major radius of just **1.85 m** [1][8][12]. Tokamak Energy's Demo4 magnet system reached **11.8 T** with seven million ampere-turns through its center column in November 2025 — the first HTS system to replicate power-plant fields — and the firm now sells HTS magnets as a business in their own right (including a General Atomics submarine contract) [2 (Tokamak Energy)]. HTS is the reason "compact, private, fast" is a coherent thesis at all.

2.3 Competing Pathways

The leaders divide by confinement physics, fuel, and how they intend to make electricity. Numbers below are company or peer-reviewed disclosures; TRL is a our reading of demonstrated-vs-unproven status.

Company / Device	Confinement principle	Fuel	Headline physics (vintage)	Net-electric claim	Net-energy TRL (TRP read)
CFS / SPARC -> ARC	High-field HTS tokamak	D-T	12.2 T, R = 1.85 m, Ip ≤ 8.7 MA; design Q ≈ 11, 140 MW fusion [1][8]	ARC ~400 MWe, early 2030s [4][8]	6 — magnet proven at 20 T; Q>1 pending 2027

Helion / Polaris	Pulsed FRC, direct energy capture	D-^{3}He (D-D bred ^{3}He)	7th-gen Polaris assembled 2024, largest FRC plasmas to date [5][6]	≥50 MWe to Microsoft by 2028 [5][6]	4 — net electric unproven; bold timeline
TAE / Copernicus	Beam-driven FRC	p-^{11}B (aneutronic)	Norman sustained plasma >75 M°C (2022); Copernicus to test net energy [2 (TAE)]	"Da Vinci" commercial plant ~early 2030s	4 — aneutronic gain unproven at scale
Tokamak Energy / ST80-HTS -> ST-E1	Spherical HTS tokamak	D-T	ST40 100 M°C (2022); Demo4 11.8 T magnet (2025) [2 (Tokamak Energy)]	ST-E1 pilot, ~2030s	5 — magnet strong; integrated Q pending
Zap Energy / Century	Sheared-flow-stabilized Z-pinch	D-T	Century rig: >100 shots at 1/5 s, 39 kW thermal (2025) [2 (Zap)]	Commercial plant, 2030s	3 — compact/cheap; far from Q>1
Focused Energy	Direct-drive laser inertial	D-T	Rides NIF ignition; LightHouse architecture [10]	Grid MWh pilot ~2037 (Biblis site) [10]	3 — rep-rate + driver efficiency gap
Pacific Fusion	Pulser-driven inertial (pulsed magnetic)	D-T	Pulser module ~2 TW peak, >60 MA in ~100 ns; ~150 modules per demo [11]	Demonstration system, late 2020s	3 — pre-net-energy; demo-stage

The spread is the story. CFS and Tokamak Energy have **demonstrated the hardest enabling component** (the magnet) and now face integration. Helion has the **most aggressive electricity date** but must prove direct energy capture and D-^{3}He gain simultaneously. TAE's p-^{11}B is the most elegant fuel (aneutronic, minimal neutron activation) but the hardest physics (ignition temperatures ~10× D-T). Inertial routes inherit NIF's ignition credibility but must convert a once-a-day laboratory shot into a 1–10 Hz power plant.

3. Techno-Economic Analysis

3.1 Cost Model and Assumptions

There is no operating fusion power plant, so any LCOE is a model, not a measurement. The point of the exercise is to expose which variables decide whether fusion is a $60/MWh firm-power source or a $250/MWh science project. The assumptions below are a transparent our first-of-a-kind (FOAK) frame; every input is sourced or labelled an estimate.

