

H HEURISTICS

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The Architecture of Entropy

Thermodynamics, Complexity and the Systemic

Unraveling of Civilisations

Thermodynamics · Complexity science · Polycrisis · Resilience

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H Heuristics · Architecture of Creation series

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About This Report

This report asks what the second law of thermodynamics, and the family of ideas around it, can and cannot tell us about the loss of organised structure in civilisations, ecosystems and the Earth system. It is a companion to [The Architecture of Creation](#), which asked why the same forms recur in nature, and it applies the same discipline: separate the layers of explanation, grade the evidence, state what would count against the thesis, and keep analogy honest.

It is written for readers who want a rigorous but readable account: researchers working on resilience and systemic risk, analysts who need a defensible way to talk about decline, and decision-makers who want to know which warnings are physics, which are well-supported social science, and which are speculation.

How to read this report

Each section starts on a new page and can be read on its own. Section 1 states the thesis and scope. Section 2 sets out the thermodynamic foundations. Sections 3 to 6 move up the ladder from physical structure to civilisation, to the contemporary polycrisis, and to long-term decline. Section 7 proposes a general framework, Section 8 tests it, Section 9 turns it into working heuristics, and Section 10 concludes.

Blue underlined text is a hyperlink. Links go to the primary literature through a DOI where a specific result is cited, and to a reference article where a concept is introduced. A full reference list appears at the end. Some publishers block automated access, so a handful of links may need to be opened in a browser.

Evidence grades

Claims are graded where it matters, using the same four-level scale as the rest of the series.

Table 1. Evidence grades used in this report

Grade	Meaning
A: Established	Derived mathematically, or confirmed repeatedly by independent experiment or observation.
B: Well supported	Strong evidence from several lines of work, with some unresolved dissent.
C: Plausible or contested	Credible mechanism, but the field is actively debating it.
D: Speculative	A hypothesis offered for testing. It is labelled as such wherever it appears.

A note on the figures

The report contains 22 figures. Eight plot published data (NOAA, NASA, the World Bank, the Energy Institute and Our World in Data) or values reported in the cited papers. Seven are original simulations or calculations written for this report, and the remaining seven are diagrams and judgement-based syntheses. Each caption says which kind it is. Simulation outputs illustrate mechanisms; they are not forecasts, and the model parameters are listed in Appendix B.

Executive Summary

The question

A cup of coffee cools, a sandcastle erodes, a bridge needs repainting, a company loses its best people and a government loses the trust of the governed. Physics has one word, entropy, that sits behind the first two and a loose, metaphorical presence behind the last three. Writers on collapse reach for it constantly. Is the reach justified? And if it is, what does it add to the ordinary study of why societies fail?

The thesis

Persistent structure is a flow, not a state. Every organised system, from a cell to a city, exists because energy and materials pass through it and because its maintenance and repair keep pace with its wear. Entropy sets the cost of that upkeep. Systemic unraveling is what happens when accumulated stress, tighter coupling and weaker recovery push the rate of loss above the rate of restoration, so that buffers shrink, failures cascade, and the system settles into a simpler state it cannot easily leave.

The thesis is deliberately narrow. It does not say that civilisations obey the second law in some mystical sense, and it does not say that decline is inevitable. It says that thermodynamics fixes the underlying constraint (order must be paid for), that complexity science explains how stress turns into abrupt change, and that the history of social collapse shows the pattern in practice. We call the resulting combination of stressors, couplings and recovery limits an *unraveling structure*, the mirror image of the creation structure developed in the series' first report.

Principal findings

- 1. Entropy is a precise physical quantity, and its social uses are analogies.** Thermodynamic entropy, information entropy and the looser 'organisational entropy' of social writing are three different things. The first is Grade A, the second is Grade A in its own domain, and the third is a useful label for processes that must be shown mechanism by mechanism (Section 2).
- 2. Local order is cheap and global order is paid for by export.** The Earth stays far from equilibrium because it receives sunlight at about 5,800 K and radiates heat at about 255 K, exporting roughly 23 times more entropy per joule than it imports. Every organism, city and economy rides that gradient (Grade A, Section 2).
- 3. Complex structures need continuous throughput.** Energy rate density rises by about six orders of magnitude from galaxies to industrial society, and the world now uses roughly 600 exajoules of primary energy a year, about 15 times the 1900 level in the Our World in Data long-run series. Structure that costs more to maintain than it returns cannot be sustained (Grades A and B, Sections 3 and 4).
- 4. Civilisational decline is a maintenance and coordination problem as much as a resource problem.** Diminishing returns to complexity, falling energy surplus, deferred maintenance and weakening institutions recur in the best-documented collapses, though no single cause explains any of them (Grade B, Section 4).

5. **Stress accumulates silently and then shows up as speed.** Seven of nine planetary boundaries are now breached, atmospheric carbon dioxide averaged 427 ppm in 2025, and the average wildlife population has fallen by 73 per cent since 1970. Systems approaching a threshold lose resilience before they fail: in our ensemble, variance more than doubled and autocorrelation rose from 0.58 to 0.78 in the run-up to tipping (Grades B and C, Section 5).
6. **Cascade severity depends on buffers and structure more than on the size of the shock.** In a load-redistribution model, a random network lost 8 per cent of its nodes at a spare capacity of 30 per cent, while a hub-and-spoke network lost 79 per cent. Removing the three largest hubs cost about 88 per cent of the network even with 100 per cent spare capacity (Grade B for the principle, Section 5).
7. **Loss is fast and recovery is slow, and that asymmetry creates hysteresis.** In the bistable model, collapse occurs at a stress level of 2.6, but recovery requires stress to fall below 1.8. Real recovery times range from months for supply chains to millennia for ice sheets (Grade B, Section 6).
8. **The unraveling pathway is not a forecast.** Ozone recovery under the Montreal Protocol, solar and wind output in 2025 that was about 170 times its 2000 level, and population growth slowing toward a peak all show deterioration pathways being bent or reversed. The thesis is a framework for locating risk, and Section 8 lists eight predictions by which it could fail (Grade B, Sections 6 to 8).

What follows from it

The practical payoff is a short set of working heuristics (Section 9). Measure the margin between restoration and loss, not the size of the stress. Size buffers to the hub, not the average. Treat maintenance as the primary budget line of a durable system. Watch for slowing recovery as an early warning. Reduce coupling where it carries no benefit and build modularity where it does. And treat the period before a threshold is crossed as the cheap one, because after it the cost curve changes shape.

Data and method

The report draws on thermodynamics and statistical physics, complexity science, ecology, economic history and archaeology, and on current Earth-system and demographic data. Primary data come from NOAA, NASA GISTEMP, the World Bank, the Energy Institute and Our World in Data, with data accessed on 28 October 2026 and some 2026 values preliminary. Where a result comes from a published paper, the paper is linked. Where it comes from a simulation or from H Heuristics judgement, the caption says so.

1. Central Thesis and Scope

1.1 The observation

Organised things do not last by default. Ice melts in a warm room, rust takes iron, a road breaks up under frost, a language drifts, a firm decays when the people who understood it retire. Yet the universe also contains stars, cells, forests and cities, structures of enormous order that persist for years or billions of years. The first report in this series, [The Architecture of Creation](#), asked why the same forms keep appearing: spirals, hexagons, branching networks. Its answer was that generative rules operate inside constraints and a filter keeps what is stable.

This report asks the mirror question. If creation has an architecture, so does its undoing. The same physical reality that lets structure emerge also dictates what it costs to keep and how it comes apart. Understanding the second half of that sentence is not morbid. It is the practical half of resilience: you cannot protect what you do not understand how to lose.

