Overcoming the Coulomb-Stopping Wall: First-Principles Exergy and Techno-Economic Audit of Terrestrial Helium-3 Production and Hybrid Cryogenic Harvesting

Bruno Luçardo Olivaes

Independent Researcher, Brazil

brunoolivaes@gmail.com · ORCID: 0009-0003-5351-446X

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Abstract

Proposals to obtain helium-3 (^{3}He) on Earth instead of mining lunar regolith frequently overlook either the nuclear Coulomb-stopping barrier of cold accelerator targets or the cryogenic exergy cost of liquefying vast volumes of ^{4}He below the superfluid transition. In this parametric exergy and techno-economic boundary audit, we evaluate all major terrestrial ^{3}He synthesis and separation pathways against the high-technology market benchmark (\$ 2,500/L STP, or \$ 18,579/g) driven by neutron detectors and quantum-computing dilution refrigerators. First, we show that one gram of ^{3}He equals 1.997×10^{23} atoms (7.432 L STP), forcing cold solid-target D–D accelerators (200 keV, yield 10^{-5} per deuteron) to consume 3.55×10^8 kWh/g (\$ 17.77M/g in electricity at \$ 0.05/kWh and 101.4 A continuous beam current for 1 g/yr), whereas recirculating hot-plasma D–D breeders bypass electron stopping to approach 17,773 kWh/g (\$ 889/g). Second, parasitic neutron capture (0.10 excess neutrons/fission) in a 3 GW_{th} reactor produces 1,479.7 g/yr of tritium, yielding 40.86 g of ^{3}He in year 1 from zero initial stock (or 81.0 g/yr from a pre-accumulated 1-year tritium batch), constrained primarily by nuclear non-proliferation licensing rather than physics. Third, evaluating a parametric two-stage quantum separation skid attached to a continuous once-through 1,000 L/day liquid-helium liquefaction stream (2.765×10^8 L STP/yr) reveals that pairing a Stage 1 nitrogen-functionalized nanoporous graphene quantum sieve at 25 K (stage cut $\theta = 0.05$, enrichment $\beta = 20$ in the ideal $\eta_{\text{rec}} = 1.00$ complete-recovery bound) with a Stage 2 multi-walled carbon nanotube (MWCNT) superfluid entropy filter at 1.8 K $< T_\lambda = 2.1768$ K cuts parasitic electrical power by 18.25× relative to full-stream 1.8 K filtration (9.92 kW vs. 181.11 kW). Under this once-through hybrid architecture, marginal electricity demand falls to 233.8 kWh/g (\$ 11.69/g) on mantle-enriched feedstocks ($x_0 = 10^{-5}$, ideal 372.05 g/yr; or 275.0 kWh/g, \$ 13.75/g, and 316.24 g/yr at realistic $\eta_{\text{rec}} = 0.85$ stage recovery) and 15,586 kWh/g (\$ 779/g ideal; \$ 917/g at $\eta_{\text{rec}} = 0.85$) on crustal gas-stream helium ($x_0 = 1.5 \times 10^{-7}$), excluding membrane CapEx and plant amortization.

1 Introduction

While terrestrial ^{3}He is scarce in the atmosphere ($x_0 = 1.38 \times 10^{-6}$ relative to ^{4}He) and crustal natural gas ($x_0 \approx 1.5 \times 10^{-7}$), demand has intensified for border neutron monitors and millikelvin ^{3}He/^{4}He dilution refrigerators cooling superconducting transmon processors [**?**, **?**]. At current commercial pricing near \$ 2,500 per STP liter (\$ 18,579/g), harvesting technologies must be judged by *total exergy and electrical cost per recovered gram* rather than fusion energy breakeven alone. Simultaneously, popular claims advocating simple tabletop proton or deuteron accelerators or uncooled ambient membranes ignore strict physical constraints [**?**]. Here we perform an end-to-end numerical audit uniting geochemical core–mantle outgassing [**?**], quantum tunneling sieves [**?**], and superfluid entropy filtration [**?**].