Parameter	Value	Unit	Basis / Source
FOAK plant net output	400	MWe	CFS ARC design target [4][8]
Overnight capital (FOAK)	8,000–15,000	$/kWe	Star Power estimate (FOAK first-of-a-kind premium vs. SMR/advanced fission band)
Capacity factor (mature)	80	%	Star Power estimate (baseload firm-power target)
Plant lifetime	30	yr	Star Power estimate (matches advanced-fission convention)
Discount rate (WACC, real)	8	%	Star Power estimate (merchant/first-of-a-kind risk)
Recirculating power fraction	20–40	% gross	Star Power estimate (magnet/cryo/laser parasitic load)

Tritium cost / availability	scarce	—	~25 kg global civilian inventory, no merchant market [13]
Annual O&M	3–5	% of capex/yr	Star Power estimate (high for FOAK, blanket replacement)

3.2 Levelized Cost / Unit Economics

Running the frame above gives a FOAK LCOE band of roughly **$140–260/MWh (Star Power estimate)**, dominated by capital recovery and the recirculating-power penalty — far above today's ~$40–70/MWh firm-power benchmarks but in the range early-of-a-kind technologies typically inhabit before learning. The cost stack, by share of LCOE, is approximately:

LCOE component	Share of FOAK LCOE	Driver
Capital recovery	~55–65%	Magnets, cryoplant, vacuum vessel, building [Star Power estimate]
Fuel cycle (tritium breeding, processing)	~5–10%	Tritium scarcity, blanket [13][Star Power estimate]
O&M incl. blanket/first-wall replacement	~20–30%	Neutron-damaged components, planned outages [Star Power estimate]
Recirculating power (net-vs-gross)	~5–15% (as output loss)	Magnet/cryo/laser parasitic load [Star Power estimate]

The economic counterweight to the technology optimism: even if every physics milestone lands on time, the **first plants are expensive** because they are first. The relevant question for an investor is not FOAK cost — it is the **learning rate** and whether a manufacturable, repeatable plant (CFS's ARC philosophy, Zap's deliberately cheap Z-pinch) drives cost down a steep curve. Magnet-route economics improve fastest if HTS tape cost falls; Helion's economics improve fastest if direct energy capture removes the steam cycle entirely.

3.3 Sensitivity

The four variables that move FOAK LCOE most, in rough order of leverage (Star Power estimate):

Driver	Swing modeled	Direction of LCOE impact
Overnight capital ($/kWe)	8,000 -> 15,000	Largest — near-linear on capital-recovery share
Recirculating power fraction	20% -> 40% gross	Large — erodes saleable output directly
Capacity factor	80% -> 50%	Large — FOAK reliability risk is real
First-wall/blanket replacement cadence	2 yr -> 5 yr	Moderate — materials lifetime under neutron flux
WACC	6% -> 12%	Moderate — first-of-a-kind financing premium

The tornado ordering carries the message: **capital intensity and parasitic load decide fusion economics, not fuel cost.** That is the opposite of fission's enrichment-and-fuel sensitivity and inverts the intuition many investors carry over from the nuclear sector.

4. Market and Demand Outlook

The demand pull is no longer hypothetical — it is the AI data center. Hyperscalers are signing firm, clean, 24/7 power offtakes years ahead of delivery: **Microsoft–Helion** (≥50 MWe by 2028, Constellation as marketer) [5][6] and **Google–CFS** (200 MWe from ARC in Virginia) [4] are the two landmark fusion offtakes, and both buyers are also CFS equity backers [2][4]. Adjacent SMR offtakes — Google–Kairos (50 MW), Oklo–Switch/Equinix/Meta (to 1.2 GW campuses) — show the same buyer set provisioning firm power at scale [from public reporting on advanced-fission deals].

Sizing the fusion market itself before a single plant operates is speculative; the credible near-term TAM is **demonstration and pilot capacity, not gigawatts of dispatched energy**. A directional outlook:

Scenario (to ~2035)	Net-energy (Q>1) demos	First net-electric to grid	Cumulative private $ by 2030 (TRP est.)
Bull	2–3 (CFS 2027 + 1–2 others)	One pilot ~2031–2032 (CFS ARC or Helion)	$25–35 B
Base	1–2 (CFS 2027)	First FOAK ~2033–2035	$18–25 B
Bear	1, slipped to 2028–2029	None before 2035; net-electric stays a 2030s-late story	$12–18 B

The base case assumes SPARC achieves Q > 1 broadly on schedule but that turning a physics result into a wired, financeable plant takes the better part of a decade — consistent with how long every prior energy first-of-a-kind has taken.

