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Engineering Vacuum-Dependent Quantum Fields for Work Extraction: A No-Go Theorem, Energy-Audit Framework, and a Testable Boundary-Cycle Protocol

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Abstract

The possibility of converting quantum-vacuum phenomena into useful work is often motivated by the enormous formal zero-point energy obtained by summing the ground-state energies of quantum fields. This paper asks a narrower and physically operational question: can time-dependent boundary conditions or engineered couplings change a quantum-field vacuum state in a controlled way so that a closed cycle yields positive net work? We review foundational and modern results on the Casimir effect, dynamical Casimir effect (DCE), quantum passivity and ergotropy, negative energy densities, quantum inequalities, and quantum energy teleportation (QET). We then formulate an explicit Hamiltonian framework in which both the field and the controller are included in the energy accounting. From this framework we prove a vacuum-only no-go statement: for an initial ground state and a cyclic return of the Hamiltonian to its initial form, the net extractable work from the isolated field-plus-controller system is non-positive. This is a direct consequence of ground-state passivity and does not depend on interpreting the divergent absolute zero-point energy as a physical reservoir. We then identify the physically relevant loophole: the protocol must be supplied with a non-equilibrium resource, a change in boundary material state, a thermal/chemical free-energy gradient, measurement/information resources, or a non-cyclic final Hamiltonian. Building on experimentally demonstrated tunable boundary conditions in superconducting microwave circuits, we propose a Vacuum-Dependent Boundary-Cycle (VDBC) architecture. In its minimal implementation, a high-Q resonator with a flux-tunable SQUID boundary is driven between two reflectivity/cavity configurations while its output field is collected and the controller work is measured. The protocol is explicitly designed as an energy-audit experiment: the Casimir/DCE contribution, controller work, material free-energy change, emitted field energy, and dissipation are independently reconstructed. The central experimental hypothesis is not free-energy generation, but whether boundary engineering can increase the fraction of externally supplied control energy converted into a useful output channel beyond conventional parametric conversion limits. We derive the governing equations, scaling laws, falsification criteria, and an efficiency bound. We also show why the result cannot currently be extrapolated to a macroscopic power source or to extraction of the cosmological vacuum energy. The main conclusion is therefore precise: within established quantum field theory and quantum thermodynamics, a cyclic vacuum-only generator is ruled out; however, quantum-vacuum boundary engineering is a legitimate route to experimentally study new energy-conversion architectures, particularly when the true input resource is explicitly identified and optimized.

Keywords: Quantum Vacuum, Vacuum Energy, Zero-Point Energy, Casimir Effect, Dynamical Casimir Effect, Quantum Thermodynamics, Passivity, Ergotropy, Negative Energy, Quantum Energy Teleportation, Superconducting Circuits, Boundary Conditions, Energy Conversion

1. Introduction

The phrase "vacuum energy" hides several physically different quantities. In a free quantum field, the formal ground-state energy is often written as a sum of zero-point contributions, while in bounded systems the change in mode structure produces finite, measurable Casimir energies and forces. The latter are experimentally established and can be engineered through geometry, material response, and time-dependent boundary conditions [1], [2], [3], [4], [5].

The original motivation for the present study is the observation that the formal vacuum-energy density associated with quantum fields is enormous compared with the observed cosmological constant, the well-known cosmological-constant problem [6], [7], [8]. It is tempting to interpret this discrepancy as evidence for an enormous latent energy reservoir. That inference is not justified by quantum field theory: the absolute normalization of the vacuum energy in nongravitational QFT can be shifted by a constant, while Casimir experiments measure boundary-dependent differences. Moreover, a ground state is passive: cyclic unitary control cannot extract net work from it [9], [10].

The question studied here is therefore operational:

Can a controllable change in quantum-field boundary conditions create a closed thermodynamic cycle in which the field returns to its initial vacuum sector while a positive net amount of useful work remains outside the field-plus-controller system?

The answer established in this paper is negative under standard assumptions. However, this no-go result does not make the engineering problem empty. It tells us exactly what must be changed to obtain nontrivial energy conversion: a non-equilibrium resource, a material-state transition, a reservoir, information-assisted control, or a non-cyclic operating mode. Those routes are physically meaningful and experimentally testable.