Table 1: First-principles electricity consumption, beam demand, and cost per gram of ^{3}He across nuclear and cryogenic pathways (assuming \$ 0.05/kWh and benchmark market value \$ 18,579/g).

Route / Operating Regime	Yield or Purity	Energy [kWh/g]	Cost [\$/g]	Output [g/yr]
Cold solid-target D–D (200 keV)	$Y = 10^{-5}$	3.55×10^8	17,772,693	1.0 @ 20.3 MW
Optimistic target D–D (300 keV)	$Y = 5 \times 10^{-5}$	1.07×10^8	5,331,808	1.0 @ 6.08 MW
Recirculating plasma D–D (50 keV)	$Y_{\text{eff}} = 0.05$	17,773	888.63	Scale-dependent
Fission excess-n ^{6}Li$(n,\alpha)^3$H (3 GW$_{\text{th}}$)	0.10 n/fiss.	Byproduct	Reg. cap	40.9–81.0 (yr 1)
Hybrid Cryo (25 K + 1.8 K, Crustal)	$\eta_{\text{rec}} = 0.85$–1.00	15,586–18,336	779.3–916.8	4.74–5.58
Hybrid Cryo (25 K + 1.8 K, Mantle)	$\eta_{\text{rec}} = 0.85$–1.00	233.8–275.0	11.69–13.75	316.2–372.1

2 Nuclear Synthesis: The Coulomb-Stopping Wall vs. Hot Plasma

With molar mass $M_{^3\text{He}} = 3.0160$ g/mol, every gram contains $N = 1.9967 \times 10^{23}$ atoms (7.4316 L STP, $\rho_{\text{STP}} = 0.1346$ g/L). Producing ^{3}He via cold beam–target fusion (D+D $\rightarrow$ ^{3}He+n or p+^{6}Li $\rightarrow$ ^{3}He + ^{4}He) suffers severe electronic stopping loss in dense targets: at 200 keV on TiD_2, only $Y \sim 10^{-5}$ fusions occur per incident deuteron before Coulomb drag thermalizes the beam. At wall-plug efficiency $\eta_{\text{wall}} = 0.50$ and industrial electricity cost \$ 0.05/kWh (Table 1), electricity alone reaches \$ 17.77M/g (957× market price), requiring 101.4 A (20.28 MW) just for 1 g/yr. Bypassing electronic stopping demands either recirculating hot plasmas ($Y_{\text{eff}} \sim 0.05$, dropping electricity to \$ 889/g) or passive thermal-neutron capture (0.10 excess neutrons/fission in a 3 GW$_{\text{th}}$ reactor producing $R_T = 1{,}479.7$ g/yr tritium, half-life $t_{1/2} = 12.32$ yr, $\lambda = 0.05626$ yr^{-1}). Explicitly distinguishing initial inventory boundary conditions, a pre-accumulated 1-year tritium batch (1,479.7 g) yields 81.0 g of ^{3}He over 1 year, whereas continuous uniform tritium production starting from zero initial stock integrates as $M_{^3\text{He}}(T) = \frac{M_3}{M_T} R_T[T - (1 - e^{-\lambda T})/\lambda] = 40.86$ g in year 1 before asymptotically approaching 1,479.7 g/yr at secular equilibrium.

3 Hybrid Two-Stage Quantum Cryogenic Harvesting

Geochemical models place core-to-mantle primordial ^{3}He degassing near 2 kg/yr [**?**], though largely diluted across oceanic ridges. Crucially, terrestrial LNG/helium liquefaction plants and accelerator cryoplants already cool substantial ^{4}He flows without extracting trace ^{3}He. Using a 1,000 L/day liquid-helium cryo-loop baseline (2.765×10^8 L STP/yr; mass flow 1.447 g/s) and modeling a realistic 1.8 K superfluid cryoplant figure of merit (FOM = 0.072 of Carnot), directly subcooling and heat-flushing the full stream through a multi-walled carbon nanotube (MWCNT) entropy filter [**?**] demands 78.71 W at 1.8 K (181.11 kW electrical power).

