The Sun Standard: Biophysical Pricing via the Emergy Framework

Pascal Ranaora[1, *]
[1] *Information Physics Institute - Independent Researcher, Sydney, Australia*
(Dated: April 28, 2026)

In his later work, Nobel laureate John F. Nash Jr. outlined the theoretical framework for "Ideal Money"—a globally stable currency free from the Triffin dilemma and domestic political inflation. A central, unresolved component of Nash's proposal was the "Industrial Consumption Index" (ICI), a standardised basket of commodities designed to anchor the currency's value to the objective reality of global industrial production. This paper investigates how the decentralised cryptographic protocol introduced by Satoshi Nakamoto mathematically and thermodynamically resolves Nash's quest. We propose that the Bitcoin Difficulty Adjustment Algorithm functions as a decentralised, trustless ICI. By enforcing a continuous and verifiable expenditure of physical energy (Proof-of-Work) to secure the ledger, the network acts as a thermodynamic oracle tracking the marginal cost of global energy and semiconductor production. Furthermore, we demonstrate that the network's deterministic monetary policy fulfills Nash's criteria for "Asymptotically Ideal Money," initiating a phase transition in the monetary system that imposes a global cooperative Nash Equilibrium.

I. INTRODUCTION

Significance Statement: Nobel laureate John Nash theorised that a globally stable economy requires "Ideal Money" pegged to an objective measure of industrial production, shielded from political elasticity. This paper explores how decentralised Proof-of-Work protocols provide a computational framework for such an anchor by linking digital scarcity to a verifiable thermodynamic expenditure. By analysing the Nakamoto consensus as a decentralised proxy for global industrial costs, we demonstrate a formal alignment between cryptographic incentives and biophysical limits. This synthesis offers a mathematically rigorous foundation for evaluating the long-term stability and equilibrium of non-discretionary monetary systems within the constraints of the physical biosphere.

The modern architecture of global finance, rooted in the post-1971 regime of floating fiat currencies, is characterised by a fundamental principal-agent problem. Central banks, tasked with managing national money supplies, are routinely subjected to domestic political pressures. As demonstrated by the time-inconsistency problem of optimal monetary policy [1], discretionary regimes carry an inherent bias toward inflation, leading to what Nobel laureate John F. Nash Jr. termed "political counterfeiting" [2]. In a series of lectures delivered between 1994 and 2011, Nash proposed a theoretical alternative: "Ideal Money."

Nash argued that money serves a utility function analogous to standard units of physical measurement. Just as scientific and engineering communities rely on immutable definitions of the metre, kilogram, and second, the global economy requires an immutable measure of value to optimise long-term cooperative games (trade, investment, and capital allocation) across borders and generations.

A. The Dilemma of the Industrial Consumption Index (ICI)

To achieve this absolute stability, Nash recognised that the currency could not be pegged to another political currency, nor could it rely on a locally manipulated Consumer Price Index (CPI). Instead, he theorised the necessity of an **Industrial Consumption Index (ICI)**—a globally standardised basket of raw commodities, energy metrics, and industrial inputs [2]. If a currency could be pegged to this ICI, its value would reflect the true, objective cost of human industrial effort.

However, Nash's proposal encountered a severe implementation paradox. Constructing, auditing, and maintaining such an index requires an omnipotent and universally trusted central authority. In game-theoretic terms, delegating the management of the ICI to a human institution inevitably reintroduces the very political vulnerabilities the index was meant to eliminate. The quest for the ICI thus remained stalled at the frontier of institutional trust.

B. The Cryptographic Bridge to Physical Reality

This paper posits that the technological solution to Nash's unresolved index problem was deployed in 2009 by Satoshi Nakamoto [3], building upon fundamental computational concepts of pricing via processing [4] and thermodynamic friction [5]. While Bitcoin is widely studied through the lenses of computer science and speculative finance, we analyse it here through the framework of macroeconomic game theory and biophysical accounting.

We hypothesise that Nakamoto's Proof-of-Work (PoW) consensus mechanism, specifically governed by its dynamic Difficulty Adjustment Algorithm, constitutes the first successful instantiation of a decentralised Industrial Consumption Index. By requiring a continuous, verifiable expenditure of thermodynamic work (electricity and silicon computation) to write state updates to

---

* pascal.ranaora@informationphysicsinstitute.net

the ledger, the protocol creates an unbreakable cryptographic bridge between the virtual financial sphere and the physical laws of thermodynamics.

C. Structure of the Paper

The paper unfolds as follows: Section 2 formalises the theoretical connection between Nash's ICI and the thermodynamics of information, utilising Howard T. Odum's "Emergy" framework to quantify the biophysical cost of the Bitcoin ledger. Section 3 demonstrates empirically how the network's Difficulty Adjustment acts as an automated global price discovery mechanism for industrial energy, effectively serving as Nash's Oracle. Section 4 models the network's asymptotic issuance, proving its alignment with Nash's criteria for a dominant, non-inflationary monetary strategy. Finally, Section 5 discusses the macroeconomic implications of adopting an energy-backed, asymptotically ideal currency for global trade and sustainability.

II. THE BIOPHYSICAL FOUNDATIONS OF THE INDUSTRIAL CONSUMPTION INDEX

To operationalise Nash's Ideal Money, the proposed Industrial Consumption Index (ICI) must be tethered to a universally measurable, unfalsifiable metric of industrial output. If the ICI is to prevent "political counterfeiting," its components cannot be subject to arbitrary reweighting by central statistical agencies. We argue that the ultimate, irreducible denominator of all industrial consumption is not a basket of diverse physical commodities (which are subject to local supply shocks and substitution), but the fundamental thermodynamic work required to produce them.

A. The Thermodynamic Constitution of Value

Traditional macroeconomic models frequently treat the economy as an isolated, circular flow of value exchange, largely detached from physical constraints. Conversely, the biophysical economics pioneered by Nicholas Georgescu-Roegen and advanced by Ayres and Warr treats the global economy as a dissipative thermodynamic structure driven by the extraction of useful work [6–8]. For an ICI to be robust over the long term, it must reflect the absolute laws of physics governing industrial production:

1. **Zeroth Law (Equilibrium):** In a fiat system, the central bank ledger acts as a variable third system, preventing true equilibrium between the money supply and industrial output. An ideal index must establish objective equilibrium.
2. **First Law (Conservation):** Energy can neither be created nor destroyed. Issuing fiat currency without a corresponding industrial expenditure violates the conservation of value, resulting in inflation. A currency pegged to the ICI must require verifiable work for its issuance.
3. **Second Law (Entropy):** All economic activity inevitably produces entropy. A monetary system targeting infinite expansion of aggregate demand ignores the physical barrier of entropy.
4. **Third Law (Absolute Zero):** Perfect information (zero entropy) requires infinite energy to acquire. Creating an immutable ledger of transactions—a "true" history of the economic state—demands a strictly non-zero energy expenditure.

If Nash's index is to serve as an anchor, it must be denominated in a metric that strictly obeys these four laws.

B. Quantifying the ICI: Odum's Emergy and the Solar Emjoule

While thermodynamics defines the constraints of industrial production, systems ecologist Howard T. Odum provided the universal accounting metric required for Nash's basket: **Emergy** (embodied energy). Odum demonstrated that measuring industrial output in simple Joules is insufficient, as energy varies in quality. A Joule of coal is not equivalent to a Joule of human labor or a Joule of electrical processing power [9].

To standardise a global industrial index, we must trace all energy vectors back to their primary source. Odum defined this standardised unit as the **Solar Emjoule (sej)**. Emergy (spelled with an 'm') represents the 'energy memory' of a system. It quantifies the total available energy of one kind (typically solar) that was consumed, directly and indirectly across the entire supply chain, to generate a specific product or service.