2. Scope and Literature-Search Method

This paper is a literature synthesis, not a claim that every paper ever published on vacuum energy has been exhaustively enumerated. The search prioritized peer-reviewed articles, major reviews, original experiments, arXiv versions of primary papers when open versions were available, and recent reviews through August 2026. The literature was grouped into six themes: (i) static Casimir theory and experiments, (ii) DCE and time-dependent boundaries, (iii) quantum thermodynamics/passivity/ergotropy, (iv) negative-energy constraints, (v) QET and information-assisted energy extraction, and (vi) proposals for Casimir or vacuum-energy transducers. Recent sources were specifically checked because the DCE and quantum-thermodynamics literature continues to evolve [11], [12], [13].

3. Operational Definition of Work

For a controlled quantum system with Hamiltonian $H(\lambda_t)$, where λ_t is an externally driven parameter, the standard average work performed on the system is

$$W_{\rm on} = \int_0^\tau d\,t\,\mathrm{Tr}\big[\rho_t\,\dot H(\lambda_t)\big]. \tag{1}$$

For an isolated system this equals the change in mean internal energy,

$$\Delta E = E(\tau) - E(0) = W_{\text{on}}, \tag{2}$$

so useful extracted work is

$$W_{\text{out}} = -W_{\text{on}}. \tag{3}$$

This sign convention prevents a common error in vacuum-energy arguments: one cannot count energy emitted by a parametrically driven cavity as output without counting the work delivered by the modulation source.

For a cyclic Hamiltonian, $H(\tau) = H(0) = H_0$, the maximum work obtainable from an initial state ρ is its ergotropy [9], [10], [14]. If ρ is passive, no cyclic unitary can yield positive work. A ground state is passive, and Gibbs states are completely passive.

4. Static Casimir Energy Is a Boundary Difference, Not an Absolute Vacuum Battery

For an idealized massless scalar field in $1 + 1$ dimensions with Dirichlet boundaries separated by a distance a, the renormalized Casimir energy is

$$E_C(a) = -\frac{\pi\hbar c}{24a}, \tag{4}$$

with corresponding force

$$F_C(a) = -\frac{\partial E_C}{\partial a} = -\frac{\pi\hbar c}{24a^2}. \tag{5}$$

For ideal parallel electromagnetic plates of area A,

$$\frac{E_C}{A} = -\frac{\pi^2\hbar c}{720a^3}, \qquad \frac{F_C}{A} = -\frac{\pi^2\hbar c}{240a^4}. \tag{6}$$

These expressions are finite after the physically appropriate subtraction/renormalization and are directly related to measurable forces. The static Casimir effect has been observed in electromechanical experiments, including the torsion-pendulum measurement of Lamoreaux [2]. Theoretical treatments emphasize that measurable quantities are differences associated with the boundaries and material response rather than an operationally extractable absolute zero-point offset [3], [5], [15].

For an ideal electromagnetic cavity at $a = 10\ nm$, Eq. (6) gives approximately

$$|E_C/A| \approx 0.43\ \mathrm{J\,m^{-2}}, \tag{7}$$

which is substantial at nanoscale separation but not remotely comparable to the formal ultraviolet vacuum-energy density obtained from an unrenormalized continuum integral. More importantly, returning the plates to their original state requires work that restores the original configuration. A single attractive stroke is not an engine cycle.

5. Dynamical Casimir Effect: Real Photons from Time-Dependent Boundaries

A time-dependent boundary condition mixes positive and negative frequency modes. In a cavity or superconducting circuit, the evolution can be represented by a Bogoliubov transformation,

$$a_j(\tau) = \sum_k \left(\alpha_{jk} a_k(0) + \beta_{jk} a_k^\dagger(0)\right), \tag{8}$$

with photon production from vacuum governed by the β coefficients,

$$N_j = \sum_k \left|\beta_{jk}\right|^2. \tag{9}$$

The first observation of the DCE in a superconducting circuit used a SQUID to modulate the effective electrical length of a coplanar waveguide at frequencies above 10 GHz, producing real photons and two-mode squeezing [16]. The theoretical circuit architecture was developed in detail by Johansson et al. [17], [18], and reviewed by Nation et al. [19] and Dodonov [11], [20].

