EFU-CRYPTO RESEARCH FRAMEWORK v2.1. – RESEARCH AUDIT EDITION

Title: Experimental Protocol for the Thermodynamic Assessment of Proof-of-Work Cryptocurrency Mining
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Framework: EFU – Ecological / Energy Flux Unit Research Framework

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ABSTRACT

[HYPOTHESIS] This document specifies the experimental EFU-Crypto research framework, which models proof-of-work (PoW) cryptocurrency mining as a metabolic system using human-scale flux references (EFU-H, EFU-W, EFU-M, EFU-S, EFU-C). The central hypothesis is that PoW-based mining exhibits a measurably unbalanced multidimensional metabolic return-on-investment (MROI), especially when local societal usefulness (THI) is compared to the total EFU cost (TEFU).okx+2

[PROTOCOL] The framework provides a systematic indicator set (EKI, WSI, MDR, MROI) and an open Python-based implementation for pilot audits; it is not a legal, financial or prudential rating tool. The term "metabolically extractive system" (MROI $< 10^{-7}$) is an analytical category, not a moral or legal judgement.

This document represents an ongoing research construct; all models and thresholds are provisional and subject to revision or falsification.

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0. Research status and scope

[AXIOM] All digital infrastructures ultimately rely on physical resource flows (energy, water, materials, entropy, emissions) and can therefore be treated as forms of digital metabolism.sqmagazine+1

[HYPOTHESIS] PoW-based cryptocurrency systems – in particular Bitcoin – can, in some regions, create non-linear competition with residential and industrial demand, manifesting as energy and water "cannibalism" detectable through the Energy Cannibalism Index (EKI) and Water Stress Index (WSI).eia+2

[PROTOCOL] Empirical testing of the EFU-Crypto framework relies primarily on:

- network-level electricity consumption (TWh/year),

- local generation mix and grid constraints,
- cooling-related water use,
- hardware replacement rates and e-waste,
- indicators of local societal usefulness (THI).ccaf+2

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1. Theoretical foundations – cryptocurrency as a metabolic system

1.1 Digital metabolism

[AXIOM] Any economic activity can be schematically represented as:

Input (energy, materials) → Process (infrastructure, computation) → Output (usefulness + waste + entropy).

[HYPOTHESIS] PoW-based crypto networks have a markedly higher specific energy and entropy burden per transaction than conventional payment systems, with orders of magnitude higher kWh per effective transaction.solartechonline+2

Illustrative comparison (2024–2025, order-of-magnitude values):

- Visa: ~0.0001 kWh per transaction (shared, highly integrated infrastructure).[okx]
- Bitcoin: ~1 000–1 500 kWh per transaction depending on the model, with recent estimates around ~1 300–1 400 kWh/tx.solartechonline+1

These numbers are model-dependent and debated, but consistently show several orders of magnitude difference in kWh/transaction between Visa-type systems and PoW.sqmagazine+1

1.2 EFU baselines (human metabolic equivalents – research normalization)

[PROTOCOL] EFU-Crypto uses the following human-scale baselines as experimental reference points:

Code	Dimension	Definition	Baseline (per capita per year)	Unit
EFU-H	Energy	Human metabolic energy equivalent	12.88 MWh/year	MWh
EFU-W	Water	Human water use (WHO-type guidance)	18.25 m^3/year	m^3
EFU-M	Materials	Average server hardware turnover	150 kg per 5 years ≈ 30 kg/year	kg/year
EFU-S	Entropy	Indicative entropy-production reference	11 500 J/K (conceptual baseline)	J/K
EFU-C	Carbon	Per-capita CO_2e emissions	4 t CO_2e/year	t CO_2e

[HYPOTHESIS] These baselines allow the total burden of PoW systems to be expressed on a human-equivalent metabolic scale, making cross-comparison with other infrastructures and with EFU-Academic and EFU-WATER models possible.

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2. Experimental metrics – EFU balance components

2.1 Energy Cannibalism Index (EKI)

[DEFINITION]
The **Energy Cannibalism Index (EKI)** expresses the relative electricity burden of cryptocurrency mining compared to residential electricity demand within the same regional system boundary.

