

# The Projected Falling Cost of Environmental Protection

## The Thermodynamic Convergence: Asymptotic Cost Decay in Planetary Stewardship

By Jed Anderson, Founder & CEO, EnviroAI

*Fourth in the Series: AI and the Environmental Profession*

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### The Thesis

This paper makes a claim that will strike many as radical:

**The marginal cost of environmental protection is converging toward zero.**

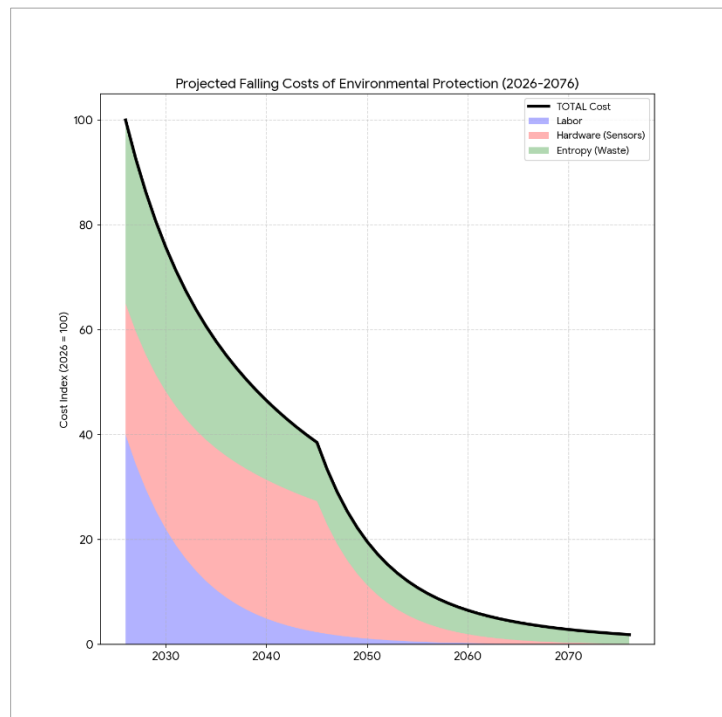
This is not policy advocacy. It is not technological optimism. It is the inevitable consequence of two physical laws approaching their limits:

1. The cost of information is falling toward the **Landauer Limit**
2. The cost of energy is transitioning to **nuclear density**

When both converge, environmental protection ceases to be a cost center and becomes what GPS and timekeeping already are: a background utility of civilization.

The work is not merely changing. It is disappearing.

And for those of us who entered this profession for love of nature rather than love of timesheets, this should be cause for celebration.



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## Part I: The Ontological Correction

### What Pollution Actually Is

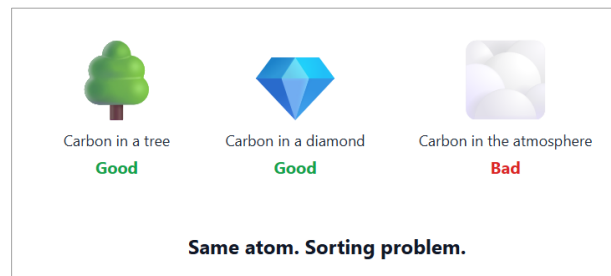
The first step toward understanding this transition is correcting a category error.

**Pollution is not a material problem. It is a configuration problem.**

A molecule of benzene in a sealed tank is an asset. The same molecule dispersed in groundwater is a liability. The atoms are identical. Only their arrangement and location differ.

Physics has a precise term for this: **entropy**—the measure of disorder in a system.

When matter is concentrated, ordered, and localized, it has low entropy. When dispersed, disordered, and uncertain, it has high entropy.



**Pollution is simply entropy increase.** Valuable matter moved from ordered states to disordered states.

**Environmental protection is entropy decrease.** Sorting. Restoring order. Returning atoms to useful configurations.

This reframing changes everything. Because entropy reduction has known physical costs—and those costs have floors.

### The Conservation of Matter

Earth approximates a closed system for matter. Atoms are neither created nor destroyed; they are rearranged. A carbon atom in atmospheric CO<sub>2</sub> is physically identical to a carbon atom in diamond. The distinction between "resource" and "pollutant" is not intrinsic to the atom. It is entirely a function of configuration and location.

- **Resource:** Methane in a storage tank. Ordered. Concentrated. Low entropy.
- **Pollutant:** That same methane dispersed at 1,900 ppb. Disordered. Dilute. High entropy.