A minimal resonant model makes the energy bookkeeping transparent. Let

$$H(t) = \hbar\omega a^\dagger a + \frac{i\hbar g}{2}\left(e^{-2i\omega t}a^{\dagger 2} - e^{2i\omega t}a^2\right), \tag{10}$$

where g is proportional to the modulation depth. Starting from vacuum,

$$|\psi(t)\rangle = S[r]|0\rangle, \qquad r = gt, \tag{11}$$

and

$$\langle N\rangle = \sinh^2(gt), \qquad E_{\text{field}} = \hbar\omega\sinh^2(gt). \tag{12}$$

Equation (12) is often described as "creating photons from vacuum," which is correct operationally. It does not imply free-energy creation. The time-dependent modulation term is an external work source. In a closed energy audit, the energy delivered to the field is paid by the modulation source, plus losses. The DCE therefore demonstrates vacuum amplification, not a vacuum-only power plant.

6. The No-Go Result for Cyclic Vacuum-Only Work Extraction

Let H_0 be the initial Hamiltonian of the field-plus-boundary system and let $|0\rangle$ be its unique ground state, $H_0|0\rangle = E_0|0\rangle$. Let a control parameter λ generate a time-dependent Hamiltonian $H(\lambda_t)$ with

$$H(\lambda_0) = H(\lambda_\tau) = H_0. \tag{13}$$

The system begins in $\rho_0 = |0\rangle\langle 0|$. Under arbitrary unitary evolution U generated by the prescribed control,

$$\rho_\tau = U\rho_0 U^\dagger. \tag{14}$$

The final energy is

$$E_f = \mathrm{Tr}(H_0\rho_\tau) \geq E_0, \tag{15}$$

with equality iff the final state remains in the ground-state subspace. Therefore

$$W_{\text{on}} = E_f - E_0 \geq 0, \qquad W_{\text{out}} \leq 0. \tag{16}$$

This is the ground-state specialization of the passivity theorem of Pusz and Woronowicz [9] and the operational ergotropy framework [10]. It is independent of whether H_0 contains a Casimir contribution, provided the Hamiltonian is bounded below and the control process is genuinely cyclic.

6.0.1. Theorem 1 (vacuum-cycle no-go).

For a quantum field initially in its ground state, a cyclic unitary protocol that returns the full Hamiltonian to its initial form cannot yield positive net work. Any real excitations created by time-dependent boundary conditions increase the final field energy and therefore require nonnegative control work.

This theorem closes the simplest proposed loophole: changing a boundary, extracting energy, then restoring the boundary cannot be repeated indefinitely while retaining positive work, unless an additional resource enters the cycle.

7. What About Negative Energy Densities?

Quantum field theory permits local regions of negative renormalized energy density relative to a chosen reference state. For sampled observables, however, quantum inequalities constrain the magnitude and duration of negative energy [21], [22], [23], [24]. A representative schematic bound is

$$\int_{-\infty}^{\infty} d\,t\, g(t)^2 \,\langle T_{00}(t, \mathbf{x})\rangle \geq -\frac{C}{\tau^4}, \tag{17}$$

where g is a sampling function of characteristic duration τ and C depends on the field and sampling convention. The exact constants are model-dependent; the robust statement is that negative-energy pulses are constrained in magnitude-duration and compensation structure.

The "quantum interest" picture makes this especially important for any cyclic energy-harvesting concept: negative-energy pulses must be compensated by positive energy, with the constraints becoming more severe for temporally separated pulses [24]. Thus a local negative-energy region cannot simply be treated as an inexhaustible negative-heat reservoir.

8. Quantum Energy Teleportation: A Genuine Vacuum-Related Resource Protocol

QET is a particularly relevant adjacent literature because it shows that ground-state entanglement can activate locally inaccessible energy through measurement and conditional control. Hotta introduced protocols in spin chains and quantum fields in which a local measurement changes the energy distribution and a distant conditional operation extracts energy from a remote subsystem [25], [26], [27].
In a schematic bipartite model with Hamiltonian

$$H = H_A + H_B + H_{AB}, \tag{18}$$

a local measurement at A produces a conditional state at B whose local energy can become negative relative to the original ground-state decomposition. A classical message carrying the measurement result permits Bob to choose a unitary that extracts positive work. The total protocol still respects global energy conservation; the measurement and conditional operations are part of the resource accounting.
QET is not merely hypothetical. Experimental demonstrations have been reported using nuclear magnetic resonance and superconducting quantum hardware [28], [29]. Thus the correct lesson is not “vacuum energy is free,” but rather “ground-state correlations can serve as a resource for relocating and activating energy under carefully specified local operations.”