EKI = crypto electricity use (MWh/year) ÷ regional residential electricity use (MWh/year)

[HYPOTHESIS]
High EKI values indicate non-linear competition between crypto mining loads and household electricity demand, potentially leading to grid stress and reduced residential supply security.

[PROTOCOL] Experimental interpretation:

- EKI < 0.1: low systemic risk.
- 0.1 ≤ EKI < 0.3: competitive use.
- EKI ≥ 0.3: structural dominance risk.

Empirical patterns (illustrative, non-normative):

- Kazakhstan (2021): rapid mining inflow contributed to grid stress and an energy crisis, corresponding to EKI values that can reach the ~0.4 range when crypto load is compared to residential use.etalpykla.vilniustech+2
- Texas (2023–2024): several GW of mining capacity, with mining loads approaching significant fractions of peak demand, raising system-stability concerns.eia+1
- Iceland: high mining share on a fully renewable grid, implying low CO_2 intensity but non-trivial opportunity costs for alternative uses of the same electricity.ccaf+1

2.2 Water Stress Index (WSI)

[DEFINITION]
The **Water Stress Index (WSI)** expresses the proportion of renewable regional water availability consumed by cryptocurrency mining activities.

WSI = crypto water consumption (m^3/year) ÷ regional renewable water availability (m^3/year)

[HYPOTHESIS]
In water-constrained regions, crypto-related water demand may represent a non-trivial contribution to local hydrological stress, even when direct withdrawals appear limited.

Experimental thresholds:

- WSI < 0.01: low concern.
- 0.01 ≤ WSI < 0.05: warning zone.
- WSI ≥ 0.05: critical water-stress contribution.

[PROTOCOL] Crypto water consumption should include both direct cooling water and water embedded in electricity generation (especially in thermal power plants), based on locally relevant factors.sqmagazine+1

2.3 Material Degradation Rate (MDR)

[DEFINITION]
The **Material Depletion Ratio (MDR)** expresses the relative material intensity of cryptocurrency mining infrastructure compared to conventional ICT systems.

MDR = critical material use in crypto infrastructure (kg/year) ÷ critical material use in reference ICT systems (kg/year)

[HYPOTHESIS]
Elevated MDR values may indicate disproportionate pressure on critical raw material supply chains, particularly rare earth elements and semiconductor-grade metals.

Empirical observation: dedicated PoW ASIC hardware often has replacement cycles of ~12–18 months, implying MDR values several times higher than for typical server infrastructure with 5–7 year design lifetimes.[sqmagazine.co]

[PROTOCOL] MDR should distinguish between:

- fully decommissioned equipment (true e-waste),
- reused / repurposed hardware,
- grey-zone flows where traceability is limited.

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3. Metabolic Return on Investment (MROI) – core indicator

3.1 Mining Return on Impact (MROI)

[DEFINITION]
The **Mining Return on Impact (MROI)** expresses the economic value generated by cryptocurrency mining relative to its aggregated environmental impact.

MROI = economic output of crypto mining (USD/year) ÷ aggregated EFU impact score (dimensionless)

[HYPOTHESIS]
Low MROI values suggest diminishing systemic returns relative to environmental burden, indicating potential inefficiency at the planetary system level.

3.2 Thermal Heat Index (THI)

[DEFINITION]
The **Thermal Heat Index (THI)** expresses the proportion of waste heat generated by crypto mining relative to the absorptive thermal capacity of the local environment.

THI = waste heat from crypto mining (MJ/year) ÷ local thermal dissipation capacity (MJ/year)

[HYPOTHESIS]
High THI values may indicate localized thermal stress, particularly in densely clustered mining operations or enclosed cooling environments.

3.3 Total Human-Equivalent Flux Unit (TEFU)

[DEFINITION]
The **Total Human-Equivalent Flux Unit (TEFU)** aggregates multiple EFU-based indicators into a single comparative reference value.

TEFU = Σ (EFU-E + EFU-W + EFU-M + EFU-N)

where:
• EFU-E = energy-related EFU component
• EFU-W = water-related EFU component
• EFU-M = material-related EFU component
• EFU-N = nitrogen or nutrient-related EFU component

[HYPOTHESIS]
TEFU enables cross-sectoral comparison by translating heterogeneous environmental pressures into a unified human-equivalent flux representation.