Pollution is disordered wealth.

### The Second Law

The Second Law of Thermodynamics dictates that entropy increases spontaneously. Pollution is this law in action—the mixing of byproducts into the biosphere along the path of least resistance. To reverse mixing requires work. The governing relationship is Gibbs Free Energy:

$$\Delta G = \Delta H - T\Delta S$$

For pollution (mixing),  $\Delta S > 0$  and  $\Delta G < 0$ . The process is spontaneous.

For remediation (sorting),  $\Delta S < 0$  and  $\Delta G > 0$ . The process requires external work.

The cost of a clean planet reduces to two inputs:

1. **Energy (W)** — the work to overcome mixing
2. **Intelligence (I)** — the information to apply that work precisely

### The Equivalence of Entropy

Boltzmann defined physical entropy:

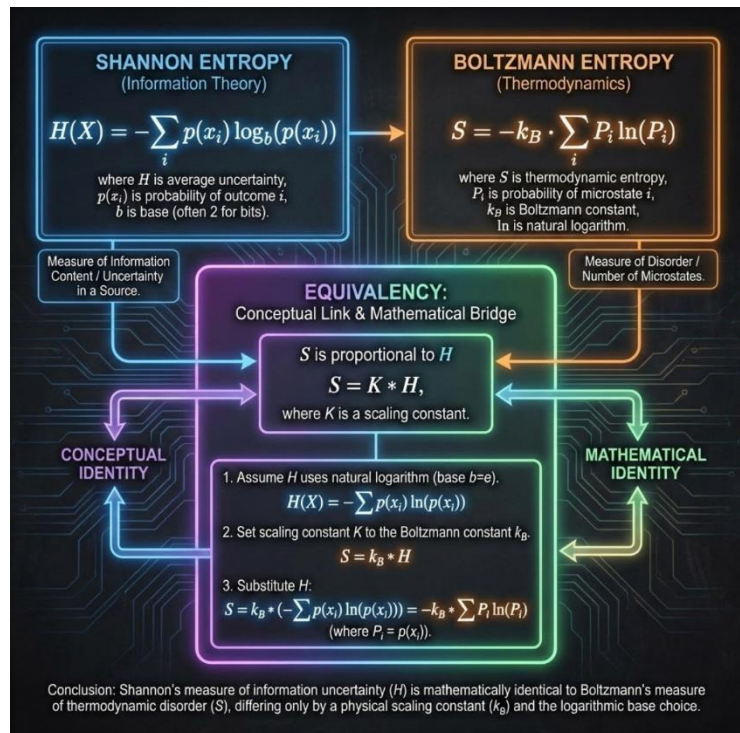
$$S = k_B \ln W$$

Shannon defined information entropy:

$$H = -\sum p_i \ln p_i$$

These differ only by a constant. They are the same phenomenon measured in different units. A high-entropy system is one where we lack information about the location of its particles. Pollution is missing information.

If we knew the trajectory of every SO<sub>2</sub> molecule leaving a smokestack, capture would require precise actuation, not brute filtration. **Environmental order is an information processing problem.** To reduce physical entropy, we must reduce informational uncertainty. This leads to the floor.



## Part II: The Bond-Bit Asymmetry

### The Twenty Orders of Magnitude

Here is the insight at the heart of this paper:

## Prevention and remediation operate at vastly different energy scales.

Consider a chemical storage tank with a failing valve:

### Scenario A: Remediation (After the Fact)

The valve fails. Chemical disperses into soil and groundwater. To remediate requires:

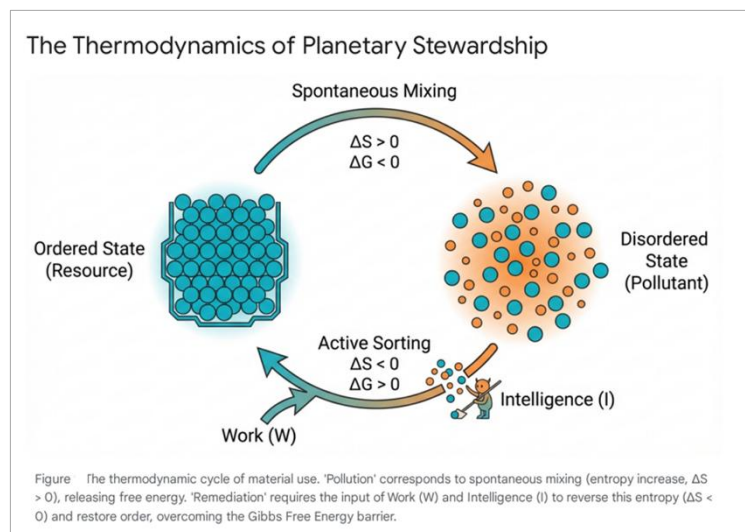
- Excavation and transport of contaminated soil
- Pump-and-treat systems for groundwater
- Chemical oxidation or bioremediation
- Breaking and reforming molecular bonds