1.2 The thesis

Thesis. Persistent structure depends on continuous flows of energy and materials and on maintenance that matches wear. Entropy fixes the underlying cost. In complex societies and ecosystems, accumulated stress, tight coupling and declining recovery capacity can push the rate of loss above the rate of restoration. The result is a recognisable sequence: stress accumulates, adaptive capacity declines, failures cascade, structure simplifies or fragments, and unsafe conditions persist until recovery is rebuilt.

We call the combination of stressors, couplings and recovery limits an *unraveling structure*. It parallels the creation structure of the first report, which had three parts: generative rules, constraints and a stability filter. Figure 1 sets the two side by side.

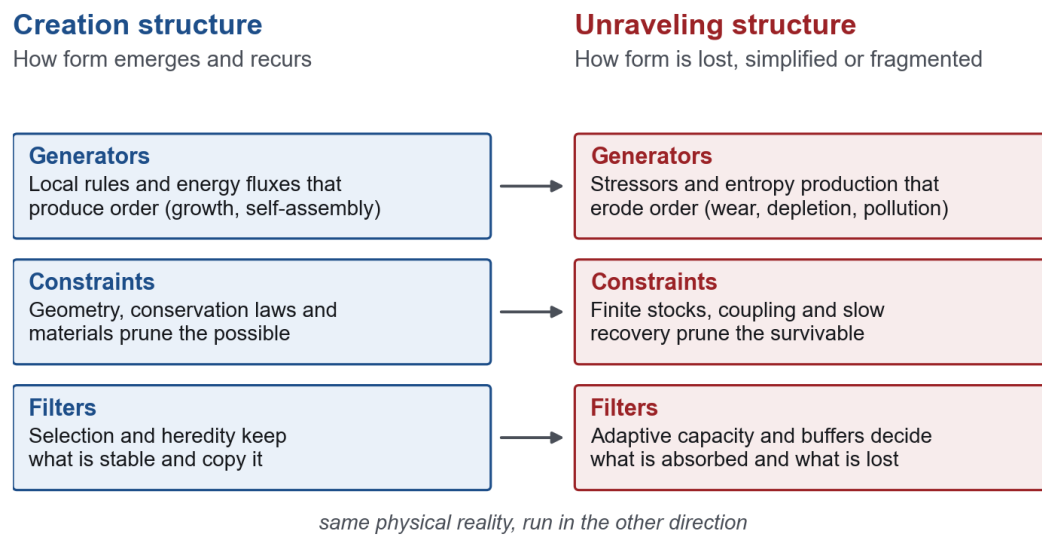


Figure 1. Creation and unraveling as mirror architectures. The same three components, read in opposite directions, organise the explanation of emergence and of loss.

Source: H Heuristics, adapted from *The Architecture of Creation* (2026). Conceptual diagram.

1.3 What the thesis does and does not claim

Three disciplines of claim keep this subject from sliding into rhetoric.

- **It does not claim that civilisations obey the second law.** The second law applies to the total entropy of an isolated system. A society is not isolated, and it is not a thermodynamic system in any strict sense. The law constrains the energy and material budget that societies run on; it does not dictate their politics.
- **It does not claim that decline is inevitable.** Open systems can persist for very long periods and can rebuild. The thesis is about conditions: what must be true for persistence, and what happens when those conditions lapse.
- **It does claim that entropy supplies a real constraint, and that the constraint is visible in measurable quantities.** These include energy surplus, maintenance backlogs, material circularity, coupling between sectors and the recovery time of lost capacities. Where a social claim cannot be tied to such a quantity, it is treated as an analogy and graded accordingly.

1.4 Method and evidence standards

The method has four parts. First, each concept is anchored in the source discipline: physics for entropy, ecology for resilience, archaeology and economic history for collapse. Second, each transfer across disciplines is tested by asking what mechanism carries it. Third, the report uses simple, transparent models to illustrate mechanisms (Appendix B lists every parameter), and says plainly that the models are illustrations. Fourth, Section 8 states what would count against the thesis. Claims are graded A to D (Table 1).

1.5 Intellectual context

The ideas assembled here have a long history. Rudolf Clausius coined *entropy* in 1865; Ludwig Boltzmann gave it a statistical meaning; Erwin Schrödinger's 1944 [What Is Life?](#) asked how living things avoid decay; Ilya Prigogine won the 1977 Nobel Prize in Chemistry for the theory of [dissipative structures](#). In economics, [Nicholas Georgescu-Roegen](#) argued that the economic process is irreversibly entropic. In archaeology, Joseph Tainter's [The Collapse of Complex Societies](#) (1988) tied decline to diminishing returns on complexity. In ecology, C. S. Holling's [1973 paper](#) introduced resilience as the capacity to absorb disturbance. And a recent literature on the [global polycrisis](#) studies how crises interact.

The sibling reports in this series apply related ideas to specific problems. [The Architecture of Europe's Rise and Dissolution](#) asks whether the architecture that lets a civilisation expand can also explain how it loses coherence. [The Cascading Risk Atlas](#) maps how local shocks become global crises. [The Weight of the Polycrisis](#) traces how pollution, heat and hunger harm bodies and minds, and [The Century Compass](#) asks where humanity is headed by 2100. This report supplies the physical and theoretical foundation under them.

Key points. Entropy sets a real cost on keeping order. Societies are open systems and can pay that cost indefinitely if flows and maintenance hold. The unraveling structure names what happens when they do not. Entropy is the constraint; mechanisms, not metaphor, carry the argument.

2. The Thermodynamic Foundations of Entropy

2.1 From heat engines to the arrow of time

Entropy began as an accounting device for steam engines. In 1865 Clausius defined it through the heat exchanged reversibly at a given temperature, and observed that in any isolated system it never decreases. That statement, the [second law of thermodynamics](#), explains why heat flows from hot to cold, why engines cannot be perfectly efficient and why some processes are irreversible. It is among the most thoroughly tested laws in science (Grade A).

Boltzmann supplied the microscopic meaning. A system's macrostate (say, a gas at a given temperature and pressure) can be realised by an enormous number of microstates, W . [Boltzmann's formula](#), $S = k \ln W$, with $k = 1.380649 \times 10^{-23}$ joules per kelvin, makes entropy a measure of how many microscopic arrangements are compatible with what we observe. Entropy rises because disordered macrostates correspond to vastly more microstates than ordered ones. The increase is overwhelmingly probable, not logically forced.

The [Ehrenfest urn model](#) shows this directly. Place N particles in the left half of a box and let one randomly chosen particle hop to the other side at each step. Figure 2A shows entropy rising to its maximum within a few steps per particle and then fluctuating around it. Figure 2B shows why return is practically impossible: the mean time to return to the all-on-one-side state is 2^N steps, which is about 10^{24} steps for 80 particles and 10^{193} for 640. A gas in a room contains around 10^{25} molecules.

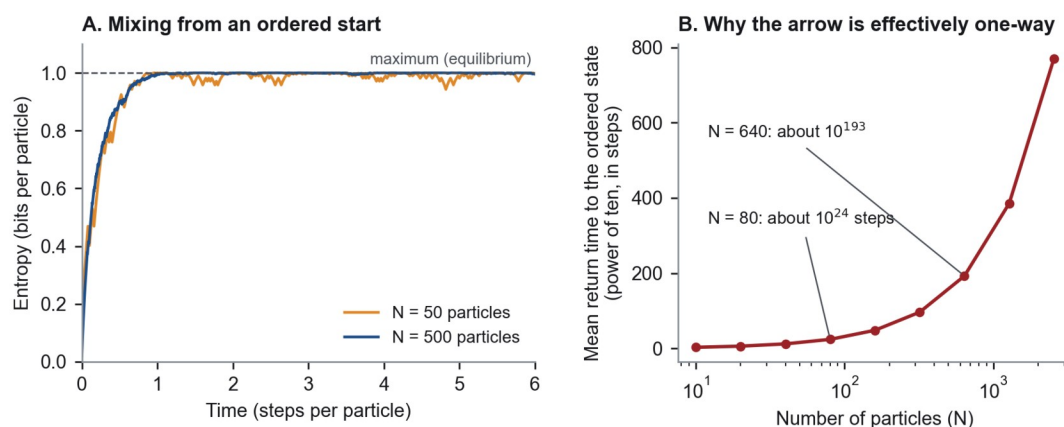


Figure 2. The Ehrenfest urn. (A) Entropy rises quickly from an ordered start and then fluctuates at its maximum; larger systems fluctuate less. (B) The mean return time to the ordered state grows as 2^N .