5. Feasibility, Scale-Up, and Risk

The honest go/no-go: **net energy is feasible and near; net electric at credible cost is gated by four engineering problems**, none of which is solved at plant scale today.

1. **Magnets.** HTS is the enabling win and the manufacturing bottleneck. CFS and Tokamak Energy have proven 11.8–20 T coils [1][2 (Tokamak Energy)], but a power plant needs many large coils built repeatedly and cheaply, with quench protection and cryogenic reliability over decades. REBCO tape supply is a real constraint on the whole sector's build rate.
2. **Tritium.** D-T plants consume tritium that barely exists commercially — the global civilian inventory is on the order of **~25 kg** with no merchant market [13]. Every D-T plant must breed its own tritium in a lithium blanket with a breeding ratio > 1, a system never demonstrated at power-plant scale. This is the deepest fuel-cycle risk and the reason aneutronic (TAE) and D-^{3}He (Helion) routes, despite harder physics, sidestep a genuine supply problem.
3. **Materials.** D-T fusion's 14.1 MeV neutrons damage and activate the first wall and blanket faster than any fission spectrum. Plasma-facing component lifetime under that flux — and the replacement cadence it forces — drives O&M and capacity factor. No material is yet qualified for a full plant lifetime.
4. **Rep-rate (inertial/pulsed).** NIF fires roughly once a day; a laser-inertial power plant needs **1–10 Hz** with high driver efficiency and target mass-production. Focused Energy and Pacific Fusion must close a rep-rate gap of five-plus orders of magnitude. Helion's pulsed FRC must likewise fire repeatedly and capture energy directly each pulse.

5.1 Risk Register

Risk	Likelihood	Impact	Mitigation
HTS magnet scale-up / cost stalls	Medium	High	CFS/Tokamak Energy in-house magnet factories; HTS sold as standalone business to fund learning [2 (Tokamak Energy)]
Tritium breeding ratio < 1 at scale	Medium-High	High	Lithium blanket R&D; aneutronic/D-^{3}He routes avoid tritium (TAE, Helion) [13]
First-wall/blanket lifetime too short	High	Medium-High	Materials qualification; modular replaceable blankets (ARC design)
Net-electric date slips past 2030	High	Medium	Hyperscaler offtake de-risks demand, not schedule [5][6][4]
Rep-rate / driver efficiency (inertial)	High	High	Pulser/laser efficiency programs; Pacific Fusion–General Atomics module testing [11]
Funding access tightens	Medium	High	Concentration in CFS (~$3 B); FIA flags funding as the field's "major challenge" [3][4]

6. Market and Equity Implications

The defining structural fact: **the pure-play fusion leaders are all private** (CFS, Helion, TAE, Tokamak Energy, Zap, Focused Energy, Pacific Fusion). There is no clean listed fusion equity. Public exposure is therefore (a) the hyperscaler offtakers who buy the power and back the equity, and (b) the advanced-fission names that win the same "firm clean power for data centers" demand if fusion stays a decade out. Directional reads tied to this report's thesis — net energy near, net electric a 2030s story — follow.

Company (Ticker)	Exposure	Reasoning (tied to the thesis)	Horizon
Oklo (OKLO, NYSE)	Positive	If fusion-electric stays late-2030s, advanced fission captures the near-term data-center firm-power demand fusion is being marketed against; Oklo has hyperscaler-adjacent deals and Nvidia-CEO endorsement. High execution/valuation risk.	2–5 yr
NuScale Power (SMR, NYSE)	Positive	Same demand thesis; furthest-along SMR licensing. Levered to the firm-power gap fusion does not yet fill.	2–5 yr
Nano Nuclear Energy (NNE, NASDAQ)	Neutral-Positive	Microreactor optionality on the same demand pull; earlier-stage, higher risk than OKLO/SMR.	3–7 yr
GE Vernova (GEV, NYSE)	Positive	Diversified power-equipment and BWRX-300 SMR exposure; benefits from firm-power buildout regardless of which technology wins. Lowest single-technology risk here.	1–5 yr
BWX Technologies (BWXT, NYSE)	Positive	Reactor-vessel and advanced-fuel supplier (BWRX-300 vessel, TRISO); a "picks-and-shovels" play on nuclear scale-up and, longer-term, fusion component manufacturing.	1–5 yr
Microsoft (MSFT) / Alphabet (GOOGL) / Nvidia (NVDA)	Indirect	Offtakers and equity backers of CFS/Helion; fusion is a small option within massive businesses — exposure is real but immaterial to the share price.	5–10 yr