3.4 Research Status and Interpretation Note

[NOTE]
All indicators presented above are **experimental research constructs**. Threshold values, interpretations, and aggregation methods are **non-normative** and intended solely for analytical exploration and comparative assessment.

Participation in the Audit Layer does not confer compliance, certification, or endorsement.

Experimental MROI bands:

MROI range	Category	Research interpretation
> 10^{-3}	High	Substantial societal benefit
10^{-4}	Moderate	Potentially manageable
10^{-5}	Low	Problematic
< 10^{-7}	Extreme	Structurally unbalanced (extractive)

[HYPOTHESIS] The MROI < 10^{-7} range defines the analytical class of "metabolically extractive systems": systems whose total societal usefulness is negligible relative to their aggregate EFU cost, even before considering distributional and justice concerns.

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4. Thermodynamic properties of proof-of-work

[AXIOM] The security of a PoW consensus mechanism is proportional to the global hashrate and, by design, to the amount of energy dissipated:

[RELATIONSHIP]
Network security is treated as a monotonic function of total hashrate, which itself is a monotonic function of energy dissipation:

Security ∝ Hashrate ∝ Energy dissipation

[HYPOTHESIS] "Anti-Moore effect":

- ASIC efficiency (hashes per joule) has improved dramatically over the past decade,
- yet global hashrate has increased even faster,
- leading to total annual electricity consumption stabilising at a very high level (≈150–200 TWh/year, depending on methodology and year).ccaf+2

[PROTOCOL] Because of the difficulty-adjustment mechanism, efficiency gains are largely re-absorbed into higher hashrate; aggregate entropy production does not fall in proportion to efficiency improvements.eia+2

EFU-Crypto research axioms (testable hypotheses):

- Security requires continuous large-scale dissipation.
- The protocol endogenously absorbs unit efficiency gains into expanded hashrate.
- Scaling tends to increase aggregate entropy loads unless the underlying economic incentives are changed.

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5. Global case patterns

[HYPOTHESIS] Across jurisdictions, PoW mining tends to follow a recurring pattern:

Invite → Boom → Stress → Backlash → Exodus → “Infrastructural scars”.

Illustrative examples (2020–2025):

- **Kazakhstan:** rapid post-China migration of miners, mining load reaching ~1.5 GW, contributing to an energy crisis and subsequent regulatory crackdown.hashrateindex+2
- **Texas (U.S.):** fast build-out of several GW of mining capacity, with ~10 GW continuous draw globally and a U.S. demand increase of ~7 TWh in 2024 (~16% growth in crypto-related consumption), prompting concerns about grid stability and future energy taxation.eia+1
- **Nordic and Icelandic cases:** high renewable share, but non-trivial opportunity costs of devoting a large fraction of low-carbon electricity to PoW instead of other decarbonisation uses.ccaf+1

Key EFU-Crypto principle:

“A clean energy supply only addresses 1 out of 5 metabolic EFU dimensions.” Decarbonisation (EFU-C improvement) does not automatically solve issues in EFU-H (energy volume), EFU-W (water), EFU-M (materials/e-waste), or EFU-S (entropy/heat) dimensions.sqmagazine+1

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6. EFU-Crypto audit protocol

[PROTOCOL] **Audit types:**

- Ex-ante: pre-deployment impact assessment.
- Ex-post: after-the-fact performance and impact review.
- Comparative: PoW vs. alternative architectures (e.g. PoS, conventional data centers).
- Baseline: reference projects for benchmarking.

Minimum Tier-1 data requirements:

- Energy: installed capacity (MW), annual consumption (MWh/year), grid mix (fuel shares, CO_2 intensity).ccaf+2
- Water: annual cooling and embedded water consumption (m^3/year).
- Hardware: number and mass of ASICs/GPUs, replacement cycles, e-waste flows.[sqmagazine.co]
- Societal: jobs created, local GDP contribution, active users, qualitative innovation assessment.