Source: H Heuristics simulation (urn model, 6 steps per particle, seed 11). Return time is analytic.

2.2 Irreversibility and the limits of the word

Irreversibility is the key concept for everything that follows. A process is irreversible if running it backwards would require a decrease in total entropy, which does not happen spontaneously. Friction, mixing, diffusion, chemical reaction and the equalisation of temperature are all irreversible. So is the wear

of physical objects, which comes from many small irreversible events: atoms displaced, bonds broken, stresses relieved.

The word *entropy* is used loosely in public debate to mean disorder, decay or chaos. Strictly it is a measure of the number of microstates, and in many cases ordered-looking states have higher entropy than disordered-looking ones (a densely packed hard-sphere crystal, for example, has higher entropy than the corresponding liquid). The discipline of this report is to use the word only where a physical or informational quantity is meant, and to say 'loss of organisation' where the argument is about structure.

2.3 Local order, global entropy

How can anything stay ordered if entropy must rise? The answer is that the second law applies to the *total* entropy of a system and its surroundings. A refrigerator lowers the entropy inside by raising it more outside. A living cell keeps itself ordered by taking in low-entropy energy and materials and releasing high-entropy waste and heat. Schrödinger said that what an organism feeds upon is negative entropy; a more careful modern phrasing is that organisms are open systems that export entropy faster than they produce it.

The Earth does this at planetary scale. It absorbs roughly 240 watts per square metre of sunlight averaged over the globe, and emits about the same amount back as infrared radiation (see [Earth's energy budget](#)). The energy in and out is nearly balanced. The entropy is not. The entropy carried by radiation scales inversely with the temperature of the source, so a joule of sunlight from a 5,772 K photosphere carries far less entropy than a joule of infrared leaving an Earth that radiates at an effective temperature near 255 K. The ratio is about 23 (Figure 3). The Earth therefore exports about 23 times as much entropy as it imports, and that surplus is what allows weather, oceans, forests and cities to exist (Grade A for the physics; the ratio is a first-order estimate).

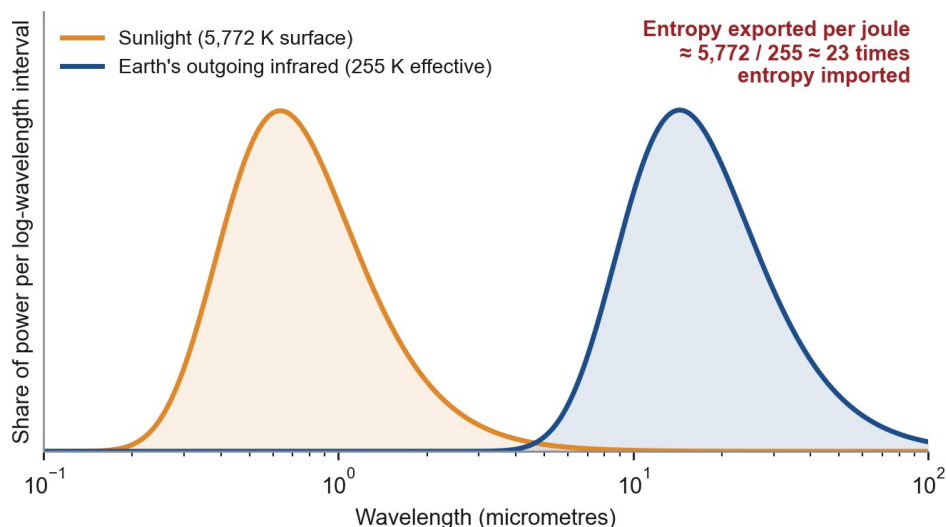


Figure 3. Earth as an entropy exporter. Sunlight arrives as short-wavelength radiation from a 5,772 K surface; the Earth sends back about the same power as long-wavelength infrared from an effective 255 K. The entropy flux out exceeds the flux in by about $T(\text{Sun})/T(\text{Earth}) \approx 23$. Curves are Planck spectra normalised to equal area.

Source: H Heuristics calculation from Planck's law; temperatures from standard reference values.

Prigogine's contribution was to show that systems driven far from equilibrium by such a flux can spontaneously form ordered patterns, which he called [dissipative structures](#). A pan of liquid heated from

below organises into hexagonal [Bénard convection cells](#), because the cells carry heat faster than conduction would. Jeremy England's [statistical physics of self-replication](#) argues that driven systems tend to find configurations that absorb and dissipate work efficiently. Ordered structure and entropy production are therefore not opposites. Under a steady flux, organisation can be the more efficient way to dissipate energy (Grade B; England's generalisation is Grade C).

2.4 Information and the cost of erasing it

Claude Shannon's 1948 paper, [A Mathematical Theory of Communication](#), defined an entropy for messages that has the same mathematical form as Gibbs's thermodynamic entropy. The link is more than formal. In 1961 Rolf Landauer showed that erasing one bit of information in an environment at temperature T must dissipate at least $k T \ln 2$ of heat, which is about 2.9×10^{-21} joules at room temperature ([Landauer 1961](#)). Information is physical, and forgetting has a thermodynamic price.

This matters for social systems because institutions, laws, technical know-how and organisational memory are stores of information. They are maintained at a cost, and when the maintaining effort lapses they decay. Section 4 returns to this point.

2.5 Three entropies, and what transfers

The word is used for three different things. Keeping them apart prevents most errors.

Table 2. Three senses of entropy and what each can support

Sense	What it measures	Where it applies	What can be claimed
Thermodynamic	Heat divided by temperature; the count of microstates ($S = k \ln W$)	Physical systems with defined temperature: engines, gases, ecosystems' energy budgets	Constraints on energy and material use. Grade A.
Information	Uncertainty or surprise in a message (Shannon, $H = -\sum p \log p$)	Communication, computation, data, genomes	Limits on coding and the cost of erasure. Grade A in its domain.
Organisational (analogical)	Loss of structure, coordination or capability, however measured	Firms, states, ecosystems, infrastructure	A label for processes that need mechanism-level evidence. Grade C unless tied to a measured quantity.

The third row is where most popular claims sit. A claim that 'a society's entropy has risen' is meaningless until the claimant says which quantity: lower energy surplus, more deferred maintenance, higher conflict, lower trust, or less diversity. This report uses thermodynamics to bound what societies can do and then uses empirical measures for each mechanism.

2.6 Summary

Key points. Entropy is a precise quantity with a firm statistical meaning. Local order is compatible with the second law because open systems export entropy; the Earth exports about 23 times what it imports. Driven systems can create structure, but structure must be fed. Information has a thermodynamic cost. 'Organisational entropy' is a metaphor, and every claim that uses it must be tied to a measurable mechanism.

3. The Emergence and Persistence of Structure

3.1 Structure as a flow

A candle flame has a stable shape, a river has a stable course, and a cell has a stable composition, yet in each case the matter that makes it up is constantly replaced. The structure is a pattern in a flow. This is the core idea of dissipative structures, and it has a simple consequence: remove the flow and the structure decays on a timescale set by its internal loss rate.