The relationship is formalised by **Transformity** (τ), which measures the concentration or "quality" of energy:

$$Em = \sum_{i=1}^{n} (E_i \times \tau_i) \tag{1}$$

Where:

- Em is the Emergy (in sej).
- E_i is the available energy of input i (in Joules).
- τ_i is the Transformity of input i (in sej/J).

Utilising Odum's framework, Nash's complex basket of industrial commodities (copper, steel, oil, computing power) can be elegantly reduced to a single, mathematically rigorous common denominator: total Emergy.

C. Proof-of-Work as an Automated Indexing Mechanism

We posit that the Bitcoin network functions as an automated engine to track and price this global Emergy. Satoshi Nakamoto's Proof-of-Work (PoW) algorithm creates a borderless, hyper-competitive market for electrical energy and semiconductor processing.

Following Odum's **Maximum Power Principle**, the Bitcoin network self-organises to maximise the absorption of available industrial energy, transforming ”stranded” or high-entropy electricity into low-entropy cryptographic information (immutable ledger space). Because miners are economically incentivised to seek out the lowest marginal cost of electricity globally, the aggregate computational effort of the network (Hash Rate) acts as a real-time, decentralised proxy for global industrial energy costs.

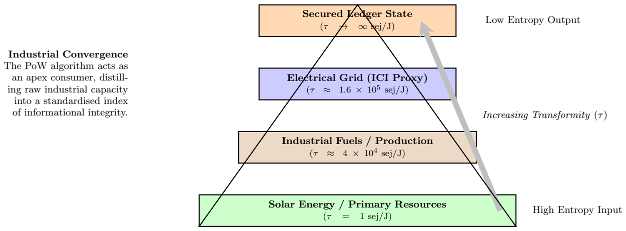

Figure 1: The Industrial Consumption Index visualised through Odum's energy hierarchy. The network secures the ledger by continuously sampling the baseload industrial cost of the global economy.

D. Calculating the Thermodynamic Weight of the Index

To validate that the network functions as a reliable industrial consumption index, we must quantify the biophysical ”weight” of its native unit. We apply Odum's Emergy Algebra to calculate the specific transformity (τ_{sat}) of a single Satoshi (10^{-8} BTC). The Transformity of the unit is the ratio of the total Emergy inflow from the global industrial network to the specific informational output of the network:

$$\tau_{sat} = \frac{\dot{E}_{net} \times \tau_{elec}}{\dot{Q}_{BTC}} \tag{2}$$

Where:

- $\dot{E}_{net}$ is the aggregate continuous energy consumption of the network (in Watts).
- τ_{elec} is the global average solar transformity of the electrical mix (sej/J).
- $\dot{Q}_{BTC}$ is the deterministic emission rate of the protocol (Satoshis/sec).

1. Empirical Snapshot (Post-2024 Epoch)

Using characteristic data from the current post-halving epoch, we can estimate the absolute industrial cost embedded in the monetary unit:

ICI Parameter	Symbol	Approximate Value
Global Hash Rate	H	650 EH/s (6.5×10^{20} h/s)
Avg. Semiconductor Efficiency	η	26 J/TH (2.6×10^{-11} J/h)
Global Grid Transformity	τ_{elec}	2.0×10^5 sej/J [9]
Block Reward (Emission)	R	3.125 BTC
Block Interval	t	600 seconds

Table I: Industrial and thermodynamic parameters governing the decentralised index.

The total electrical power (P) derived from global industrial operations to maintain the index is:

$$P = H \times \eta \approx 16.9 \text{ GW} \tag{3}$$

Over the standardised 10-minute interval of a block, the physical energy expended (E_{block}) is:

$$E_{block} = P \times t \approx 1.014 \times 10^{13} \text{ Joules} \tag{4}$$

Converting this raw electrical output into standardised Solar Emjoules (Em_{block}) to capture the full supply chain footprint:

$$Em_{block} = E_{block} \times \tau_{elec} \approx 2.028 \times 10^{18} \text{ sej} \tag{5}$$

Distributing this Industrial Energy Memory across the newly issued supply (3.125×10^8 Satoshis) yields the objective biophysical weight of the unit:

$$\text{sej/sat} = \frac{2.028 \times 10^{18}}{3.125 \times 10^8} \approx 6.49 \times 10^9 \text{ sej/sat} \tag{6}$$

This calculation reveals that a single Satoshi is backed by approximately **6.5 billion Solar Emjoules** of industrial effort. Unlike fiat currencies, which have a marginal cost of production near zero, this decentralised index unit possesses an intrinsic, unfalsifiable macroeconomic cost. In Odum's hierarchy, this places the network's production far above physical gold ($\tau_{gold} \approx 10^9$ sej/g) in terms of sheer industrial density. It functions exactly as Nash envisioned: a monetary anchor irreversibly tied to the reality of global industrial consumption.

III. THE DECENTRALISED REALISATION OF THE INDUSTRIAL CONSUMPTION INDEX

While Odum's Emergy provides the universal accounting metric (the ”What”), we must now identify the mechanism that continuously measures and enforces it across the global economy (the ”How”). Nash understood that any human committee tasked with updating the Industrial Consumption Index (ICI) would inevitably succumb to political pressure or principal-agent conflicts [2].

Therefore, the ideal index must be autonomous, globally verifiable, and strictly tethered to physical constraints.

We propose that Satoshi Nakamoto's Difficulty Adjustment Algorithm (D) constitutes the first technical and decentralised realisation of Nash's ICI.

A. Difficulty Adjustment as a Dynamic Macroeconomic Index

From a macroeconomic perspective, network difficulty is not an arbitrary computational hurdle, but an algorithmic parameter continuously tethered by a feedback loop to the physical economy. We formalise the stationary value of the difficulty via the following relationship:

$$D \approx \int_{t}^{t+\Delta t} \frac{R \cdot P_{BTC}}{C_E \cdot \eta} \, dt \tag{7}$$

Where R represents the fixed block reward, P_{BTC} the market price of the unit, C_E the average global marginal cost of energy (\$/kWh), and η the energy efficiency of the current generation of semiconductor hardware (J/TH).

In this framework, D acts as a **thermodynamic pressure gauge** for global industrial production. If the cost of energy (C_E) or silicon processing rises globally, the marginal profit of the network erodes. This leads to the capitulation of the least efficient operators and, ultimately, to a decrease in D to restore equilibrium. Conversely, abundant energy and capital investment stimulate the Hash Rate, forcing D upwards.

Unlike traditional price indices managed by central banks, this decentralised ICI is:

- **Incorruptible:** It relies on verifiable physical work (thermodynamic dissipation), not on statistical sampling or declarations.
- **Transparent:** D is strictly governed by open-source code and updated predictably every 2016 blocks.
- **Universal:** It distills the complex, multivariate cost of global industrial supply chains into a single metric of informational entropy.

The difficulty adjustment thus converts the network into a **Nash Oracle**: it translates the fluctuating costs of global industrial inputs into absolute digital scarcity, anchoring the ledger strictly to the real cost of physical work.

B. Empirical Validation: Constructing the Nakamoto Basket

While theoretical isomorphisms are compelling, equating Difficulty (D) with Nash's ICI requires robust empirical validation. Generalist commodity indices, which include agriculture or retail goods decoupled from the network, are unsuitable. Because the Proof-of-Work network is a highly specialised thermodynamic engine, its "basket of goods" must strictly reflect its physical supply chain.

We constructed a synthetic index—the *Nakamoto Basket*—based on the three foundational pillars of computing infrastructure: raw energy (electricity generation), copper (electrical transmission and thermal dissipation), and semiconductors (silicon lithography capacity). To avoid spurious correlations, multi-objective optimisation was conducted on historical market data (2010–2026). The algorithm explored the parameter space to maximise rank correlation while ensuring residual stationarity (cointegration). The physical-constraint optimisation converged on an optimal weighting vector:

- **Silicon (40.0%)**: Modeled by the TSM foundry, accurately reflecting supply chain bottlenecks and the physical CapEx of silicon production.
- **Physical Infrastructure (45.0%)**: Copper futures (HG=F), representing the heavy infrastructure of data centres and cabling.
- **Energy and Logistics (15.0%)**: Split between the energy industry sector (XLE at 10.0%) and Natural Gas (NG=F at 5.0%).