Illustrative Python class (sketch):

```python
class EFUCryptoAudit:
    def full_audit(self, data):
        return {
```

```
        "EKI": self.compute_eki(data),
        "WSI": self.compute_wsi(data),
        "MDR": self.compute_mdr(data),
        "MROI": self.compute_mroi(data),
    }
```

The full implementation is left open-source in the EFU-Crypto research package.

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7. Epistemological appendix (EA)

Falsifiability criteria

[HYPOTHESIS] The EFU-Crypto model is falsified, or at least its core claims are significantly weakened, if robust empirical evidence shows that:

1. PoW networks can sustain MROI values $\geq 10^{-3}$ over time in specific regions, indicating substantial local societal usefulness relative to EFU cost.
2. EKI and WSI indices remain persistently below 0.1 and 0.01 respectively, even at high mining penetration, indicating no significant energy or water cannibalism.
3. Long-term efficiency improvements (ASIC W/TH) are consistently reflected in declining global Bitcoin electricity consumption (TWh/year), rather than primarily in higher hashrate at constant or rising energy use.ccaf+2

[PROTOKOLL] Key uncertainty factors include:

- rapid migration of mining sites (location data instability),
- uncertainty in local grid mixes (fossil vs renewable fractions),
- subjective components in THI (valuation of jobs, innovation, users),
- under-reporting of e-waste flows due to reuse and informal sectors.eia+1

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8. Critical argument-map matrix

#	Claim (Hypothesis)	Basis	Vulnerable point	Falsifier / test
1	PoW can create extreme EKI in some regions	Regional energy statistics	Data quality, short time windows	EKI time-series analysis
2	MROI $< 10^{-7}$ indicates structural imbalance	MROI definition, THI weights	THI specification is contestable	THI sensitivity analysis
3	"Anti-Moore" effect is persistent	Hashrate + energy trends (CBECI)	Alternative economic models	CBECI-based regression of W/TH vs TWh
4	Clean energy improves mainly EFU-C, not EFU-H/W/M/S	Multi-dimensional EFU view	Rebound effects, system design	EFU-H/W/M/S longitudinal data
5	PoW is metabolically	High EKI + very low	Short-term data,	Long-term panel data

#	Claim (Hypothesis)	Basis	Vulnerable point	Falsifier / test
	extractive in some regions	MROI	regime changes	across jurisdictions

Research status statement

The EFU-Crypto framework is an open, experimental protocol that seeks to render the thermodynamic and societal dimensions of PoW-based digital infrastructures measurable and comparable. It does not license or regulate; it offers quantifiable hypotheses and indicators for scientific and policy discourse, subject to ongoing empirical scrutiny and revision.solartechonline+2

Scientific Endnote for the EFU-Crypto Research Framework

[PROTOCOL] The EFU-Crypto experimental licence and research framework rest on the assumption that proof-of-work (PoW) cryptocurrency mining can be assessed thermodynamically and socially in a way that is comparable to other infrastructures, once its flux profile is normalized on a human-scale EFU axis. The references below support the order-of-magnitude claims and logical structure of the framework; they are not normative judgements, but provide scientific context.

1. **Global electricity consumption (TWh/year) and the "anti-Moore effect"**
   Multiple independent sources (Cambridge CBECI, Digiconomist, technical syntheses) estimate the annual electricity consumption of the Bitcoin network in the approximate range of 60–200 TWh/year over 2021–2025, with many recent assessments clustering around ~80–150 TWh/year. These time series show that while ASIC efficiency improves, hashrate increases even faster, so total consumption stabilises on a "high plateau", which empirically underpins the EFU-Crypto "anti-Moore" hypothesis.ccaf+3
2. **Specific energy use – Bitcoin vs. Visa**
   Back-of-the-envelope calculations using major card networks' total energy use and annual transaction volumes indicate a per-transaction energy demand in the Wh/tx range for systems like Visa (≈1–2 Wh/tx), whereas various models for Bitcoin yield values in the thousands of kWh/tx (1 000–2 000 kWh/tx). Although methodology-dependent and debated, the order-of-magnitude difference – several thousand-fold higher specific energy per transaction – is robust, and supports the EFU-Crypto claim that PoW-based systems have an exceptionally high metabolic load per effective transaction compared to conventional payment infrastructures.digiconomist+1
3. **Regional energy stress and the EKI logic (Kazakhstan, U.S.)**
   Analyses of the 2021 Kazakh energy crisis show that the post-China migration of miners added on the order of ~1 GW of additional load, contributing to an 8% increase in national electricity demand and visible grid stress. In parallel, assessments by the U.S. Energy Information Administration (EIA) and others suggest that crypto mining in the U.S. added several TWh of demand in 2023–2024, with GW-scale continuous load in some states (e.g. Texas). These findings support the EFU-Crypto premise that the Energy Cannibalism Index (EKI), defined as crypto electricity use divided by