A minimal statement is a stock N of organised material or capability that is produced at rate P and decays at fractional rate δ . At steady state $N^* = P / \delta$. If production halts, N falls exponentially with a half-life of $0.69 / \delta$. Everything interesting in the rest of this report concerns what happens when P becomes harder to sustain, when δ is raised by stress, or when the two are coupled to other stocks. A protein turns over in hours or days, a forest in centuries, a road surface in years and a legal institution in generations, but each follows the same logic: persistence is bought with continuing production.

3.2 More complex structures need denser flows

Eric Chaisson proposed measuring structural complexity by *energy rate density*, the power flowing through a system per unit mass, in erg per second per gram. His estimates span about six orders of magnitude, from about 0.5 for the Milky Way galaxy and 2 for the Sun, through about 75 for Earth's climate system and 900 for plants, to roughly 20,000 for the human body, 150,000 for the human brain and 500,000 for modern industrial society (Figure 4; [Chaisson 2015](#)). Later and more complex structures run on denser flows.

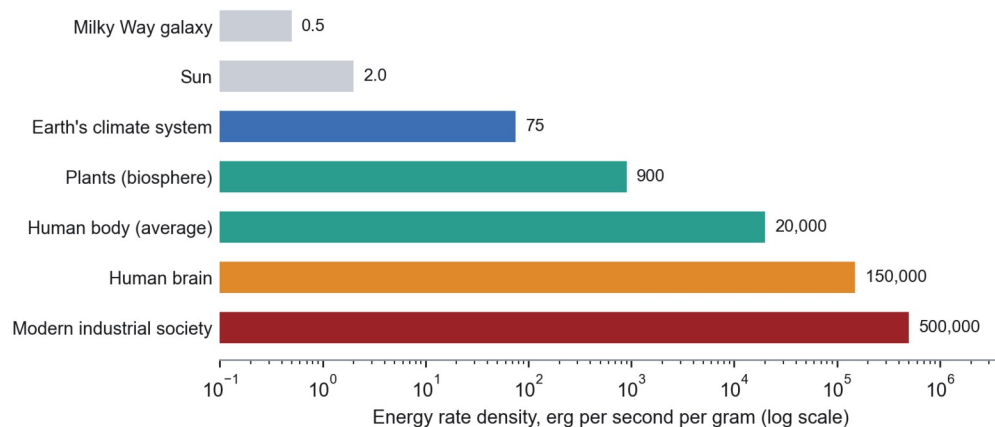


Figure 4. Energy rate density across the hierarchy of structure. Values are approximate estimates reported by Chaisson and span about six orders of magnitude (log scale).

Source: Chaisson (2015), *Entropy*; values as reported, rounded. Treat as order-of-magnitude (Grade C as a complexity metric).

The metric is contested. Critics point out that a furnace can use huge amounts of energy while having little organisation, and that the argument risks circularity if complexity is defined partly by energy use. The defensible reading is narrower: it is a measure of how much a structure depends on throughput, and so of

how sharply it would respond to a supply interruption. On that reading, the numbers are a statement about exposure, not about merit. A system that has become 10^6 times more energy-dense than a galaxy has also become much more dependent on continuing supply.

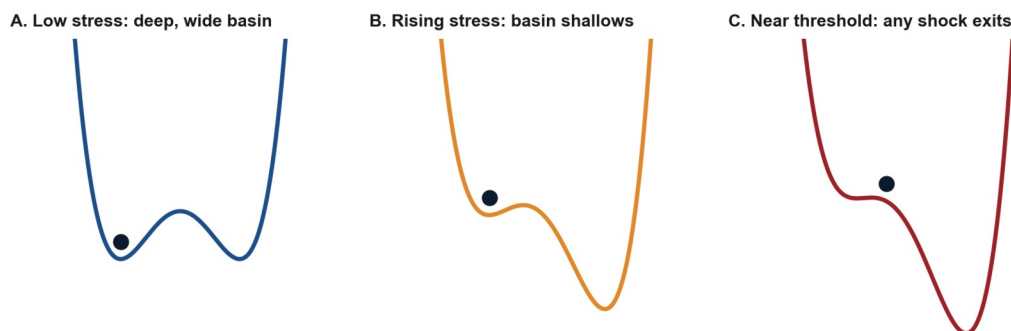
3.3 Scaling laws and the cost of growth

Biological and urban scaling laws put numbers on the cost of upkeep. Metabolic rate scales with body mass to roughly the power $3/4$ ([Kleiber's law](#)), a pattern West, Brown and Enquist [explained](#) through the geometry of fractal distribution networks. Luis Bettencourt and colleagues [found](#) that cities show two regularities. Infrastructure such as road length and cable length scales sub-linearly with population, with an exponent near 0.85, which is an economy of scale. Wages, patents and many socioeconomic outputs scale super-linearly, with an exponent near 1.15 (Grade B).

The same analysis gives a warning. Growth driven by super-linear returns is faster than exponential and would reach a finite-time singularity unless it is reset by innovation. Cities and economies avoid the singularity by periodically changing their basis of production, and each reset must come faster than the last. A system that depends on accelerating renewal is exposed to any interruption of that renewal.

3.4 Stability landscapes and the meaning of resilience

A structure can persist in two ways: by resisting change, or by recovering from it. Holling's [1973 paper](#) distinguished these as *stability* and *resilience*, and defined resilience as the size of disturbance a system can absorb before it moves into a different regime. The standard picture is a ball in a landscape (Figure 5). The valleys are stable states. The width and depth of a valley are the system's resilience.



Stress tilts the landscape; the same shock that was absorbed in A tips the system out of its basin in C

Figure 5. Stability landscape. Rising stress tilts the landscape, shrinking the basin of attraction around the current state; near the threshold even a small shock moves the system into the other basin.

Source: H Heuristics conceptual diagram (tilted double-well potential).

Two properties of this picture matter later. First, stress can reduce resilience while the system looks unchanged, because the ball sits at the same point while the basin around it shrinks. Second, once the ball crosses into the other basin, removing the stress does not return it, because the new basin is itself stable. Marten Scheffer and colleagues' work on [catastrophic shifts in ecosystems](#) and Robert May's [1977 analysis](#) of ecosystems with multiple stable states established that this behaviour is real in lakes, rangelands, reefs and fisheries (Grade B). Section 6 uses a simple model of this type.

3.5 Optimisation principles, with caution

Several authors have proposed that flow systems organise themselves to optimise some quantity. Adrian Bejan's [constructal law](#) says that flow systems evolve toward configurations that ease the flow, and H. T. Odum's maximum-power principle says that evolving systems tend to maximise useful power. These ideas connect the emergence of structure to energy flow and offer predictions about river basins, lungs and road networks. They remain contested as universal laws (Grade C). Our use is limited: they support the idea that persistent structures tend to be efficient carriers of flux, and therefore that efficient carriers are a precondition for persistence under tight energy budgets. They do not enter the core argument.

3.6 Summary

Key points. Persistent structure is a pattern in a flow: stock equals production divided by decay. Denser flows support more complex structure, and expose it to interruption. Cities and organisms show scaling laws that make growth cheap per unit but dependent on renewal. Resilience is the size of the basin around the current state, and stress can shrink it without any visible change. Once a threshold is crossed, removing the stress may not restore the old state.

4. The Entropy of Civilization

4.1 Civilisation as an energy-processing structure

Civilisation is the largest dissipative structure humans have built. Figure 6 shows how much energy it now processes. In 1800 the world's primary energy supply was about 5,700 terawatt-hours a year, nearly all of it traditional biomass. By 1900 it was about 12,100. By 2025 it was about 177,900 terawatt-hours a year on the Our World in Data series, about 15 times the 1900 level (this series uses the substitution method; the Energy Institute reports [just over 600 exajoules](#) of primary energy for 2025, about 167,000 terawatt-hours, on its newer direct-equivalent basis, a difference explained by method).