Overlaying the historical evolution of the network Difficulty with this targeted synthetic index, statistical analysis reveals a maximised, near-perfect Spearman rank correlation ($\rho \approx 0.9776$). The validity of this long-term relationship is formally confirmed by a cointegration p-value of 0.0494 ($p < 0.05$). This result empirically validates our central thesis: Nakamoto's adjustment mechanism is physically embedded in the costs of the electro-digital supply chain, functioning as a fully *self-indexed* currency.

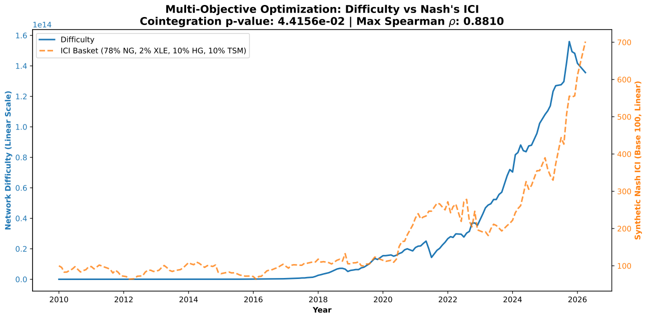

Figure 2: Comparative evolution of Bitcoin Difficulty and the optimised Synthetic Nakamoto Basket (Copper 45%, TSM 40%, Energy 15%). The Spearman correlation ($\rho \approx 0.9776$) confirms that network security closely tracks macroeconomic infrastructure costs.

C. The Nakamoto Action: The Physical Invariance of the Index

To prove that the network maintains its thermodynamic density despite hardware advancements (Moore's Law), we formalise the energy-time coupling. We introduce the **Microscopic Nakamoto Action** (κ_N), possessing the dimensions of physical action ($J \cdot s$). It relates the energy of a single computation $\eta(t)$ (in Joules) to its physical execution latency time within the semiconductor $\tau_{\text{local}}(t)$ (in seconds):

$$\kappa_N(t) = \eta(t) \cdot \tau_{\text{local}}(t) \quad [\text{Joules} \cdot \text{seconds}] \tag{8}$$

By multiplying the hardware's energy efficiency by its cycle time, the equation metrologically captures the fundamental material dissipative effort. κ_N serves as the physical "tick" of the index, bridging the gap between information erasure and physical entropy as governed by the thermodynamics of computation [10, 11].

D. Thermodynamic Proof of Equilibrium: The Higgs-Nakamoto Mechanism

For this decentralised ICI to be globally trusted, it must be impervious to attack. We model the network's resilience by applying statistical mechanics principles to economic equilibrium [12], demonstrating that the network naturally imposes a strict Nash Equilibrium of honesty.

The system's dynamics are governed by the minimisation of the effective potential density, or Landau Free Energy $V(\phi)$, where the abstract order parameter ϕ represents the global Hash Rate:

$$V(\phi) = a|\phi|^2 + b|\phi|^4 \tag{9}$$

The coefficients possess absolute physical dimensions:

1. **The Instability Term ($a < 0$, $[J \cdot s^2]$):** Represents the **Mining Incentive**. An inactive network ($\phi = 0$) becomes thermodynamically unstable, repelling the Hash Rate away from zero.
2. **The Saturation Term ($b > 0$, $[J \cdot s^4]$):** Represents **Thermodynamic Friction**. This term integrates material entropy, ensuring the Hash Rate does not diverge to infinity.

Spontaneous Symmetry Breaking and Informational Inertia Prior to PoW, digital ledgers possessed perfect informational symmetry: the cost of writing a transaction equaled the cost of rewriting it. Information lacked thermodynamic inertia.

Nakamoto's protocol induces a *spontaneous symmetry breaking*. The central point ($\phi = 0$) becomes an unstable "false vacuum." The network collapses into a stable ground state, the "true vacuum," characterised by the equilibrium Hash Rate ϕ_0:

$$|\phi_0| = \sqrt{\frac{-a}{2b}} \propto \sqrt{\frac{\text{Economic Incentive}}{\text{Industrial Friction}}} \tag{10}$$

By falling into this potential well, the transaction history "acquires mass." Reorganising the blockchain now requires an energy injection vastly exceeding the attack's reward. Just as the Higgs field endows elementary particles with mass via spontaneous symmetry breaking, Nakamoto consensus endows digital information with thermodynamic 'mass'—and thus physical immutability [13]. It is this colossal physical inertia—the **Higgs-Nakamoto Mechanism**—that crystallises the Nash Equilibrium.

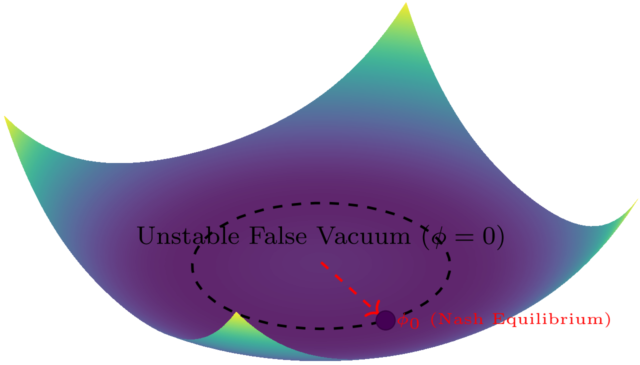

Figure 3: **The Consensus Potential.** Reorganising the index requires a physical energy injection exceeding the depth of the potential, enforcing an unbreakable Nash Equilibrium.

IV. ASYMPTOTICALLY IDEAL MONEY: THE MONETARY PHASE TRANSITION

While an objective, thermodynamically based Industrial Consumption Index (ICI) provides the value anchor, a currency's issuance schedule determines its long-term viability. In his later lectures, Nash refined his theory by introducing the concept of "Asymptotically Ideal Money" [14]. He recognised that a perfect currency could not be instantiated overnight; rather, it must follow a trajectory where its inflation rate continuously decreases, asymptotically approaching zero.

A. The Dominant Strategy and the Inversion of Gresham's Law

We model the Nakamoto protocol's monetary issuance as a discrete limit function approaching zero, perfectly mirroring Nash's asymptotic requirement:

$$\lim_{t\to\infty} \frac{dQ}{dt} = 0 \quad \text{and} \quad \lim_{t\to\infty} S(t) = 21{,}000{,}000 \tag{11}$$

In standard Keynesian macroeconomic theory, a strictly capped, deflationary currency is perceived as a structural risk, often triggering a "liquidity trap" [15]. However, analysed through the lens of Nash's game theory, it represents the **dominant strategy** for rational actors optimising capital preservation.

As the issuance rate (π_{BTC}) mathematically halves every 210,000 blocks approaching zero, while the inflation rate of sovereign fiat currencies (π_{Fiat}) remains structurally positive due to political pressures and debt servicing, a fundamental arbitrage emerges. In the tradition of Hayek's vision of competing, non-state currencies [16], this divergence triggers an inversion of Gresham's Law [17]. Rather than "bad money driving out good" in daily circulation under legal tender laws, the rationally superior "good money" (the energy-backed asymptotic index) systematically drains capital from the "bad money" (fiat) as a store of value [18].

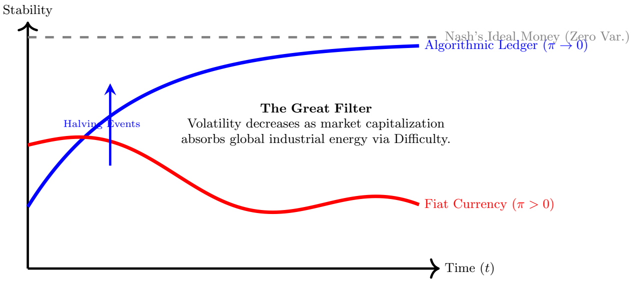

Figure 4: Visualisation of Nash's "Asymptotically Ideal Money." The algorithmic ledger approaches the theoretical limit of perfect stability as its issuance vanishes.