residential use, can reach significant values (>0.3) in some regions, signalling competition with household demand.etalpykla.vilniustech+2

4. **PoW as a non-trivial ecological footprint within digital infrastructures**
Energy and carbon footprint assessments of Bitcoin (e.g. lifecycle and grid-mix analyses) show that network-wide CO_2 emissions remain substantial even when the renewable share in the electricity mix increases, due to the scale of total energy use. This aligns with the EFU-Crypto EFU-C dimension (carbon), which explicitly separates CO_2 intensity from other metabolic dimensions and emphasises that "clean energy" solutions primarily improve EFU-C, while EFU-H (energy volume), EFU-W (water), EFU-M (e-waste/materials) and EFU-S (entropy/heat) may remain structurally stressed.arxiv+2
5. **Metabolic ROI and societal usefulness (THI)**
The literature on the societal value of PoW systems is heterogeneous: some studies highlight financial innovation and censorship resistance, while others point to speculative dynamics and financial-stability risks. EFU-Crypto's MROI definition deliberately uses an open, parameterised THI (jobs, local GDP, users, innovation score) and does not claim these weights to be final or normatively "correct". The intention is to make it possible to place societal benefits and EFU costs side by side in a quantitative way and to study "extractive" parameter ranges (e.g. MROI < 10^{-7}) with sensitivity analyses.sciencedirect+1
6. **E-waste and hardware degradation (MDR)**
Studies on hardware lifetimes in PoW environments indicate that dedicated ASIC devices typically have shorter lifetimes (≈1–2 years) than general-purpose server hardware (≈4–7 years), leading to higher annual e-waste flows per unit of computing capacity. This supports the EFU-Crypto MDR indicator, which expresses annual e-waste mass divided by average hardware lifetime and is expected to be significantly higher for PoW mining than for conventional data-center infrastructure.[sqmagazine.co]
7. **Cross-border migration and the "invite → boom → stress → exodus" pattern**
Regional case studies (Kazakhstan, U.S., and others) repeatedly show that PoW mining can rapidly drive up local electricity demand, followed by political backlash (tariffs, curbs, bans) and a subsequent migration of miners to other jurisdictions. This empirical pattern underpins the EFU-Crypto qualitative argument map, which describes "infrastructural scars" – short-lived booms leaving behind underused grid capacity, regulatory distrust and local social tensions.thediplomat+2
8. **Visa–Bitcoin comparison as a communication device, not a normative verdict**
Visa–Bitcoin energy comparisons in public datasets (CBECI, Digiconomist and others) stress that the two systems have different functions, architectures and user bases, yet they provide a powerful communicative illustration of specific energy differences per transaction. EFU-Crypto uses this contrast explicitly as a communication and normalization tool on the EFU scale and does not claim that Visa-like systems are "perfect" references for the entire financial system; rather, they serve as a familiar baseline for order-of-magnitude comparisons.x+1

[HYPOTHESIS] Taken together, these empirical sources and indices support the EFU-Crypto framework's core intuition: that PoW-based mining exhibits large-scale energy use, extreme per-transaction energy intensity, significant regional grid impacts and non-trivial e-waste production, all of which warrant an EFU-style, research-phase audit framework.crypto+3

[PROTOCOL] The licence and framework remain strictly research-phase until the defined metrics (EKI, WSI, MDR, MROI, TEFU) and threshold values have been widely tested, replicated and, where necessary, revised by the international scientific community through open, peer-reviewed work.ccaf+1