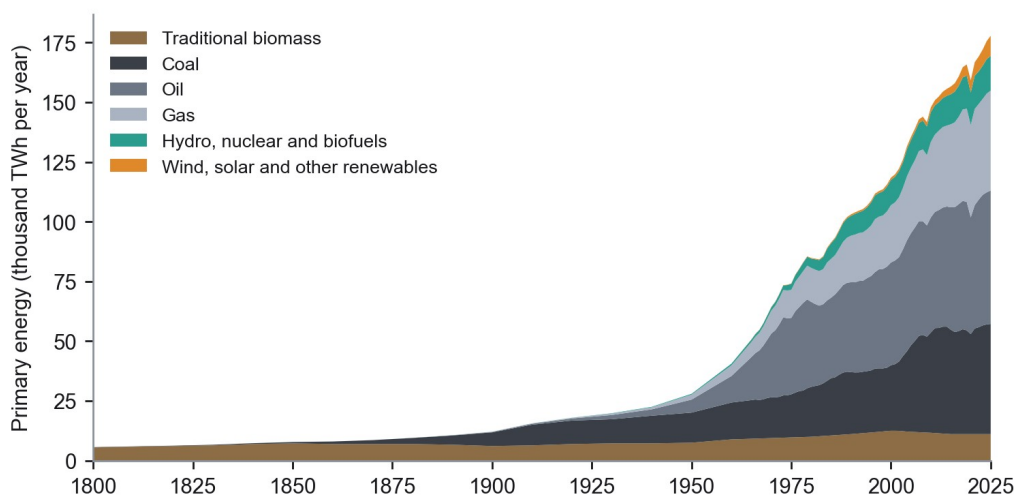


Figure 6. World primary energy supply by source, 1800 to 2025. The substitution-method series inflates non-fossil sources relative to the Energy Institute's current headline, which puts fossil fuels at about 86 per cent of 2025 supply; in this series the fossil share is 81 per cent.

Source: Our World in Data, based on the Energy Institute Statistical Review and Smil (2017); accessed 28 October 2026.

The composition matters as much as the size. Fossil fuels supply roughly four-fifths or more of the energy that runs the system, according to the accounting method used. The [Energy Institute's 2026 review](#) and [Carbon Brief's analysis](#) report that clean power was the world's largest source of new energy in 2025 and that fossil use still grew. That combination, a rising stock of dependence and a slow turn in its composition, is the most important thermodynamic fact about the present.

4.2 Energy and wealth

Energy use and income move together. Across 142 countries with data for 2022, the logarithm of energy use per capita is correlated with the logarithm of GDP per capita at $R^2 = 0.77$, with a slope of 0.82 (Figure 7). On average, a country with 10 per cent more income uses about 8 per cent more energy. The relationship is not causal in a strict sense, and rich countries have decoupled partially, but it shows that the economic structures people value are tied to energy flows.

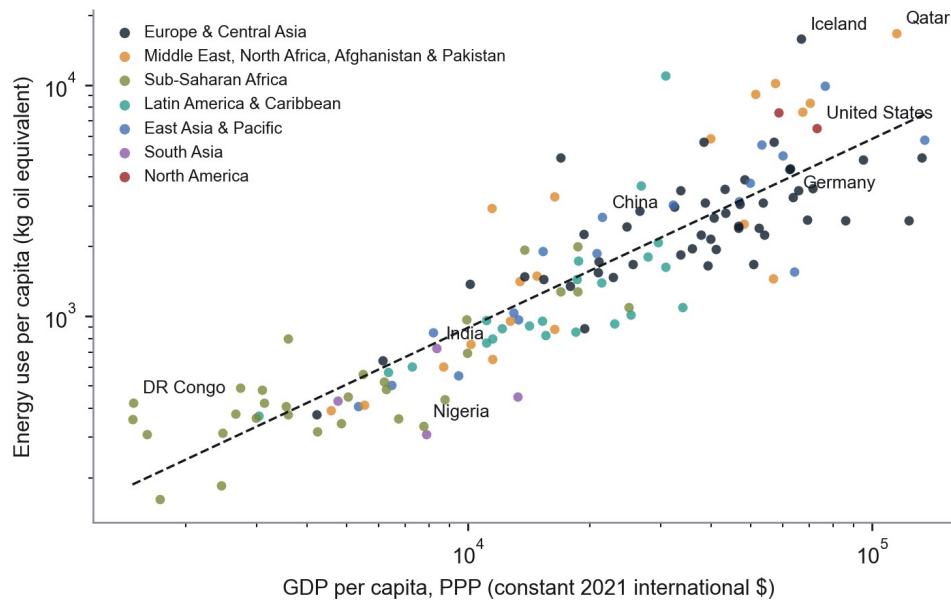


Figure 7. Energy use per capita against GDP per capita, 2022, 142 countries (log scales). The dashed line is an ordinary least-squares fit: slope 0.82, $R^2 = 0.77$.

Source: World Bank WDI (EG.USE.PCAP.KG.OE, NY.GDP.PCAP.PP.KD), accessed 28 October 2026; H Heuristics calculation. Regions follow World Bank classification.

4.3 Materials and the second law

Entropy also governs materials. Georgescu-Roegen observed that matter, like energy, degrades: concentrated ores become dispersed products, and dispersed materials cannot be re-concentrated without energy. Global material use now exceeds 100 billion tonnes a year, and the [Circularity Gap Report 2025](#) puts the share that comes from recycled sources at 6.9 per cent, down from 9 per cent in 2018. A 2020 study in *Nature* by [Elhacham and colleagues](#) estimated that the mass of human-made objects, about 1.1 trillion tonnes, passed the dry mass of all living biomass in 2020, having doubled roughly every 20 years (Grade B).

These figures show a very large structure that is built to a large extent from non-renewable stocks. All of it eventually needs maintenance, replacement and, at end of life, handling as waste. Dispersal is the default.

4.4 The energy surplus

A society is sustained by the net energy left after the cost of getting energy. The standard measure is *energy return on energy invested* (EROI). [Hall, Lambert and Balogh](#) reviewed the evidence in 2014 and reported mean EROI of about 20:1 for world oil and gas, 46:1 for coal, 14:1 for nuclear, 84:1 for hydroelectricity and about 2:1 for biomass diesel (Figure 8). They also reported that EROI for oil and gas had declined in the countries examined. Values depend strongly on the boundary chosen and are disputed; the numbers are indicative, not exact (Grade C).

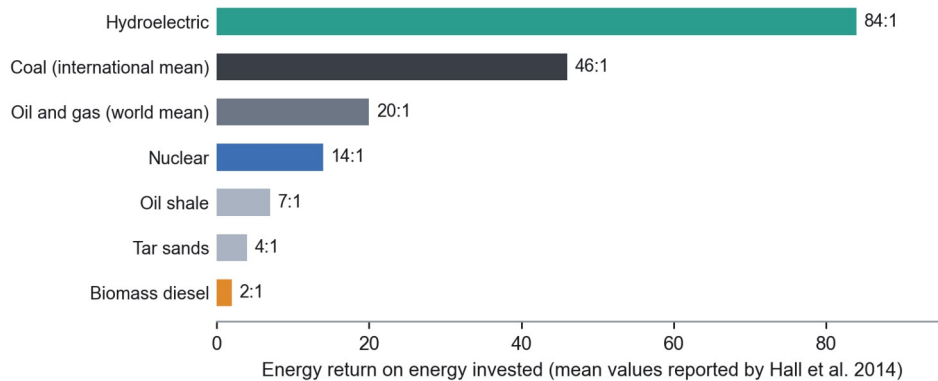


Figure 8. Energy return on energy invested for selected fuels. Values are mean estimates reported in Hall et al. (2014) and vary by region, time and boundary definition.