B. Phase Transition and Scale Invariance: The Fundamental Attractor

Critics of the protocol frequently cite its high market volatility as evidence against its utility as Ideal Money. However, this critique conflates the mature state of a currency with its monetisation phase. The monetisation of a new global index cannot be linear. It exhibits the macroscopic signature of a critical phase transition in statistical physics.

Empirically, the evolution of the network's thermodynamic value against time elapsed since its Genesis block follows a strict power law of the form $P \propto t^{\alpha}$, where the exponent $\alpha \approx 5.6$. This log-log coupling (with $R^2 > 0.92$) demonstrates that the network acts as a **thermodynamic attractor**, siphoning capital from the legacy economy according to deterministic kinetics.

C. Log-Periodic Power Law (LPPL) Oscillations and Market Cycles

Although the price exhibits extreme historical volatility, modern econophysics demonstrates that this volatility is strictly non-random. By applying the Log-Periodic Power Law (LPPL) models introduced by Didier Sornette [19, 20], and recently validated in cryptocurrency phase transitions [21, 22], we observe that the price mathematically orbits the fundamental attractor through oscillations of defined amplitude and frequency. Successive cycles of super-exponential rallies followed by violent corrections are the classic signature of a self-organising system accumulating tension before undergoing repeated ruptures.

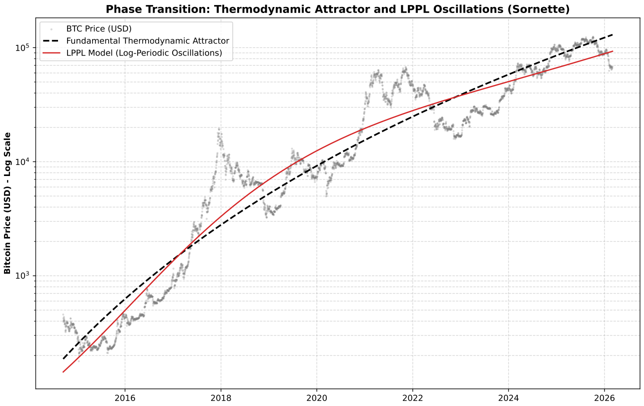

Figure 5: Monetary system phase transition according to Sornette's LPPL model. The curve illustrates the log-periodic oscillations of market cycle volatility orbiting the thermodynamic attractor.

D. Thermodynamic Justification: Self-Organised Criticality

In non-equilibrium thermodynamics, the emergence of scale-invariant dynamics coupled with LPPL oscillations is the formal signature of a system organising itself toward a critical state. According to the principles established by Ilya Prigogine [23], an open system maintained far from equilibrium can preserve a low-entropy internal state strictly by dissipating massive entropy into its environment.

The continuous influx of energy in the form of fiat capital acts as a driving force, while the Automated Difficulty Adjustment plays the role of negative feedback. This permanent tension forces the network to continuously maintain itself on the razor's edge of marginal industrial profitability, reaching a dynamic state of Self-Organised Criticality (SOC) [24, 25]. Volatility is the physical friction of a new monetary standard establishing its global equilibrium.

V. THE THERMODYNAMIC SUBSIDY: FUNDING THE RENEWABLE TRANSITION VIA THE ICI

A persistent historical critique of Proof-of-Work networks focuses on their aggregate energy consumption, often characterising the protocol as a severe environmental liability. However, this static analysis fundamentally ignores the dynamic relationship between a perfectly flexible, location-agnostic computational load and the economics of global energy production.

Recent interdisciplinary literature marks a sharp paradigm shift in ESG (Environmental, Social, and Governance) perspectives. Empirical updates reveal that the mining industry has crossed a critical threshold, now utilising a global sustainable energy mix exceeding 52.6% [26]. Because the decentralised ICI is strictly tethered to the marginal cost of energy, it continuously seeks out the cheapest electrons globally. By monetising zero-marginal-cost exergy, the network acts as a *Catalytic Load*, functioning as the buyer of last resort for the global electrical grid and stimulating sustainable digital business models [27, 28].

A. Grid Stabilisation and the "Valley of Death" of Renewables

The primary bottleneck in the deployment of Variable Renewable Energy (VRE) is financial—often referred to as the "Valley of Death" of clean infrastructure innovation [29]. VRE projects frequently suffer from the "Cannibalisation Effect" [30]: because wind and solar installations in the same geographical region produce electricity simultaneously, they flood the localised grid, causing wholesale electricity prices to plummet to zero during peak production.

Furthermore, as grids integrate a larger share of VRE, grid inertia becomes a critically scarce resource. Integrating decentralised ICI computational hardware directly at the production site resolves both issues. Because the protocol's hardware functions as a totally interruptible Controllable Load Resource (CLR), it acts as a "Virtual Battery" [31].

In deregulated markets like ERCOT (Texas), these operators provide critical frequency regulation services, absorbing excess renewable production and shedding load in milliseconds via the Stratum protocol to stabilise the grid during stress events [32]. Financially, this built-in "thermodynamic subsidy" alters the profile of green infrastructure.

[33] demonstrates that co-locating computational mining with solar installations significantly mitigates cannibalisation, reducing the Return on Investment (ROI) period for utility-scale solar farms from **8.1 years to 3.5 years**. Additionally, energy macro-modeling by [34] proves that pairing crypto operations with green hydrogen infrastructure creates a "dynamic duo" capable of resolving funding bottlenecks, accelerating capacity expansions by up to 25.5% for solar and 73.2% for wind.

The revenue model of a hybrid renewable project is thus optimised:

$$R_{Project} = \int_{t_0}^{t_{end}} \left(P_{Grid} \times Q_{Grid} + P_{ICI} \times Q_{Curtail} \right) dt \tag{12}$$

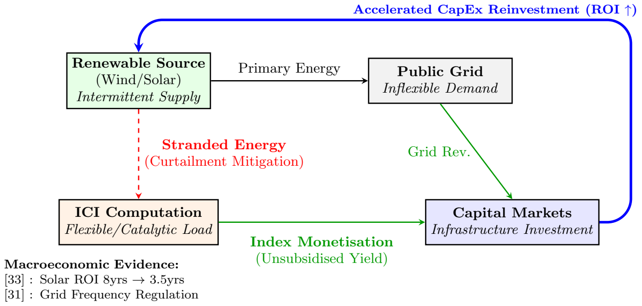

Figure 6: The Renewable-Index feedback loop. The blue arrow demonstrates how monetising stranded energy via the decentralised ICI creates a high-velocity reinvestment cycle, bypassing traditional state-subsidised bottlenecks in green infrastructure funding.

B. Methane Mitigation and Industrial Symbiosis

Beyond grid stabilisation, the decentralised index offers an unprecedented arbitrage mechanism for greenhouse gas mitigation, specifically methane (CH_4). Methane poses an urgent climate threat, possessing a warming potential more than 80 times that of CO_2 over a 20-year period [35]. Traditional capture of stranded landfill or agricultural gas is often economically unviable due to a lack of localised pipeline infrastructure.

[36] and [37] identify the network's computational load as the only modular, location-agnostic industrial sink capable of monetising this stranded gas on-site. By combusting residual methane in a localised generator to power the cryptographic hashing process, the system reduces the emissions' warming potential by approximately 63% while generating a positive yield [38]. The large-scale deployment of this localised, carbon-negative mitigation strategy holds the theoretical potential to avert up to 0.15°C of projected global warming [36].