Energy requirement:  $\sim 10^5$  Joules per mole of contaminant (the energy scale of chemical bonds)

### Scenario B: Prevention (Before the Fact)

A sensor detects micro-vibrations indicating valve degradation. A signal is sent. The valve is closed or replaced before failure.

Energy requirement:  $\sim 10^{-15}$  Joules (the energy of a digital signal in current computing)



## The ratio: $10^{20}$

Twenty orders of magnitude. One hundred quintillion to one.

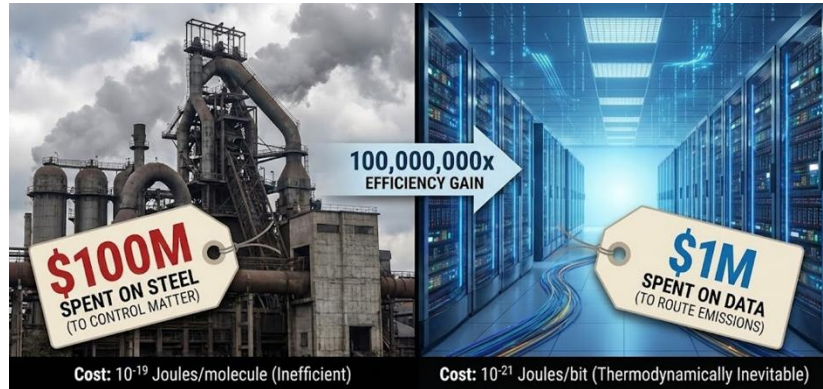
This is not an approximation. These are the actual energy scales at which chemistry and computation operate.

## Information Substitutes for Energy

This asymmetry reveals the fundamental nature of the transition we are undergoing.

In the old paradigm, environmental protection meant **work**—physically moving matter, breaking bonds, pumping fluids, treating waste. Work operates at the energy scale of chemistry: electron-volts, kilojoules per mole.

In the new paradigm, environmental protection means **information**—knowing where matter is, predicting where it will go, intervening before entropy cascades begin. Information operates at the energy scale of computation: approaching  $10^{-21}$  Joules per bit.



**We are substituting bits for bonds.**

Every increment of better sensing, better prediction, better real-time control shifts work from the expensive regime (chemistry) to the cheap regime (information).

This is Maxwell's Demon realized at industrial scale.

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## Part III: The Two Falling Curves

### Curve 1: Intelligence Approaching the Landauer Limit

In 1961, physicist Rolf Landauer established the theoretical minimum energy required to process information:

$$E_{\min} = k_B \times T \times \ln 2$$

At room temperature (300K), this equals approximately  $2.9 \times 10^{-21}$  Joules per bit.

This is not an engineering estimate. It is a consequence of the Second Law of Thermodynamics. No technology, no matter how advanced, can process information for less energy than this.

**Current state:** Modern computing operates at approximately  $10^{-12}$  Joules per operation.

**The gap:** We are currently  $10^9 \times$  above the theoretical floor—one billion times less efficient than physics permits.

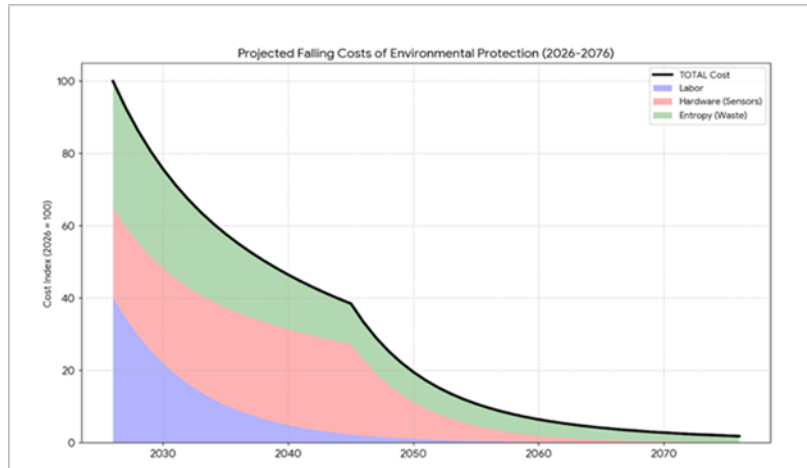
This gap is closing. Koomey's Law observes that computational efficiency doubles approximately every 1.6 years. As architectures evolve—neuromorphic, optical, quantum, eventually reversible—we slide down a frictionless slope toward the Landauer Limit.