9. Why Earlier Vacuum-Engine Proposals Require Caution

The literature contains explicit proposals for Casimir/vacuum-energy transducers. Pinto proposed an optically controlled vacuum-energy transducer based on semiconducting boundaries whose material response is changed during a cycle [30]. Related work considers thermodynamic cycles with boundary-dependent energies and micro/nanoscale systems [31], [32]. These works are useful because they correctly identify that material response can change the dispersion force and therefore the work associated with a controlled path in parameter space.
However, the existence of a nonzero line integral of a Casimir force along a path in a reduced effective model does not by itself establish net free-energy production. The full thermodynamic cycle must include the work required to change optical properties, carrier densities, polarizability, mechanical constraints, and internal material state. This is precisely why later literature emphasizes first- and second-law consistency in dispersion-force engineering [31], [33].
The appropriate research target is therefore not a perpetuum mobile, but a vacuum-dependent transducer: a device in which the quantum-field contribution materially changes the optimal conversion pathway of an external resource.

10. Proposed Protocol: Vacuum-Dependent Boundary-Cycle (VDBC)

We propose a minimal, falsifiable architecture suitable for superconducting circuit experiments.

10.1. Physical system

Consider a high-Q microwave resonator of bare frequency ω_c, terminated by a SQUID whose effective inductance $L_J(\Phi)$ depends on an applied flux Φ. The boundary parameter is therefore

$$\lambda(t) = \Phi(t), \tag{19}$$

and the field Hamiltonian may be approximated by

$$H_f(\Phi) = \hbar\omega_c(\Phi)a^\dagger a + E_{\mathrm{vac}}(\Phi) + H_{\mathrm{residual}}. \tag{20}$$

The experimentally established tunability of SQUID boundary conditions makes this platform preferable to mechanically moving relativistic mirrors [16], [17], [18].

10.2. Four-stage cycle

The proposed cycle is:

1. **Configuration A:** cool the resonator to its ground state and set $\Phi = \Phi_A$.
2. **Boundary transformation:** change $\Phi_A \to \Phi_B$ with a prescribed waveform designed to maximize the difference between field energy transfer and controller cost.
3. **Harvest:** route generated photons into a matched output channel or a quantum detector and measure the field energy.
4. **Reset:** return $\Phi_B \to \Phi_A$ and restore the same material/field state.

The defining experimental observable is not the emitted power alone but the cycle-level balance

$$W_{\mathrm{net}} = E_{\mathrm{useful}} - (W_{\mathrm{drive}} + W_{\mathrm{reset}} + Q_{\mathrm{diss}} + \Delta F_{\mathrm{material}}). \tag{21}$$

For an ideal vacuum-only cyclic process, the theorem above requires

$$W_{\mathrm{net}} \leq 0. \tag{22}$$

The experiment is valuable precisely because every term can be independently measured or bounded.

10.3. Control waveform and Bogoliubov gain

Near a parametric resonance, let

$$\omega_c(t) = \omega_0[1 + \epsilon\cos(2\omega_0 t + \varphi)], \qquad |\epsilon| \ll 1. \tag{23}$$

The rotating-wave Hamiltonian reduces to Eq. (10), with $g \propto \epsilon\omega_0$. The field gain is then

$$G_f(t) = \frac{E_f(t)}{E_0} \sim \sinh^2(gt), \tag{24}$$

up to mode bandwidth, leakage, and nonideal corrections. The useful-output rate is bounded by the cavity leakage rate κ and the generated photon occupation,

$$P_{\mathrm{out}} \approx \hbar\omega_0\kappa_{\mathrm{out}}\, n(t). \tag{25}$$

10.4. Energy-accounting target

Define the vacuum-assisted conversion factor

$$\eta_{\mathrm{VAC}} = \frac{E_{\mathrm{useful}}}{W_{\mathrm{control}}} \tag{26}$$

and the full cycle efficiency

$$\eta_{\mathrm{cycle}} = \frac{E_{\mathrm{useful}}}{W_{\mathrm{control}} + W_{\mathrm{material}} + Q_{\mathrm{diss}}}. \tag{27}$$

For an ordinary driven DCE experiment, $\eta_{\mathrm{cycle}} < 1$ and no vacuum-only term is expected. The interesting engineering objective is to maximize η_{cycle} while keeping the external control energy fixed, and to determine whether boundary engineering produces a genuine advantage over an equivalent classical parametric device.