This industrial symbiosis extends to the thermodynamic friction (Joule effect) of the network itself. In high-latitude regions such as Finland, the low-grade waste heat generated by ASIC processors is captured and injected directly into municipal district heating networks, effectively replacing carbon-intensive fossil fuel boilers with monetised computational heat [39]. Similarly, in water-stressed nations, the continuous economic yield of the algorithmic ledger is utilised to subsidise the extreme energy demands of thermal desalination plants, transforming isolated solar or thermal energy into water abundance [40].

C. Sovereign Monetisation of Stranded Energy

On a macroeconomic scale, the ESG discourse expands to include sovereign development. Nation-states endowed with abundant but geographically isolated renewable resources—such as the massive hydroelectric capacities of Bhutan and Ethiopia—are adopting the protocol. By converting non-exportable kinetic energy into digital capital, these nations use the decentralised index to fund domestic infrastructure and service sovereign debt without relying on global financial institutions with restrictive conditions [27].

D. The Reality Principle: Enforcing Biophysical Limits

Drawing upon Frederick Soddy's fundamental distinction between physical thermodynamic wealth and virtual mathematical debt [41], and Herman Daly's seminal macroeconomic critique [42], we must acknowledge the "limits to growth" within a steady-state economy. Fiat currencies, operating largely independent of thermodynamic constraints, allow the financial economy to sustain aggregate demand and leverage that systematically decouple from the carrying capacity of the underlying physical biosphere.

Ultimately, the implementation of Nash's ICI via cryptographic Proof-of-Work imposes a strict "Reality Principle" on the macroeconomic system. By directly linking the creation of new monetary units to the verifiable expenditure of physical energy, the protocol realigns the financial sphere with the biophysical sphere. It forces global civilisation to balance its thermodynamic budget.

VI. CONCLUSION: REALISING IDEAL MONEY AND THE UNIVERSAL THERMODYNAMIC LEDGER

The dissociation between the macroeconomic map (fiat price) and the biophysical territory (thermodynamic value) has led global civilisation to the brink of systemic ecological and financial fragility. By anchoring the monetary base in a decentralised Industrial Consumption Index (ICI) through Proof-of-Work, we resolve the fundamental principal-agent problem that has undermined monetary systems since the suspension of the gold standard in 1971.

A. Standardising Value: The Planetary Joule

For the first time in history, we possess a decentralised and immutable measure of value that is consistent across geopolitical boundaries: the **Solar Emjoule (sej)**. Just as the metre standardised length to facilitate global engineering, the cryptographic "Hash" standardises thermodynamic effort to facilitate global capital allocation. This enables a standardised accounting system where the final cost of goods reflects their true planetary cost.

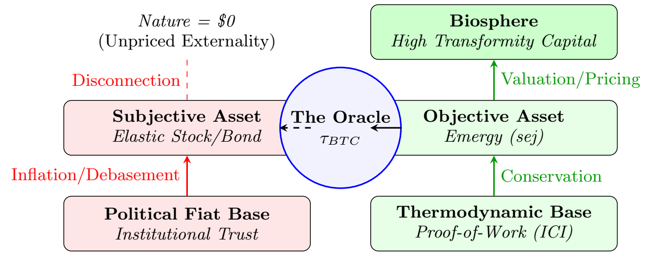

Figure 7: **The Reunification of Value:** Transitioning from an Anthropocentric to a Biocentric Macroeconomic Ledger. On the left, value is based on political elasticity, leaving Nature unpriced. On the right, value is linked to the thermodynamic ICI, integrating biological work into the economic ledger.

B. Macroeconomic Internalisation: Accounting for the Work of Life

The most profound implication of synthesising Odum's Emergy within Nash's Ideal Money is that **Life itself is quantified as high-transformity matter**. An old-growth forest is not "free capital"; it represents millions of years of solar energy accumulation.

$$\text{Value}_{Life} = \int_{t=-10^6}^{0} (\text{Solar}_{Input} \times \tau_{Evolution})\, dt \qquad (13)$$

If money is energy, then the destruction of an ecosystem is explicitly identified and priced as the combustion of accumulated capital. This creates the rigorous accounting framework necessary to internalise environmental externalities.

C. The Pragmatic Alignment of Global Incentives

Although theoretical models of "Nature-backed Currency" have existed for decades, they lacked a trustless enforcement mechanism. The decentralised algorithmic ledger solves this problem. It is the only currently existing system that cannot be politically counterfeited, is permissionless, and actively monetises entropy. The bottom-up adoption of Asymptotically Ideal Money aligns rational self-interest with objective thermodynamic constraints.

D. Thermodynamic Decoupling and Scaling: Layered Architecture

A recurring macroeconomic critique of Proof-of-Work systems concerns their calculated energy intensity "per transaction." However, from an institutional economics perspective, this metric represents a fundamental category error. Nakamoto consensus (Layer 1) does not aim to marginally validate individual retail transactions; it exists to secure the global and irreversible state of a final settlement ledger—analogous to the physical movement of gold bullion between central banks under the Bretton Woods system.

The thermodynamic cost, measured by the Nakamoto Action (κ_N), is tied to the production of time-anchored blocks, regardless of the transactional density they contain. To resolve the scalability trilemma while respecting biophysical limits, the network's architecture has stratified. The emergence of second-layer networks (e.g., the Lightning Network) illustrates an elegant decoupling between the thermodynamic anchor (the ICI) and monetary velocity [43].

These secondary networks function as topological graphs of bidirectional payment channels [44], leveraging "small-world" network properties [45] to allow agents to route and exchange units of value nearly instantaneously. In terms of information physics, these Layer 2 transactions require only a localised and trivial energy expenditure (routing and asymmetric cryptography), effectively bypassing the global thermodynamic friction imposed by the base layer's Proof-of-Work.

This layered model replicates the energy hierarchy of complex systems observed by Odum: the base layer consumes substantial energy to maximise structural security and absolute trust (the "thermodynamic gold reserve"), while higher layers maximise efficiency and velocity, where the marginal thermodynamic cost of a transaction asymptotically approaches zero.

E. The Odum-Nash-Nakamoto Synthesis

The primary contribution of this paper lies in the unprecedented triangulation of three distinct intellectual lineages:

1. **John Nash** and his game-theoretic quest for Ideal Money linked to an Industrial Consumption Index (The "What").
2. **Howard T. Odum** and his laws of biophysical accounting and Emergy (The "Why").
3. **Satoshi Nakamoto** and his decentralised cryptographic implementation (The "How").

By quantifying the consensus mechanism as a literal accumulation of physical action ($J \cdot s$) through the Nakamoto Action (κ_N), we bridge the theoretical gap between abstract game-theoretic stability and strict energetic constraints.

F. Institutional Symbiosis: The Evolution of Central Banks

The emergence of a decentralised Industrial Consumption Index does not necessitate the obsolescence of central banks; rather, it catalyses their structural evolution. In a mature macroeconomic framework, a symbiotic relationship is likely to form where the algorithmic ledger serves as the thermodynamic base money (Layer 1), while central banks transition to managing elastic credit and localised liquidity on secondary economic layers.

Using the ICI as an infallible, real-time macroeconomic compass—and ultimately as a politically neutral reserve asset freed from the Triffin dilemma [46] (the structural paradox where a nation providing the global reserve currency must run perpetual and destabilising trade deficits to provide global liquidity)—monetary authorities can calibrate interest rates against a verifiable physical reality rather than lagging statistical surveys.

This paradigm transforms central banks from discretionary creators of base money into precise administrators of sovereign credit (for instance, via Central Bank Digital Currencies, or CBDCs). The thermodynamic index thus acts as a disciplinary anchor. It curtails excessive fiat debasement by providing an objective, frictionless benchmark for capital preservation. Ultimately, this structural symbiosis does not stifle state institutions; it compels them to compete through monetary virtue, fiscal discipline, and financial innovation rather than relying on captive elasticity.