**Implication:** The energy cost of "knowing"—sensing, modeling, predicting, deciding—is converging toward the thermodynamic floor. The intelligence required to monitor every valve, model every flow, track every atom, optimize every process is becoming energetically trivial.

## Curve 2: Energy Approaching Nuclear Density

The second curve concerns the energy available to do whatever physical work remains necessary.

Civilization currently runs primarily on **chemical energy**: breaking carbon-hydrogen bonds releases approximately **4 electron-volts** per reaction.



We are moving from chemical energy (atom surface) to nuclear (core).

- Chemical (Fossil): Breaking C-H bond releases  $\sim 4$  eV.
- Nuclear (Fusion/Solar): Fusing Hydrogen releases  $\sim 17.6$  million eV.

**The Gap:** Nuclear physics is 4 million times more energy-dense. As we harvest this (fusion/solar), marginal energy costs will asymptote toward simple equipment costs.

A kilogram of uranium contains the energy equivalent of roughly 3 million kilograms of coal. This is not engineering—it is the difference between the electromagnetic force (which governs chemistry) and the strong nuclear force (which governs nuclear reactions).

As energy production shifts to nuclear fission, fusion, and solar (which is fusion at 93 million miles), the marginal cost of energy again approaches the cost of infrastructure amortization alone. Energy transitions from scarce commodity to abundant utility.

**Implication:** Whatever physical work remains necessary for environmental protection—pumping, filtering, separating—becomes cheap. Not free, but cheap enough to be unremarkable.

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## Part IV: The Convergence

### What Happens at the Limits

When both curves approach their physics floors:

| Input                      | Current State               | Physical Floor           | Current Gap                        |
|----------------------------|-----------------------------|--------------------------|------------------------------------|
| Intelligence               | $\sim 10^{-12}$ J/operation | $\sim 10^{-21}$ J/bit    | $10^9\times$                       |
| Energy                     | $\sim \$0.05/\text{kWh}$    | $\sim \$0.01/\text{kWh}$ | $5\times$                          |
| Prevention vs. Remediation | Remediation dominates       | Prevention dominates     | $10^{20}\times$ leverage available |

The **labor** cost of environmental protection (humans reading, writing, analyzing, deciding) is automated away. This is already happening.

The **hardware** cost (sensors, monitors, infrastructure) follows learning curves downward and is increasingly replaced by "virtual sensors"—inference from existing data streams.

What remains is the **irreducible thermodynamic cost** of physical entropy reduction—and that cost is far lower than what we currently spend on labor and hardware combined.

Environmental protection becomes a background utility. The cost of a clean operation converges toward the cost of the information infrastructure that prevents disorder—which is converging toward the Landauer Limit.

**This is not speculation. This is the physics playing out.**

## Part V: The Work Is Disappearing

### A Professional Confession

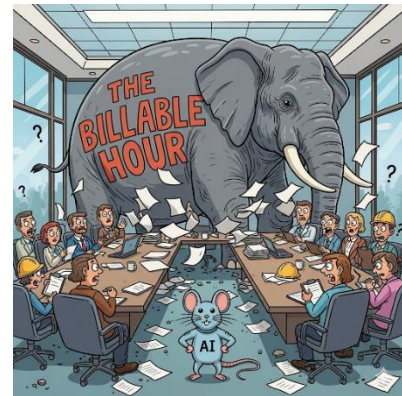
I have spent 25 years in the environmental profession. I have billed thousands of hours. I have helped write permits, compliance reports, impact assessments, audits, and applicability determinations.



And I must tell you the truth:

**Most of that work existed because we lacked information.**

We monitored because we could not predict. We remediated because we could not prevent. We documented extensively because we could not verify in real time.



The work was a tax on ignorance—the friction cost of operating without sufficient intelligence.