11. A Stronger Design: Two-Boundary, Two-State Cycle

A more ambitious protocol uses two switchable boundaries with different reflection spectra. Let the cavity energy be

$$E_{\mathrm{cav}}(a, \mathcal{R}_1, \mathcal{R}_2) = E_{\mathrm{zp}}(a, \mathcal{R}_1, \mathcal{R}_2) + E_{\mathrm{ex}}. \tag{28}$$

Switching between two reflectivity configurations, $A = (\mathcal{R}_1^A, \mathcal{R}_2^A)$ and $B = (\mathcal{R}_1^B, \mathcal{R}_2^B)$, changes the renormalized mode spectrum and hence the boundary contribution

$$\Delta E_C = E_C(B) - E_C(A). \tag{29}$$

If the switching transition itself has a free-energy cost ΔF_{ctrl}, the maximum one-shot output satisfies

$$W_{\text{out}}^{\max} \le -\Delta E_C - \Delta F_{\text{ctrl}} \tag{30}$$

when $\Delta E_C < 0$ is a genuine stored-energy drop in the chosen reduced subsystem. A repeatable cycle requires that the material/control state be restored, contributing an additional positive reset cost. Hence the true cycle condition becomes

$$W_{\text{cycle}} \le -\oint dF_{\text{total}} = 0 \tag{31}$$

for an equilibrium, single-valued thermodynamic state function with no external non-equilibrium resource.

This result suggests a design principle: to get positive net work, the boundary switch must be coupled to a non-equilibrium resource such that the cycle is not a closed loop in the total thermodynamic state space. That resource could be a chemical potential difference, a temperature gradient, a photon bath, a pumped condensate, or information.

12. Information-Assisted Variant

A measurement-powered version combines boundary engineering with feedback. Let a detector measure a field observable M and produce outcome m. The controller applies U_m to maximize the conditional energy decrease,

$$W_{\text{out}} = \sum_m p_m \left[\mathrm{Tr}(H\rho_m) - \mathrm{Tr}\big(HU_m\rho_m U_m^\dagger\big)\right]. \tag{32}$$

The information resource introduces an additional thermodynamic term, bounded in classical settings by a $k_B T I$-type scale and in quantum settings by quantum-information free-energy inequalities. QET is the field-theory analogue showing that entanglement and classical communication can activate locally inaccessible energy [27], [28], [34]. Again, the protocol is not an energy-from-nothing mechanism: the measurement, memory reset, communication, and state preparation are part of the thermodynamic cycle.

13. Quantitative Scaling and Practical Limits

For static parallel plates,

$$|E_C| \propto \frac{A}{a^3}, \qquad |F_C| \propto \frac{A}{a^4}. \tag{33}$$

Reducing a therefore rapidly increases the force and energy density. But the following effects become increasingly important:

1. finite conductivity and skin-depth corrections;
2. patch potentials and electrostatic backgrounds;
3. surface roughness and stiction;
4. dielectric loss and absorption;
5. nonlocal material response;
6. thermal radiation and near-field heat transfer;
7. the work required to switch the boundary conditions;
8. mechanical and electromagnetic dissipation.

Real-material Casimir physics is therefore more accurately described by Lifshitz theory than by ideal perfectly conducting plates. The material dispersion relation and reflection coefficients are part of the thermodynamic device, not external decorations [5], [33].

For the superconducting DCE route, another limitation is that the modulation source must supply the energy associated with the generated squeezed field. The experimentally observed two-mode squeezing provides a clear quantum signature, but it does not change the first-law accounting [16], [19].

14. Falsification Criteria

The proposal is scientifically useful only if it is falsifiable. We therefore define four levels.

14.0.1. F1: DCE reproduction.

Demonstrate the expected vacuum-to-photon Bogoliubov spectrum and squeezing as a function of boundary modulation frequency and amplitude.

14.0.2. F2: Closed-cycle energy audit.

Return all controllable parameters to their initial values and demonstrate experimentally that

$$W_{\text{useful}} \le W_{\text{control}} + W_{\text{reset}} + Q_{\text{diss}}. \tag{34}$$

A violation would signal either a bookkeeping error, an unmodeled resource, or physics beyond the assumed Hamiltonian.

14.0.3. F3: Classical-control comparison.

Replace the quantum vacuum input with a calibrated classical state of equal incident power and compare useful output. A quantum advantage is interesting even if $\eta_{\text{cycle}} < 1$.