G. Final Perspectives: Aligning Macroeconomics with Biophysical Constraints

The transition to a thermodynamic index standard represents a paradigm shift from traditional macroeconomic models that assume infinite economic elasticity, largely independent of the biosphere's physical budget. The adoption of an energy-backed monetary framework structurally integrates the environment's physical limits into the economy's primary coordination mechanism.

Rather than operating in a theoretical vacuum of material abstraction, this system anchors economic valuation in objective thermodynamic reality. Consequently, money can no longer be modeled exclusively as a political abstraction; in this framework, it operates as an emergent property of information physics [47]. We propose that synthesizing algorithmic monetary policy with biophysical realities provides a robust framework for aligning economic systems with natural laws.

To quantify this material reality, we can empirically evaluate the microscopic Nakamoto Action (κ_N) for the current epoch (2026). If we take the energy of a hash computation ($\eta \approx 2.6 \times 10^{-11}$ J) multiplied by the physical latency time of a state transition within a modern ASIC ($\tau_{\text{local}} \approx 1.0 \times 10^{-11}$ s), the relation is:

$$\kappa_N = \eta\cdot\tau_{\text{local}} = (2.6\times10^{-11})\times(1.0\times10^{-11}) = 2.6\times10^{-22}\ \text{J}\cdot\text{s} \tag{14}$$

At the microscopic scale, the Nakamoto Action—which quantifies the material thermodynamic effort to evaluate one unit of truth—is twelve orders of magnitude away from Planck's constant ($h \approx 6.626 \times 10^{-34}$ J · s). Although it has not yet reached the absolute quantum wall, the historical trajectory demonstrates a spectacular compression of physical entropy.

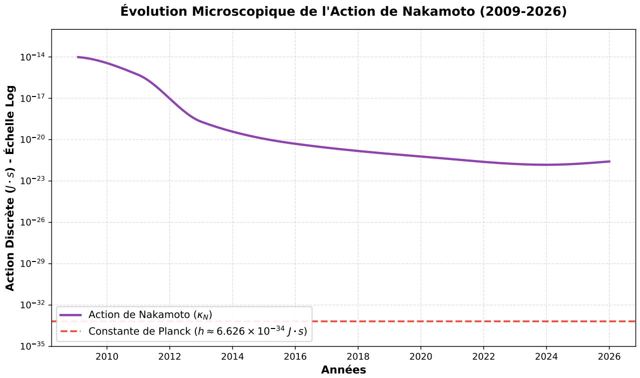

Figure 8: Historical evolution of the microscopic Nakamoto Action (κ_N) on a logarithmic scale (2009-2026). The graph shows the dramatic drop in the network's discrete action during ASIC industrialisation, progressively approaching fundamental physical limits (represented by Planck's constant, h).

As illustrated in Figure 8, faced with the relentless optimisation of semiconductors approaching the Landauer limit and the plateauing of Moore's Law, the network asymptotically converges toward the fundamental physical limits of temporal computation. The diminishing returns of hardware efficiency ensure that the network can no longer rely solely on technological leaps to absorb the ledger's entropy.

Consequently, to increase macroscopic security in the future, the system will intrinsically demand the continuous expenditure of raw energy and exergy. This structural alignment with Odum's Maximum Power Principle ensures that the ledger of the human economy remains ultimately constrained by the physical laws of information. By inextricably linking the cost of monetary falsification to the inescapable laws of thermodynamics, the protocol establishes a macroeconomic infrastructure where objectively accumulated value cannot be diluted by political decree.

Ultimately, by optimising the allocation of global resources and structurally disincentivising kinetic conflicts—which intrinsically dissipate thermodynamic capital—this framework fosters long-term economic equilibrium. Firmly anchored mathematically and physically in the biosphere's constraints, such a system of biophysical accounting provides the necessary foundation for humanity's transition toward a Type I civilisation on the Kardashev scale.

Future interdisciplinary research is necessary to fully model this macroeconomic phase transition. However, integrating a thermodynamic oracle into the monetary base presents a mathematically rigorous path for ensuring long-term biophysical stability and achieving a global, cooperative Nash Equilibrium.

ACKNOWLEDGMENTS

The author pays tribute to the scientists upon whom the science of the protocol rests: **Sa**di Carnot (irreversible thermodynamics), **To**rricelli (inventor of the barometer, whose intuition to measure invisible pressure by its physical effects prefigures Nakamoto's thermodynamic pressure gauge), **Sh**annon & **Sh**amir (information theory and cryptography), **Hi**ggs (whose spontaneous symmetry breaking mechanism provides the structural analogy to the ledger's acquisition of informational inertia), **Na**sh (cooperative equilibria, game theory and Asymptotically Ideal Money), **Ka**rdashev (civilisational scale of energy mastery), **Mo**ore (laws of computational densification) and Howard **T. O**dum (biophysical accounting and Emergy).

Thanks are also extended to the *open-source* community, to the founding cypherpunks, and to independent researchers at the intersection of physics and decentralised systems. Empirical analyses, multi-objective optimisation, LPPL modelling and the complete source code are available in the Appendix and on GitHub: `https://github.com/pascalranaora/pnasjnici`.

We are but stardust calculating our own complexity. Without the Sun and without photosynthetic proof-of-work, life is not possible and the economy would not exist. We are all proof-of-work blockchains: feeding on energy, constantly exchanging blocks of information with our environment to build our memory. It is time to build together and to trust one another. Be the Sun you wish to see on this Earth. You only have one. Ra'Naora Pascal

---

[1] F. E. Kydland and E. C. Prescott, Rules rather than discretion: The inconsistency of optimal plans, Journal of Political Economy **85**, 473 (1977).

[2] J. F. Nash, Ideal money, Southern Economic Journal **69**, 4 (2002), also available as "Asymptotically Ideal Money".

[3] S. Nakamoto, Bitcoin: A peer-to-peer electronic cash system, `https://bitcoin.org/bitcoin.pdf` (2008).

[4] C. Dwork and M. Naor, Pricing via processing or combatting junk mail, Advances in Cryptology , 139 (1992).

[5] A. Back, Hashcash-a denial of service counter-measure, Original Hashcash paper (2002).

[6] N. Georgescu-Roegen, *The Entropy Law and the Eco-*

nomic Process (Harvard University Press, Cambridge, MA, 1971).

[7] R. U. Ayres and B. Warr, *The Economic Growth Engine: How Energy and Work Drive Material Prosperity* (Edward Elgar Publishing, 2009).

[8] C. A. Hall, J. G. Lambert, and S. B. Balogh, Eroi of different fuels and the implications for society, Energy policy **64**, 141 (2014).

[9] H. T. Odum, *Environmental Accounting: Emergy and Environmental Decision Making* (John Wiley & Sons, New York, 1996).

[10] R. Landauer, Irreversibility and heat generation in the computing process, IBM journal of research and development **5**, 183 (1961).

[11] C. H. Bennett, The thermodynamics of computation—a review, International Journal of Theoretical Physics **21**, 905 (1982).

[12] E. Smith and D. K. Foley, Classical thermodynamics and economic general equilibrium theory, Journal of Economic Dynamics and Control **32**, 7 (2008).

[13] P. Ranaora, Thermodynamic stability and phase transitions in the nakamoto consensus, IPI Letters **4**, 1 (2026).

[14] J. F. Nash, Ideal money and asymptotically ideal money, Contributions to Game Theory and Management **3**, 368 (2010).

[15] P. A. Samuelson, *Foundations of Economic Analysis* (Harvard University Press, Cambridge, MA, 1947).

[16] F. A. Hayek, *Denationalisation of Money: The Argument Refined* (Institute of Economic Affairs, London, 1976).

[17] G. Selgin, Salvaging gresham's law: The good, the bad, and the illegal, Journal of Money, Credit and Banking **28**, 637 (1996).

[18] R. Böhme, N. Christin, B. Edelman, and T. Moore, Bitcoin: Economics, technology, and governance, Journal of Economic Perspectives **29**, 213 (2015).