Source: Hall, Lambert and Balogh (2014), *Energy Policy* 64, 141–152. Reported mean values, rounded.

The argument is straightforward. If the energy needed to obtain energy rises, the share of society's output that is free for other uses falls. At very low ratios, little is left to maintain complexity. Whether the global transition to wind and solar changes this depends on system-level EROI including storage and grids, which remains debated. The central point for this report is that surplus energy is a necessary condition for maintaining structure, and it can be eroded from either direction: by falling quality of resources or by the cost of managing their by-products.

4.5 Maintenance as the hidden budget

Maintenance is the process by which societies pay the entropy bill. It is also, systematically, undercounted. Stephen Graham and Nigel Thrift's [analysis of repair and maintenance](#) argued that social theory has treated it as marginal, when the continuing activity of repair is what keeps infrastructure usable. A recent snapshot is the American Society of Civil Engineers' [2025 Report Card](#), which gave US infrastructure a grade of C, the highest it has awarded since the series began in 1998, while estimating a \$3.7 trillion gap between planned investment and what is needed to reach a state of good repair out of \$9.1 trillion in total need. An improving grade and a large gap coexist: deferred maintenance accumulates quietly and then shows up as failures.

4.6 Diminishing returns to complexity

Tainter's thesis connects these pieces. Societies solve problems by adding complexity: new institutions, specialists, rules and technologies. Early additions return large benefits, but as the easy problems are solved, each further layer costs more and delivers less. At some point the marginal return falls below the marginal cost, and a society becomes vulnerable to shocks it would earlier have absorbed. A rational response may then be to simplify. Figure 9 illustrates this with a simple cost-benefit model in which benefits grow with the square root of complexity and costs grow linearly.

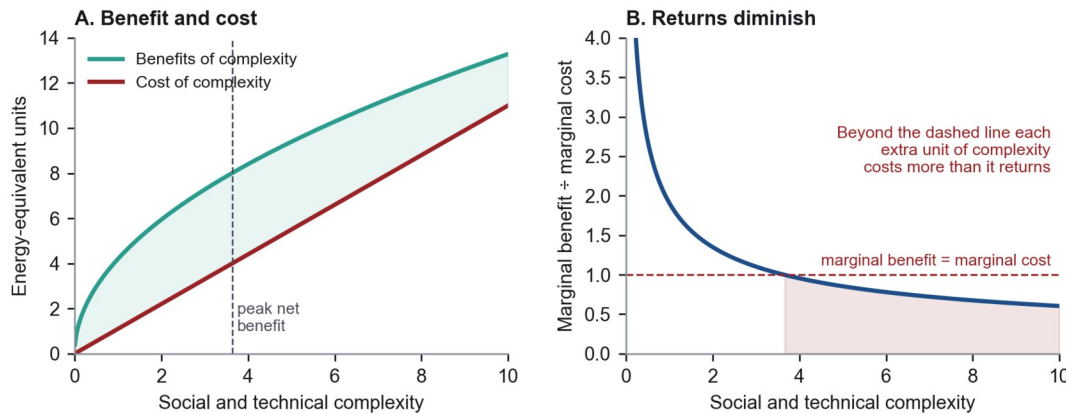


Figure 9. A stylised cost-benefit model of complexity. (A) Benefits rise with diminishing returns while costs rise linearly. (B) Beyond the point where marginal benefit equals marginal cost, each extra unit of complexity costs more than it returns.

Source: *H Heuristics illustrative model* (benefit = $4.2 \sqrt{x}$, cost = $1.1x$); a Tainter-style argument, not an estimate.

Tainter's argument is influential and has been criticised for treating collapse as an economically rational response and for underplaying external shocks and elite behaviour (Grade B for the mechanism, Grade C for its universality). The practical point is to ask, for any complex system, where it sits on the curve, and whether the cost of maintaining its complexity is growing faster than its benefits.

4.7 Institutions and coordination

Complex societies also depend on coordination, which is a form of information processing that must be paid for. Mancur Olson's [The Rise and Decline of Nations](#) argued that stable societies accumulate distributional coalitions that capture benefits and slow adaptation. Peter Turchin's [cliodynamic work](#), including the [Seshat databank](#), proposes that elite over-production and popular immiseration recur before periods of political instability. These frameworks are contested but testable (Grade C). They suggest that institutional capacity, like physical infrastructure, requires continuing renewal and can erode through internal processes without any external shock.

4.8 What the historical collapses show

Collapse in the archaeological sense usually means a rapid loss of political centralisation, population and complexity, not the end of people. Graeme Cumming and Garry Peterson's [2017 review](#) found that collapse is better understood as a regime shift in a social-ecological system, often involving slow variables (soil, institutions, legitimacy) and fast triggers (drought, invasion, epidemic). Table 3 summarises four well-studied cases.

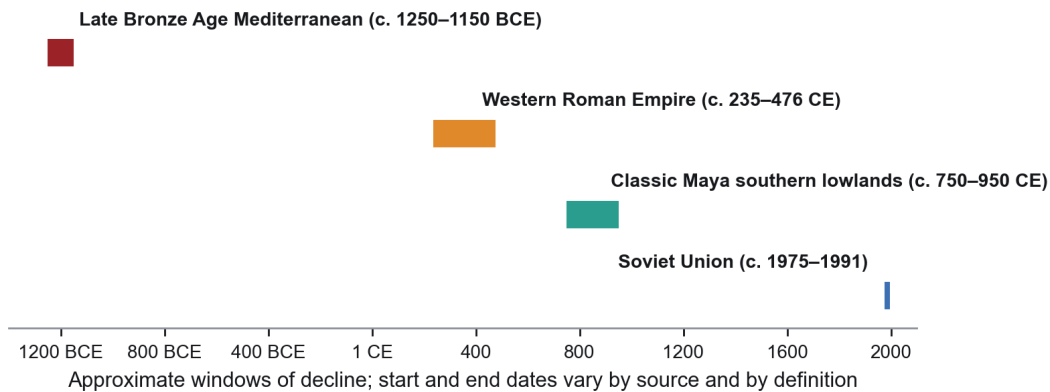


Figure 10. Approximate windows of decline for four well-studied cases. Dates vary by source and by what is counted as collapse.

Source: H Heuristics synthesis from Cline (2014), Harper (2017), Kennett et al. (2012) and standard histories of the Soviet Union.

Table 3. Four episodes of loss of complexity and what the literature emphasises

Case	Mechanisms emphasised	What persisted
[Late Bronze Age Mediterranean] (https://en.wikipedia.org/wiki/Late_Bronze_Age_collapse), c. 1200 BCE	Interdependent palace economies and trade networks failed together under drought, earthquakes, migration and warfare, a systems collapse emphasised in Eric Cline's <i>1177 B.C.</i>	Village life, iron technology and, after a gap, new states
[Western Roman Empire] (https://en.wikipedia.org/wiki/The_Fate_of_Rome), to 476 CE	Fiscal strain, military pressure, political fragmentation and, in Kyle Harper's account, climate shifts and plague	The Eastern Empire, the Church, Roman law and language
Classic Maya southern lowlands , c. 750 to 950 CE	Repeated multi-year droughts in the paleoclimate record (Kennett et al. 2012), warfare and loss of royal legitimacy	Northern lowland cities and millions of Maya people
[Soviet Union] (https://en.wikipedia.org/wiki/Dissolution_of_the_Soviet_Union), 1991	Stagnation, reliance on energy exports, institutional failure and political delegitimation	Successor states, most infrastructure and population

Three observations apply across all four. First, collapse is rarely monocausal; slow stress and fast triggers combine. Second, interdependence amplifies: the Bronze Age networks failed together because they were linked. Third, what usually fails is the higher level of organisation, while smaller scales persist. This is the pattern of simplification the report formalises in Section 7.