As an engineered solution, we couple two complementary quantum regimes inside the existing plant cold box:

1. **Stage 1 ($T_1 = 25$ K, Nanoporous N-Graphene Quantum Sieve):** Operating at cryogenic gas temperatures where zero-point and tunneling selectivity between ^{3}He and ^{4}He are maximized [**?**], the stage-cut mass balance enforces $\eta_{\text{rec},1} = \theta\beta \leq 1$, where $\theta = 0.05$ is the enriched slipstream cut and β is the enrichment factor on a continuous *once-through* liquefaction feed stream (fresh geological/LNG feed rather than recirculating a closed cryostat inventory). Taking $\beta = 20$ defines the ideal complete-recovery upper bound ($\eta_{\text{rec},1} = 1.00$), consuming 2.25 kW electric (ambient permeate ΔP recompression plus 15 W cold-box thermal intercept at FOM = 0.15). Under a realistic finite-recovery membrane operating point ($\eta_{\text{rec}} = 0.85$, corresponding to $\beta = 17.0$ and stage selectivity $\alpha_{^3\text{He}/^4\text{He}} > 30$, pending pilot permeance and area sizing), recovered mass scales by 0.85× while marginal electricity per gram scales by $1/0.85 = 1.176$×.

2. **Stage 2 ($T_2 = 1.8$ K $< T_\lambda$, MWCNT Superfluid Entropy Filter):** Passing only the 5% enriched slipstream (0.072 g/s) below the lambda transition allows zero-entropy superfluid