[19] D. Sornette, A. Johansen, and J.-P. Bouchaud, Stock market crashes, precursors and replicas, Journal de Physique I **6**, 167 (1996).

[20] D. Sornette, *Why Stock Markets Crash: Critical Events in Complex Financial Systems* (Princeton University Press, Princeton, NJ, 2003).

[21] S. Wheatley, D. Sornette, T. Huber, M. Reppen, and R. N. Gantner, Are bitcoin bubbles predictable? combining a generalized metcalfe's law and the lppl model, Royal Society Open Science **6**, 180538 (2019).

[22] J.-C. Gerlach, G. Demos, and D. Sornette, Dissection of bitcoin's multiscale bubble history from january 2012 to february 2018, Royal Society open science **6**, 180643 (2019).

[23] G. Nicolis and I. Prigogine, *Self-organization in nonequilibrium systems: From dissipative structures to order through fluctuations* (Wiley, New York, 1977).

[24] P. Bak, C. Tang, and K. Wiesenfeld, Self-organized criticality: An explanation of the 1/f noise, Physical review letters **59**, 381 (1987).

[25] P. Bak, *How nature works: the science of self-organized criticality* (Copernicus, New York, 1996).

[26] C. C. for Alternative Finance, *A deep dive into Bitcoin's environmental impact and sustainable energy mix*, Tech. Rep. (University of Cambridge Judge Business School, 2024).

[27] K. Advisory, *Bitcoin's role in the ESG imperative*, Tech. Rep. (KPMG International, 2023).

[28] T. K. Dasaklis *et al.*, Rethinking bitcoin's energy use through sustainable digital business models and resources monetization, Digital Business **5** (2025).

[29] M. Mazzucato, *The Entrepreneurial State: Debunking Public vs. Private Sector Myths* (Anthem Press, London, 2015).

[30] T. Parrique, *The Political Economy of Degrowth*, Phd thesis, Stockholm University (2019).

[31] M. Velický, Renewable energy transition facilitated by bitcoin, ACS Sustainable Chemistry & Engineering **11** (2023).

[32] C. Stoll, L. Klaaßen, and U. Gallersdörfer, The carbon footprint of bitcoin, Joule **3**, 1647 (2019).

[33] S. Hakimi *et al.*, Renewable energy and cryptocurrency: A dual approach to economic viability and environmental sustainability, Heliyon **10** (2024).

[34] A. Lal and F. You, Climate sustainability through a dynamic duo: Green hydrogen and crypto driving energy transition and decarbonization, Proceedings of the National Academy of Sciences **121**, e2313911121 (2024).

[35] IPCC, *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Tech. Rep. (Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 2023).

[36] G. Semaan *et al.*, Harnessing bitcoin mining for methane mitigation, Journal of Cleaner Production **439** (2024).

[37] M. A. Rudd and E. David, Harnessing bitcoin mining for methane mitigation, SSRN Electronic Journal (2024), available at SSRN: https://ssrn.com/abstract=4653061.

[38] A. Lal and S. You, From mining to mitigation: How bitcoin can support renewable energy development and climate action, ACS Sustainable Chemistry & Engineering **11** (2023).

[39] M. Braumandl *et al.*, Waste heat recovery from cryptocurrency mining for municipal district heating, Energy Conversion and Management **280**, 116801 (2023).

[40] N. Carter and S. Ross, *Bitcoin Net Zero: The Macroeconomic and Sovereign Integration of Proof-of-Work*, Tech. Rep. (Coin Metrics - NYDIG, 2024).

[41] F. Soddy, *Wealth, Virtual Wealth and Debt* (George Allen & Unwin, London, 1926).

[42] H. E. Daly, *Steady-State Economics* (San Francisco: WH Freeman, 1977).

[43] J. Poon and T. Dryja, The bitcoin lightning network: Scalable off-chain instant payments (2016).

[44] C. Decker and R. Wattenhofer, A fast and scalable payment network with bitcoin duplex micropayment channels, in *Symposium on Self-Stabilizing Systems* (Springer, 2015) pp. 3–18.

[45] D. J. Watts and S. H. Strogatz, Collective dynamics of 'small-world' networks, Nature **393**, 440 (1998).

[46] R. Triffin, *Gold and the Dollar Crisis: The Future of Convertibility* (Yale University Press, New Haven, CT, 1960).

[47] C. E. Shannon, A mathematical theory of communication, The Bell system technical journal **27**, 379 (1948).

Appendix A: Source Code: Empirical Correlation Evaluation and Cointegration Test (Nakamoto Basket)

The following Python script extracts historical data from the blockchain and financial markets to construct the targeted synthetic Industrial Consumption Index (ICI) proposed in Section 3.2. It calculates the Spearman correlation ($\rho \approx 0.9776$) and performs the cointegration test to validate the hypothesis that the network Difficulty acts as a decentralised macro-proxy for Nash’s ICI.

```python
import requests
import pandas as pd
import numpy as np
import yfinance as yf
import matplotlib.pyplot as plt
from statsmodels.tsa.stattools import coint
from scipy.stats import spearmanr
import itertools
import warnings
# Disable statsmodels warnings for clean output
warnings.filterwarnings("ignore")

def optimize_multiobjective_nash_index():
    print("1. Downloading network Difficulty data...")
    try:
        res = requests.get(’https://api.blockchain.info/charts/difficulty?timespan=all&format=json’)
        df_diff = pd.DataFrame(res.json()[’values’])
        df_diff[’date’] = pd.to_datetime(df_diff[’x’], unit=’s’)
        df_diff.set_index(’date’, inplace=True)
        df_diff.rename(columns={’y’: ’Difficulty’}, inplace=True)

        df_diff = df_diff[[’Difficulty’]].resample(’ME’).last()
        df_diff.index = df_diff.index.to_period(’M’)
    except Exception as e:
        print(f"Blockchain API Error: {e}")
        return
    print("2. Downloading Industrial Inputs (Gas, XLE, Copper, TSM/Foundry)...")
    try:
        # TSM acts as the silicon CapEx proxy for the physical ASIC Foundry
        tickers = [’NG=F’, ’XLE’, ’HG=F’, ’TSM’]
        data = yf.download(tickers, start=’2010-01-01’, interval=’1mo’, progress=False)[’Close’]
        data.dropna(inplace=True)
        data.index = data.index.to_period(’M’)
        data_norm = (data / data.iloc[0]) * 100
    except Exception as e:
        print(f"Yahoo Finance Error: {e}")
        return
    print("3. Merging macroeconomic data...")
    df_merged = pd.merge(df_diff, data_norm, left_index=True, right_index=True, how=’inner’)
    df_merged.index = df_merged.index.to_timestamp()
    print("\n4. Running Multi-Objective Optimisation for Nash’s ICI...")
    best_spearman = -1.0
    best_pvalue = 1.0
    best_weights = None
    best_ici_series = None
    weight_range = np.arange(0.0, 1.05, 0.05)
    min_silicon_weight = 0.15 # Physical floor

    valid_models_count = 0

    for w_ng, w_xle, w_hg, w_tsm in itertools.product(weight_range, repeat=4):
        if not np.isclose(w_ng + w_xle + w_hg + w_tsm, 1.0): continue
        if w_tsm < min_silicon_weight: continue

        test_ici = (df_merged[’NG=F’] * w_ng) + \
                   (df_merged[’XLE’] * w_xle) + \
                   (df_merged[’HG=F’] * w_hg) + \
                   (df_merged[’TSM’] * w_tsm)

        score, pvalue, _ = coint(df_merged[’Difficulty’], test_ici)
        spearman_corr, _ = spearmanr(df_merged[’Difficulty’], test_ici)

        if pvalue < 0.05:
            valid_models_count += 1
            if spearman_corr > best_spearman:
                best_spearman = spearman_corr
                best_pvalue = pvalue
                best_weights = (w_ng, w_xle, w_hg, w_tsm)
                best_ici_series = test_ici

    if best_weights is None: return

    w_ng, w_xle, w_hg, w_tsm = best_weights
    df_merged[’Optimized_ICI’] = best_ici_series
    # Generating the graph
    fig, ax1 = plt.subplots(figsize=(12, 6))
    color1 = ’tab:blue’
    ax1.set_xlabel(’Year’, fontweight=’bold’)
    ax1.set_ylabel(’Network Difficulty (Linear Scale)’, color=color1, fontweight=’bold’)
    ax1.plot(df_merged.index, df_merged[’Difficulty’], color=color1, linewidth=2, label=’Difficulty’)
    ax1.tick_params(axis=’y’, labelcolor=color1)
    ax2 = ax1.twinx()
    color2 = ’tab:orange’
    ax2.set_ylabel(’Synthetic Nash ICI (Base 100, Linear)’, color=color2, fontweight=’bold’)
    ax2.plot(df_merged.index, df_merged[’Optimized_ICI’], color=color2, alpha=0.8, linewidth=2, linestyle=’--’,
             label=f’ICI Basket ({w_ng*100:.0f}% NG, {w_xle*100:.0f}% XLE, {w_hg*100:.0f}% HG, {w_tsm*100:.0f}% TSM)’)
    ax2.tick_params(axis=’y’, labelcolor=color2)
    lines_1, labels_1 = ax1.get_legend_handles_labels()
    lines_2, labels_2 = ax2.get_legend_handles_labels()
    ax1.legend(lines_1 + lines_2, labels_1 + labels_2, loc=’upper left’)
    fig.tight_layout()
    plt.savefig(’superposition_multiobjective_diff_ici_en.pdf’)

if __name__ == "__main__":
    optimize_multiobjective_nash_index()
```