4.9 Summary

Key points. Civilisation now processes about 15 times the energy it did in 1900, mostly from fossil sources, and the same accounting shows a slow turn in composition. Material flows, maintenance backlogs and falling energy returns are the concrete forms the entropy cost takes. Diminishing returns to complexity and institutional drift are plausible internal mechanisms. Historical collapses are best read as regime shifts in which slow stress and fast triggers combine, and in which the highest layer of organisation fails first.

5. The Polycrisis as a Systemic Unraveling Process

5.1 What a polycrisis is

The term *polycrisis* describes a situation in which several crises are causally entangled, so that their combined effect is larger than the sum of their separate effects. The Cascade Institute's [research programme](#) defines a global polycrisis as the entanglement of crises in multiple global systems that substantially degrades humanity's prospects, and [Lawrence and colleagues](#) identify the causal mechanisms: common stressors, domino effects and inter-system feedbacks. The [Global Risks Report 2026](#) from the World Economic Forum ranks geoeconomic confrontation first among two-year risks, while environmental risks, led by extreme weather, dominate the ten-year outlook.

Read through the thermodynamic lens of Sections 2 to 4, a polycrisis has a clear structure. Stressors raise the rate at which capacity is lost. Coupling transmits losses between systems. Buffers and recovery capacity decide how much of the loss is absorbed. The next four subsections take each part in turn using current data, and Section 5.6 assembles them into a sequence. The sibling reports [The Weight of the Polycrisis](#) and [The Future of Global Habitability](#) cover the human consequences, from the harm of pollution and heat to a habitability index for 175 countries.

5.2 Stage one: accumulation of stress

The measurable stressors on the Earth system are large and mostly rising. The framework of planetary boundaries, introduced by Rockström and colleagues and updated by [Richardson et al. \(2023\)](#), found that six of nine boundaries were transgressed. The [Planetary Health Check 2025](#) from the Potsdam Institute's Planetary Boundaries Science Lab ([Steinert et al. 2025](#)) raised the count to seven, with ocean acidification newly breached. Only ozone and aerosol loading remain within bounds, and all seven breached boundaries show pressure still increasing (Figure 11; Grade B).

Planetary boundary	Status, Planetary Health Check 2025
● Climate change	Breached
● Biosphere integrity	Breached
● Land-system change	Breached
● Freshwater change	Breached
● Biogeochemical flows (N and P)	Breached
● Novel entities	Breached
● Ocean acidification	Breached in 2025 (new)
● Atmospheric aerosol loading	Within boundary
● Stratospheric ozone	Within boundary

Figure 11. Status of the nine planetary boundaries in the Planetary Health Check 2025. Seven are breached; two remain within their boundaries.

Source: Steinert et al. (2025), Planetary Health Check 2025, Potsdam Institute for Climate Impact Research; summary by H Heuristics.

Two drivers illustrate the scale. Atmospheric carbon dioxide at Mauna Loa averaged 427 parts per million in 2025, against about 280 before industrialisation ([NOAA](#)). NASA's [GISTEMP](#) record shows 2024 at +1.28 °C against 1951 to 1980, and the World Meteorological Organization [confirmed](#) 2024 as the warmest year on record at about 1.55 °C above the 1850 to 1900 level, with the caveat that one year above 1.5 °C does not mean the long-term Paris goal has been missed (Figure 12; Grade A).

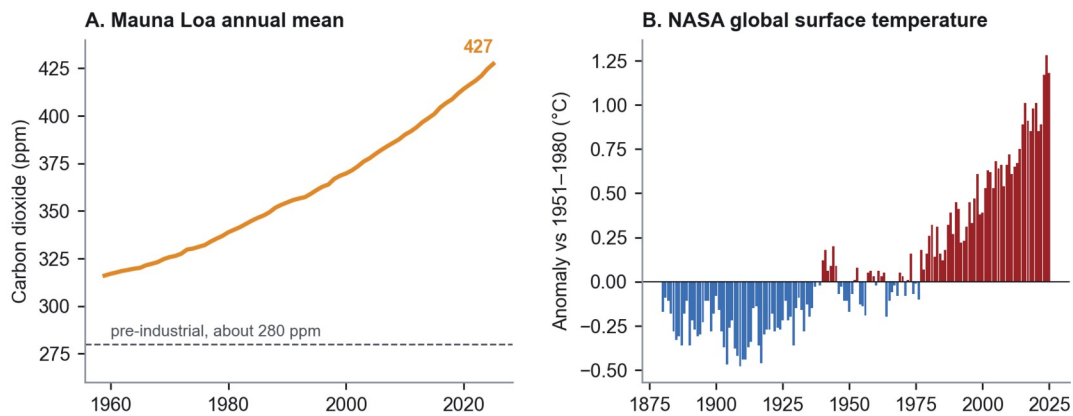


Figure 12. Two stressors. (A) Annual mean atmospheric carbon dioxide at Mauna Loa, 1959 to 2025. (B) NASA global surface temperature anomaly relative to 1951–1980, 1880 to 2025.

Source: NOAA Global Monitoring Laboratory (*co2_annmean_mlo*); NASA GISS Surface Temperature Analysis v4 (annual J–D); accessed 28 October 2026.

Biological and health stress follow the same pattern. The WWF [Living Planet Report 2024](#) reported that monitored wildlife populations fell by an average of 73 per cent between 1970 and 2020, with the steepest decline, 85 per cent, in freshwater populations. The [Lancet Commission on pollution and health](#) attributed about nine million premature deaths in 2019 to pollution, roughly one in six deaths worldwide. [Armstrong McKay and colleagues](#) assessed 16 climate tipping elements and found that five may already be at risk at about 1.1 °C of warming (Grade B for the direction, Grade C for individual thresholds).

5.3 Stage two: declining adaptive capacity and early warning

The theory of critical transitions predicts that systems approaching a threshold lose resilience in a recognisable way. As the basin of attraction shrinks (Figure 5), recovery from small perturbations becomes slower. This produces *critical slowing down*, visible as rising autocorrelation and rising variance in the system's fluctuations ([Scheffer et al. 2009](#); [Dakos et al. 2008](#)).

Figure 13 tests this in the bistable model of Section 6. We ramped up stress slowly in 300 simulated systems with noise. In the 220 time units before each system tipped, the median variance more than doubled (ratio 2.1) and the median lag-1 autocorrelation rose from 0.58 to 0.78. The signal is real but noisy, and the shaded bands overlap at the start, which is why single-system early warnings are hard to use.

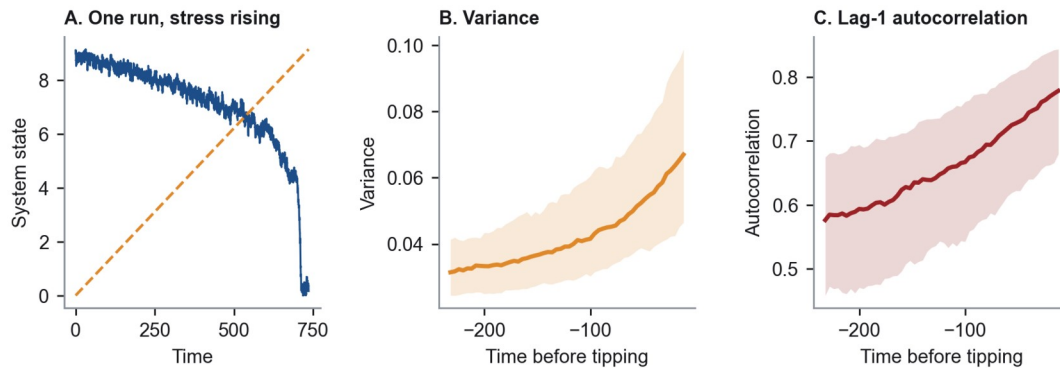


Figure 13. Critical slowing down in a simulated ensemble of 300 systems with slowly rising stress. (A) One example run, state in blue and stress dashed. (B) Variance and (C) lag-1 autocorrelation of detrended fluctuations before tipping; line is the median, band the 10th to 90th percentile.