14.0.4. F4: State-resolved test.

Measure the initial and final density matrices sufficiently well to test whether the supposed cycle truly starts and ends in the same passive state. Hidden excitation in the controller is an immediate alternative explanation for apparent over-unity conversion.

15. What Would Count as a Genuine Breakthrough?

A reproducible observation of

$$W_{\text{out}} > W_{\text{control}} + W_{\text{material}} + Q_{\text{diss}} \tag{35}$$

with all system components included and the full Hamiltonian restored would contradict the standard passivity result. Such a result would require one of the following to be true:

1. the initial state was not actually passive;
2. the final Hamiltonian was not actually the same;
3. an unaccounted non-equilibrium reservoir supplied free energy;
4. the effective quantum-field description omitted a relevant degree of freedom;
5. the assumed energy observable or coupling was incomplete;
6. or new physics invalidates the standard unitary/thermodynamic framework.

Because each option is highly consequential, a credible experiment would require independent calorimetry, state tomography where feasible, control-source metrology, electromagnetic compatibility tests, and replication using distinct hardware.

16. Implications for the AI-Era Power Problem

If the motivation is to solve the rapidly growing electricity demand created by AI, the present analysis argues against betting on vacuum energy as the primary source. The formal quantum-vacuum energy density is not an established extractable fuel. By contrast, vacuum engineering as a conversion technology could still be useful if it materially improves a real energy-conversion process. Examples include:

1. ultra-low-loss parametric microwave conversion;
2. quantum-enabled refrigeration and heat transfer;
3. energy recovery in superconducting circuits;
4. quantum transduction between electrical, optical, and mechanical modes;

5. control of near-field radiative heat transfer;
6. optimized boundary engineering for nanoscale heat engines.

A more realistic long-term target is therefore a "quantum energy operating layer" in which engineered quantum boundaries improve the efficiency, timing, or controllability of existing generation and storage technologies. The energy source remains identifiable and conventional; quantum vacuum physics modifies the conversion pathway.

17. Discussion

Three conclusions emerge from the literature synthesis. First, vacuum-dependent forces and time-dependent quantum-field effects are experimentally real. The Casimir force and DCE have been measured, and tunable superconducting boundaries permit unusually fast control [2], [16]. Second, the absolute formal zero-point energy is not operationally equivalent to a fuel reservoir. Observable effects arise primarily from differences between physical configurations, and the vacuum is passive in the thermodynamic sense [9], [10]. Third, quantum information and correlations can unlock locally inaccessible energy, as QET demonstrates, but the complete protocol still satisfies energy conservation and thermodynamic consistency [27], [28], [29].

The resulting picture is sharper than either extreme claim. It is wrong to say "the quantum vacuum does nothing." The vacuum has measurable, engineerable consequences. It is also wrong to say "the vacuum is an unlimited free-energy reservoir." Standard quantum mechanics and quantum field theory do not provide such a mechanism.

The VDBC architecture proposed here turns the question into an experimentally tractable comparison: can quantum-boundary engineering yield a measurable conversion advantage over an equivalent classical control system, after the complete control and reset energetics are included? That is a meaningful scientific and potentially commercial question.

18. Conclusion

We studied whether engineering quantum-field boundary conditions can turn vacuum-state changes into usable net work. The central mathematical result is a no-go theorem for a ground-state, cyclic, unitary protocol: when the final Hamiltonian equals the initial Hamiltonian, the final field energy cannot be below the ground-state energy, so positive net work cannot be extracted from the vacuum alone. Dynamical Casimir radiation, Casimir forces, negative-energy densities, and QET do not evade this statement; they redistribute or activate energy under additional control, correlation, measurement, material, or reservoir resources.

The physically defensible path forward is therefore not a claim of perpetual vacuum power. It is to engineer a vacuum-dependent transducer whose true input resource is explicit and whose quantum contribution is quantitatively measurable. The proposed VDBC experiment provides a concrete route: a high-Q superconducting cavity with a flux-tunable boundary, a full cycle-level energy audit, a classical-control baseline, and state-resolved falsification criteria. A positive result would be valuable even without free-energy production if it demonstrated a new quantum advantage in conversion efficiency, cooling, or transduction.

If future experiments were instead to establish a positive net cycle after every known degree of freedom and energy source were independently accounted for, the result would be extraordinarily significant and would demand a revision of current quantum thermodynamics or quantum-field-theoretic assumptions.

Until then, literature supports vacuum engineering as a promising field of quantum control, not as an established source of net macroscopic energy.

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