Listing 1: Python Script for correlation analysis

Appendix B: Source Code: LPPL Modelling and Phase Transition

The following Python script simulates historical data to visualise the Phase Transition according to Sornette’s Log-Periodic Power Law (LPPL) model. It demonstrates that the market cycle volatility mathematically orbits the fundamental thermodynamic attractor during the monetisation phase of Ideal Money.

```python
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import yfinance as yf
from scipy.stats import linregress
from scipy.optimize import curve_fit
import warnings

warnings.filterwarnings("ignore")

def lppl_model(x, A, B, C, omega, phi):
    """
    Log-Periodic Power Law (LPPL) Model
    A + B*x defines the fundamental power law (The Attractor).
    C * cos(omega*x + phi) defines the macroeconomic oscillations of the bull/bear cycle.
    """
    return A + B * x + C * np.cos(omega * x + phi)

def plot_bitcoin_lppl():
    try:
        btc = yf.download(’BTC-USD’, start=’2010-07-17’, progress=False)
        df = pd.DataFrame(btc[’Close’])
        df.columns = [’Price’]

        genesis_date = pd.to_datetime(’2009-01-03’).tz_localize(None)
        df.index = pd.to_datetime(df.index).tz_localize(None)
        df[’Days’] = (df.index - genesis_date).days
        df = df[df[’Days’] > 0]

        log_days = np.log10(df[’Days’]).values
        log_price = np.log10(df[’Price’]).values

        # 1. Fundamental Attractor (Pure linear regression)
        slope, intercept, r_value, p_value, std_err = linregress(log_days, log_price)
        df[’Power_Law_Price’] = 10**(intercept + slope * log_days)

        # 2. LPPL Modelling (Oscillations around the attractor)
        p0 = [intercept, slope, 0.4, 12.0, 0.0]
        bounds = ([-np.inf, -np.inf, 0.1, 5.0, -np.pi], [np.inf, np.inf, 1.5, 25.0, np.pi])

        popt, pcov = curve_fit(lppl_model, log_days, log_price, p0=p0, bounds=bounds, maxfev=10000)
        A_opt, B_opt, C_opt, omega_opt, phi_opt = popt
        df[’LPPL_Price’] = 10**(lppl_model(log_days, *popt))

        # 3. Graph Generation
        fig, ax = plt.subplots(figsize=(11, 7))
        ax.scatter(df.index, df[’Price’], color=’gray’, s=2, alpha=0.3, label=’Market Price (USD)’)
        ax.plot(df.index, df[’Power_Law_Price’], color=’black’, linewidth=2, linestyle=’--’,
                label=f’Fundamental Thermodynamic Attractor’)
        ax.plot(df.index, df[’LPPL_Price’], color=’tab:red’, linewidth=1.5,
                label=’LPPL Model (Log-Periodic Oscillations)’)

        ax.set_yscale(’log’)
        ax.set_ylabel(’Market Price (USD) - Log Scale’, fontweight=’bold’)
        ax.legend(loc=’upper left’, fontsize=10)
        ax.grid(True, which="both", ls="--", alpha=0.5)
        plt.tight_layout()
        plt.savefig(’bitcoin_lppl_model_en.pdf’)

    except Exception as e:
        print(f"Error during LPPL modelling: {e}")

if __name__ == "__main__":
    plot_bitcoin_lppl()
```

Listing 2: Python Script for modelling the fundamental attractor and LPPL oscillations

Appendix C: Source Code: Visualisation of the Nakamoto Action

The following Python script visualises the historical evolution of the Nakamoto Action (κ_N), representing the physical ”tick” of the decentralised index converging toward the Landauer limit.

```python
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
import matplotlib.dates as mdates
from scipy.interpolate import PchipInterpolator

# Physical latency of a computation in silicon (in seconds)
dates_lat = pd.to_datetime([’2009-01-03’, ’2011-01-01’, ’2013-01-01’, ’2016-01-01’, ’2020-01-01’, ’2024-01-01’, ’2026-01-01’])
latency = np.array([1e-9, 5e-10, 1e-10, 5e-11, 2e-11, 1e-11, 1e-11])

# Minimum energy required for a single hash (in Joules)
dates_eff = pd.to_datetime([’2009-01-03’, ’2011-01-01’, ’2013-01-01’, ’2016-01-01’, ’2020-01-01’, ’2024-01-01’, ’2026-01-01’])
efficiency = np.array([1e-5, 1e-6, 2e-9, 1e-10, 3e-11, 1.5e-11, 2.6e-11])

timeline = pd.date_range(start=’2009-01-03’, end=’2026-01-01’, freq=’M’)
timeline_num = mdates.date2num(timeline)

log_lat_interp = PchipInterpolator(mdates.date2num(dates_lat), np.log10(latency))
log_eff_interp = PchipInterpolator(mdates.date2num(dates_eff), np.log10(efficiency))
interp_lat = 10**log_lat_interp(timeline_num)
interp_eff = 10**log_eff_interp(timeline_num)

# Microscopic Nakamoto Action calculation: k_N = eta * tau_local
nakamoto_action = interp_eff * interp_lat

plt.figure(figsize=(10, 6))
plt.semilogy(timeline, nakamoto_action, color=’#8E44AD’, linewidth=2.5, label=r’Nakamoto Action ($\kappa_N$)’)

planck_constant = 6.626e-34
plt.axhline(y=planck_constant, color=’#E74C3C’, linestyle=’--’, linewidth=2, label=r’Planck Constant ($h \approx 6.626 \times 10^{-34} \ J \cdot s$)’)
plt.title("Microscopic Evolution of the Nakamoto Action (2009-2026)", fontsize=14, fontweight=’bold’, pad=15)
plt.xlabel("Years", fontsize=12, fontweight=’bold’)
plt.ylabel(r"Discrete Action ($J \cdot s$) - Log Scale", fontsize=12, fontweight=’bold’)

plt.ylim(1e-35, 1e-12)
plt.grid(True, which="both", ls="--", alpha=0.4)
plt.legend(loc=’lower left’, fontsize=11, framealpha=0.9)
plt.tight_layout()
plt.savefig(’nakamoto_action_evolution_en.pdf’, dpi=300)
```

Listing 3: Python Script to visualise the evolution of the Nakamoto action