As intelligence approaches Landauer and energy approaches nuclear density, that friction disappears:

- **Permits** become real-time continuous compliance verification
- **Reports** become automated data streams
- **Assessments** become predictive models that prevent harm before it occurs
- **Monitoring** becomes ubiquitous, embedded, invisible

The work does not evolve into different work. It evaporates into infrastructure.

## **The Three Phases**

**Phase 1: Labor Substitution (Now–2035)** AI agents replace human labor in documentation, analysis, and compliance tracking. The "Paperwork Layer" of environmental management is automated.

**Phase 2: Prevention Dominance (2035–2055)** Real-time sensing and AI-driven process control shift the balance from remediation to prevention. We stop paying to clean up messes and start paying (far less) to prevent them.

**Phase 3: Background Utility (2055–2076)** Environmental protection becomes embedded in industrial infrastructure. The marginal cost of compliance approaches the marginal cost of computation—which approaches the Landauer Limit.

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## **Part VI: The Legacy Question**

### **We Are Mortal**

This brings us to the question that matters.

We will not live forever. Our careers will end. Our expertise, accumulated over decades, will eventually be lost—unless we encode it somewhere durable.

The question is not whether this transition will happen. The physics is inexorable.

The question is whether we participate in building it—or watch from the sidelines while it is built without us.

**Option A:** Bill hours until retirement. Resist the change. Watch the profession hollow out. Leave behind a career of timesheets and paperwork.



**Option B:** Spend the next decade encoding everything we know—our understanding of ecosystems, regulations, ethics, and judgment—into systems that will protect the planet for centuries. Leave behind a legacy.

We have one window. One moment in history where human environmental expertise can be transferred into machine intelligence. One chance to imbue these systems with our values.

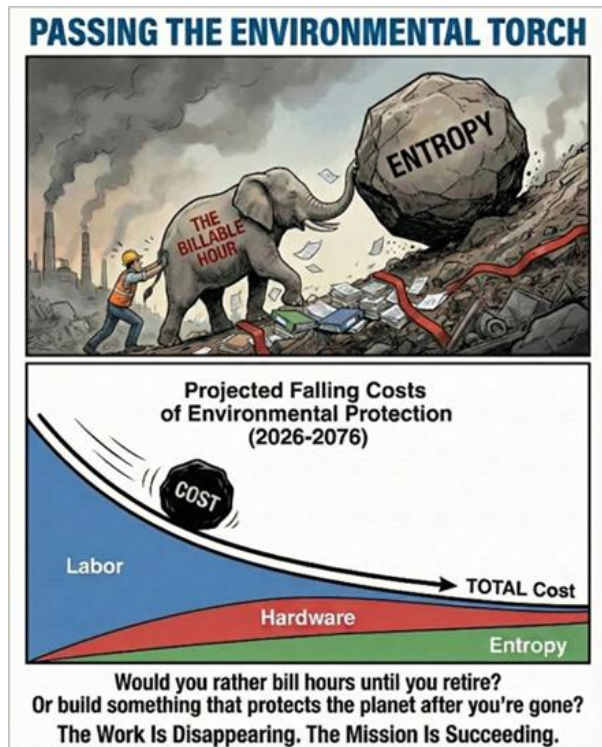
### The Sisyphus Question

For 50 years, the environmental profession has operated on the implicit assumption that our job is to push the boulder up the hill forever. To hold back entropy indefinitely through continuous human effort.

This is Sisyphus. It is exhausting. It is ultimately futile. And it was never the real goal.

**The goal was never to protect nature forever.**

The goal was to build the system that would.



That system is now being constructed. The physics permits it. The technology enables it. The only question is whether we—perhaps the last generation of environmental professionals who understand both the old world and the new—will be its architects.

# Part VII: The New Role

## What We Do Now

If the work is disappearing, what remains? The answer is: everything that matters.

**From Labor to Leadership** Stop selling hours; start selling judgment. Value-based pricing aligns compensation with outcomes rather than time. Our role becomes designing, overseeing, and auditing AI systems—ensuring they serve the public interest and respect environmental justice. The machine can execute; only we can decide what "good" looks like.

**From Paperwork to Principles** Codify the first principles of stewardship—entropy minimization, precaution, biodiversity—into the algorithms. AI lacks moral framework. We provide it. This is not a technical task; it is the most important work of our careers.