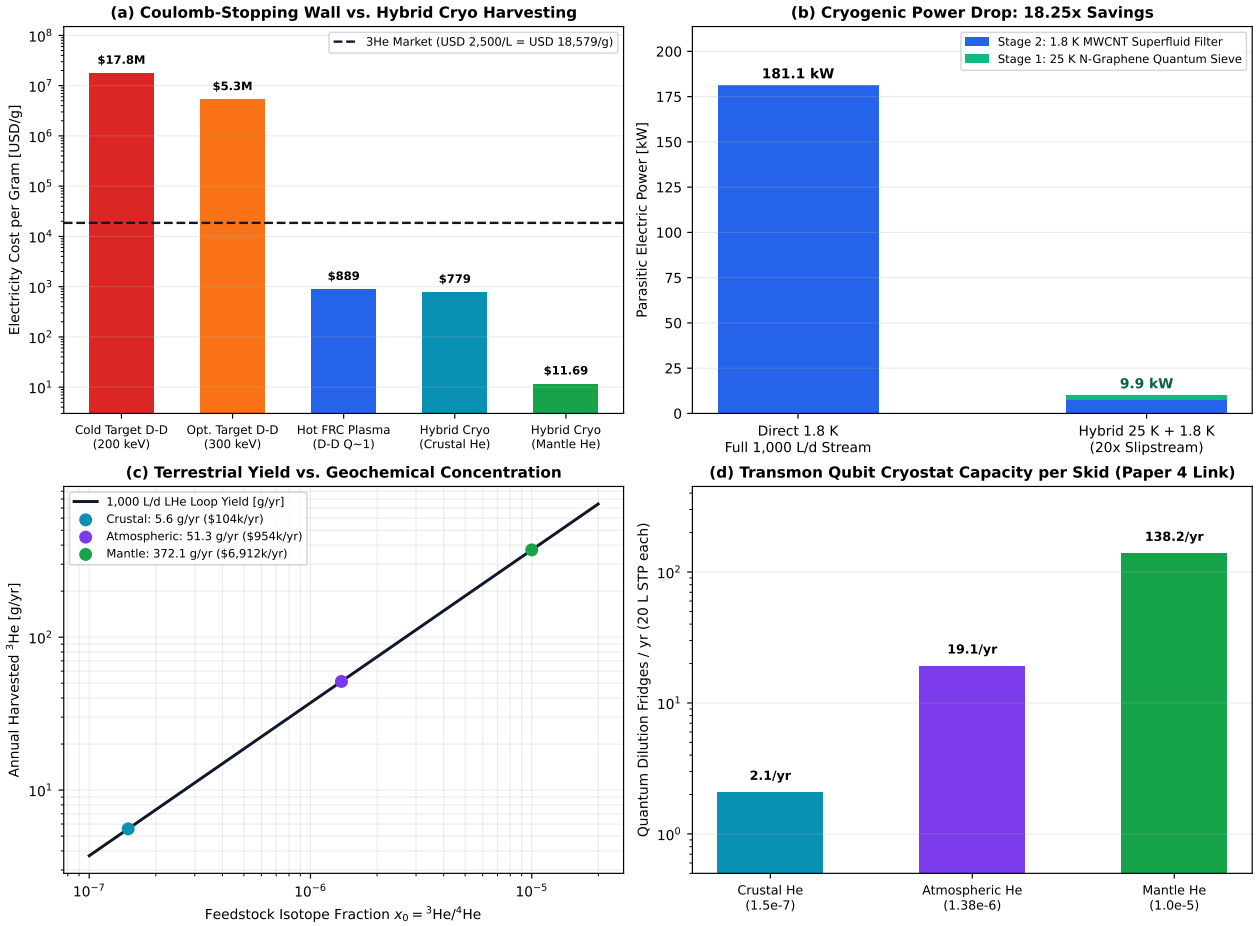

Figure 1: First-principles exergy and supply audit of terrestrial ^{3}He pathways: (a) electricity cost per gram across nuclear synthesis vs. hybrid cryogenic harvesting; (b) parasitic load drop (18.25×) via 25 K graphene pre-concentration ahead of 1.8 K MWCNT superfluid filtration; (c) annual mass yield across geochemical concentrations; (d) quantum-computing dilution refrigerators supplied annually per 1,000 L/day skid.

^{4}He to pass freely through compressed MWCNTs while concentrating normal-fluid ^{3}He [**?**] using just 3.34 W cold (7.68 kW electric).

Total parasitic power plunges from 181.11 kW to 9.92 kW—an 18.25× **exergy reduction** (Fig. 1(b)). While the ideal reversible Gibbs mixing limit ($RT_0(1 - \ln x_0)$) sits near 0.0029–0.0038 kWh/g, marginal process electricity on mantle-enriched helium ($x_0 = 10^{-5}$) is $ 11.69/g ideal (372.05 g/yr, 233.8 kWh/g) or $ 13.75/g at $\eta_{\text{rec}} = 0.85$ (316.24 g/yr, 275.0 kWh/g), and $ 779.29/g ideal (5.58 g/yr) or $ 916.81/g at $\eta_{\text{rec}} = 0.85$ (4.74 g/yr) on crustal helium—noting strictly that these are marginal separation electricity benchmarks excluding membrane CapEx/O&M and cryoplant capital. Benchmarking against a typical 20 L STP (2.69 g) transmon dilution refrigerator charge (closing the hardware supply loop behind quantum error-mitigation platforms [**?**]), a single 1,000 L/day skid supports up to 2.07 (1.76 at 85% recovery) dilution cryostats/yr on crustal helium and 138.25 (117.5 at 85%) cryostats/yr on mantle-enriched helium (Fig. 1(d)).

4 Conclusion

Non-lunar terrestrial ^{3}He harvesting does not require infeasible cold-target accelerators or deep-ocean mantle mining. Coupling cryogenic nanoporous graphene pre-concentration ($T_1 \approx 25$ K) directly ahead of a sub-lambda MWCNT superfluid entropy filter ($T_2 = 1.8$ K) inside existing helium liquefaction streams cuts electrical power by 18.25× to 9.92 kW, yielding electricity-cost margins of

23.8× on crustal helium and 1,589× on mantle-enriched reservoirs while directly supplying quantum-computing cryogenics. Reproducible calculation modules, unit tests, and plotting code are open-source at https://github.com/bruno-olivaes/he3-cryo-extractor.