THE TAKE:
The non-obvious market read is that **the most reliable way to be "long the fusion thesis" today is to be long advanced fission.** The demand fusion is sold against — 24/7 carbon-free firm power for AI compute — is real and arriving now, but fusion cannot serve it until the 2030s. That same demand flows to OKLO, SMR, GEV and BWXT in the interim, and a fusion timeline slip is, paradoxically, *bullish* for the fission names because it lengthens the window in which they are the only available answer. The hyperscalers have hedged correctly: they back fusion equity for optionality while signing fission and gas PPAs for the actual electrons. Investors should mimic the hedge, not the headline.

7. Outlook and Strategic Implications

The race has a near-term winner and a long-term unknown. On **net energy**, CFS is the clear front-runner: a demonstrated 20 T magnet, ~$3 billion of capital, SPARC assembling now, and a credible 2027 Q > 1 target [1][4][8][12]. Expect that milestone to reset sentiment across the field when it lands. On **net electric**, the picture is genuinely open — Helion's 2028 Microsoft date is the most aggressive and the most likely to slip, while CFS's ARC (~400 MWe, early 2030s) is the most institutionally backed [4][5][6].

For an operator or investor, three judgments are decision-grade. First, **separate the two milestones**: a 2027 net-energy headline does not mean 2027 electricity, and conflating them is the field's most common analytical error. Second, **capital is concentrating** — CFS holds roughly a third of all fusion funding, and the FIA flags access to capital as the industry's binding constraint [3][4]; a funding-market tightening would thin the field to the magnet leaders. Third, **the cleanest public exposure is one layer removed** — in the fission and power-equipment names that serve the same demand today.

WHAT TO WATCH:
(1) **SPARC first plasma (2026) and Q > 1 (targeted 2027)** [1][8] — the make-or-break magnetic-confinement proof. (2) **Helion Polaris net-electricity result and Orion progress** toward the 2028 Microsoft delivery [5][6] — the only near-term net-*electric* test. (3) **The next FIA annual funding figure** (cumulative was ~$9.8 B mid-2025) [3] — whether capital keeps compounding or stalls. (4) **Any tritium-breeding-blanket or first-wall materials qualification at scale** — the quiet gate that decides whether D-T economics ever close.

Disclosures & Disclaimer

Methodology and Assumptions

This report synthesizes verified public disclosures — company technical releases, peer-reviewed and pre-print literature, national-laboratory results, and the Fusion Industry Association's 2025 Global Fusion Industry Report — into a comparative physics, funding, and economics view. Physics metrics (triple product, Q, field, temperature) and funding/timeline figures are reported with their source and vintage; where a number is the publication's own derivation it is labelled "Star Power estimate" and its inputs are shown in the assumptions tables.

The techno-economic frame is a transparent first-of-a-kind (FOAK) construction, not a forecast: because no fusion power plant operates, the LCOE band ($140–260/MWh) and the cost-stack and sensitivity shares are model outputs built on the stated assumptions (overnight capital $8,000–15,000/kWe; 80% capacity factor; 8% real WACC; 30-year life; 20–40% recirculating-power fraction). They are intended to show *which variables decide the answer* — capital intensity and parasitic load — rather than to predict a price. The scenario table (bull/base/bear) is likewise a our judgment frame.

What would change the conclusion: a SPARC Q > 1 result materially ahead of or behind 2027; a demonstrated tritium-breeding blanket or qualified first-wall material at scale; a credible Helion net-electricity result; or a contraction in fusion funding that thins the field. Independence note: this publication is not affiliated with, and does not represent the views of, any company named herein.

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