**From Monitoring to Mentoring** Train the next generation of AI by curating high-quality data and contextual knowledge. Every edge case we solve, every judgment call we document, every exception we explain becomes training data for systems that will operate long after we retire. We become stewards of knowledge rather than gatekeepers of process.

**From Compliance to Co-Creation** Work with industry and regulators to build the infrastructure—the planetary nervous system—that allows environmental protection to become a ubiquitous utility. Advocate for investment in Environmental AI, sensor networks, high-density energy, and open environmental data so that the zero-cost future arrives sooner.

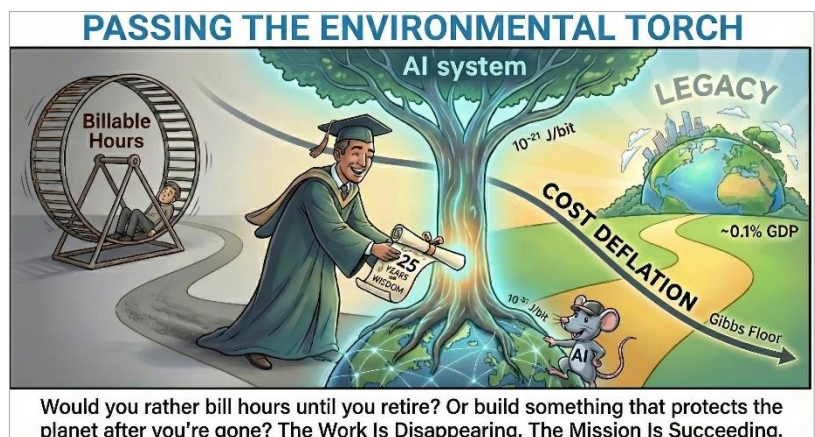
## The Paradox of Obsolescence

Here is the paradox: by making ourselves obsolete, we become more essential than ever.

The next decade is the critical window. The systems being built now will shape planetary stewardship for the next century. They can be built with our wisdom or without it. They can encode our ethics or operate without ethical grounding. They can reflect 50 years of hard-won environmental knowledge or start from scratch.

We are not optional. We are the bridge.

But only if we choose to walk across it.



# Conclusion: The Thermodynamic Equilibrium

A clean planet is not a political choice.

It is not primarily a moral aspiration.

It is the **thermodynamic equilibrium** of a civilization with sufficient intelligence and abundant energy.

When the cost of knowing approaches the Landauer Limit, and the cost of energy approaches nuclear abundance, the cheapest path for any industrial system is the clean path. Pollution becomes economically irrational—not because of regulations or values, but because prevention is  $10^{20}$  times cheaper than remediation.

We are approaching that threshold.

The environmental profession's role is not to resist this transition. Our role is to accelerate it—to ensure that when civilization crosses the threshold, it does so with systems encoded with the best of human environmental wisdom.

**The work is disappearing. The mission is succeeding.**

This is not the end of environmental protection. It is the beginning of environmental immunity.

And we—if we choose—can be the architects.

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## Appendix: Verification of Key Claims

| Claim                        | Value                                | Source                                       |
|------------------------------|--------------------------------------|--|
| Landauer Limit               | $2.87 \times 10^{-21}$ J/bit at 300K | Landauer (1961); $k_B \times T \times \ln 2$ |
| Current computing efficiency | $\sim 10^{-12}$ J/operation          | IEEE literature on CMOS                      |
| Gap to Landauer              | $\sim 10^9 \times$                   | $10^{-12} \div 10^{-21}$                     |
| Chemical bond energy         | $\sim 4$ eV (C-H bond: 4.3 eV)       | CRC Handbook                                 |
| Nuclear fission energy       | $\sim 200$ MeV per U-235 fission     | IAEA   |
| Energy density ratio         | $\sim 50,000,000:1$                  | $200 \text{ MeV} \div 4 \text{ eV}$          |
| Valve signal energy          | $\sim 10^{-15}$ J                    | Current CMOS signal energy                   |
| Remediation energy scale     | $\sim 10^5$ J/mol                    | Bond energies $\times$ molar quantities      |
| Bond-Bit leverage ratio      | $\sim 10^{20}$                       | $10^5 \div 10^{-15}$                         |
| Koomey's Law                 | $\sim 1.6$ year doubling             | Koomey et al. (2011)                         |

All figures represent order-of-magnitude values for the purpose of illustrating the fundamental asymmetry. Specific applications will vary.

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**EnviroAI** | Houston, Texas | January 2026

*The goal was to build the system that would.*