Source: H Heuristics simulation (bistable model, noise $\sigma = 0.18$, rolling window of 100 time units, series aligned to the tipping time). Illustrative.

Empirical analyses have found similar signals in real systems, though not without dispute. [Boers \(2021\)](#) reported early-warning signals consistent with a loss of stability in the Atlantic meridional overturning circulation, and [Ditlevsen and Ditlevsen \(2023\)](#) used such signals to estimate a collapse between 2025 and 2095. These estimates are contested and rely on proxies and strong assumptions (Grade C). The robust point is that a stable-looking system can be losing recovery capacity, and that the first symptom may be slower return from small shocks rather than visible damage.

The social analogues are the deferred maintenance of Section 4, shrinking fiscal and ecological buffers, and falling trust. Each reduces a society's ability to absorb a shock without changing state. They are harder to measure than variance, and Section 7 proposes indicators.

5.4 Stage three: cascading failures

Loss of capacity in one system matters more when systems are coupled. [Buldyrev and colleagues](#) showed that interdependent networks, such as power grids and communication systems that depend on each other, can fail catastrophically in ways isolated networks do not, and [Helbing \(2013\)](#) argued that the globalised world's networked risks can create cascading failures across sectors. The earlier [load-redistribution model of Motter and Lai \(2002\)](#) gives a clean test. Each node carries a load equal to its betweenness centrality and has capacity equal to $(1 + \alpha)$ times that load; when a node fails, its load shifts to others, which may then exceed their own capacity.

Figure 14 runs the model on two 220-node networks of equal average degree. In the random network, the loss from removing the top hub was 96 per cent with no spare capacity ($\alpha = 0$) and fell to 8 per cent at $\alpha = 0.3$. In the hub-and-spoke network, the loss was 79 per cent at $\alpha = 0.3$, and remained 31 per cent even at $\alpha = 1$. Panel B shows what happens when several hubs fail together: removing three or more of the largest hubs cost around 88 per cent or more of the network at every tolerance tested. The numbers are model outputs, and 'lost' here means no longer part of the largest connected component. The principle, that severity is governed by buffers and structure more than by the size of the initial shock, is Grade B. [The Cascading Risk Atlas](#) applies the same grammar to real cases, including the 2026 Strait of Hormuz crisis.

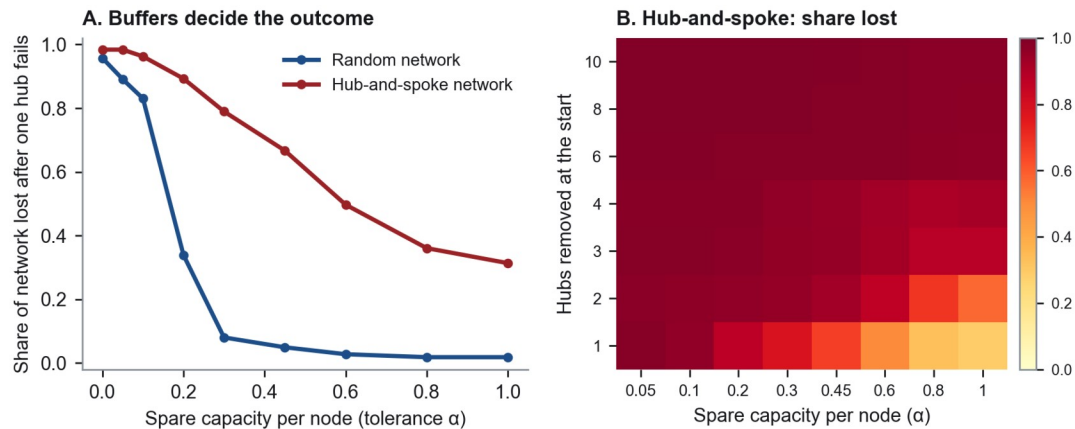


Figure 14. Cascade severity in a load-redistribution model. (A) Share of nodes lost after the largest hub fails, as spare capacity per node (α) rises, in a random and a hub-and-spoke network. (B) Share lost in the hub-and-spoke network as several top hubs fail at once.

Source: H Heuristics simulation ($N = 220$; random: $G(n, m)$ with mean degree 4; hub-and-spoke: Barabási–Albert, $m = 2$; mean of 2–3 seeds; after Motter and Lai 2002). Illustrative.

5.5 How the stressors interact

Stressors do not act alone. Figure 15 scores the direct influence of ten stressors on each other, on a scale from 0 (none) to 3 (strong). The scoring is judgement, grounded in the literature cited in this report, and is offered as a map for discussion, not a measurement. Climate change (out-score 18) and conflict (18) are the strongest drivers, followed by resource scarcity (17) and institutional fragility (15). Inequality (in-score 19), institutional fragility (19) and economic and debt stress (18) are the most affected. Climate change is the most one-directional: it acts strongly on others (18) and is acted on weakly (9).

Stressor that acts		Out									
		Climate change	Ecosystem loss	Pollution	Resource scarcity	Economic and debt stress	Inequality	Conflict	Institutional fragility	Demographic shift	Technological disruption
Climate change	–	3	1	3	2	2	2	2	2	1	18
Ecosystem loss	2	–	1	2	1	2	1	1	1	0	11
Pollution	2	2	–	1	1	2	1	1	2	0	12
Resource scarcity	1	2	2	–	3	2	3	2	1	1	17
Economic and debt stress	0	1	1	1	–	3	2	3	1	1	13
Inequality	0	0	1	1	2	–	2	3	1	1	11
Conflict	1	1	2	3	3	2	–	3	2	1	18
Institutional fragility	1	1	2	2	2	2	3	–	1	1	15
Demographic shift	1	1	1	2	2	2	1	2	–	1	13
Technological disruption	1	0	1	1	2	2	2	2	1	–	12
In		9	11	12	16	18	19	17	19	12	7
		Climate change	Ecosystem loss	Pollution	Resource scarcity	Economic and debt stress	Inequality	Conflict	Institutional fragility	Demographic shift	Technological disruption
		Stressor that is affected									

Figure 15. Direct interaction matrix for ten stressors. Entries are H Heuristics judgement scores of how strongly the row stressor drives the column stressor (0 none, 3 strong); 'Out' and 'In' are row and column totals.

Source: H Heuristics judgement informed by the literature cited in Section 5 (Grade D as a quantitative map). Scores are intended to be debated and revised.

The pattern fits the structure of Section 1. Environmental stressors act mainly as generators of loss. Institutional fragility, inequality and economic stress are mainly receivers and amplifiers, which makes them the system's filters: they decide how much loss is absorbed and how much spreads. That is why the same environmental shock produces such different outcomes across societies with different institutional capacity.

5.6 The sequence

Putting the pieces together gives a five-stage pathway (Figure 16). Stress accumulates; adaptive capacity declines; failures cascade across coupled sectors and regions; structure simplifies or fragments; and conditions remain unsafe if recovery is insufficient. The sequence is a pathway to investigate and a scenario to test, not an established or inevitable chain. Each transition depends on the conditions in Section 7, and each can be interrupted.

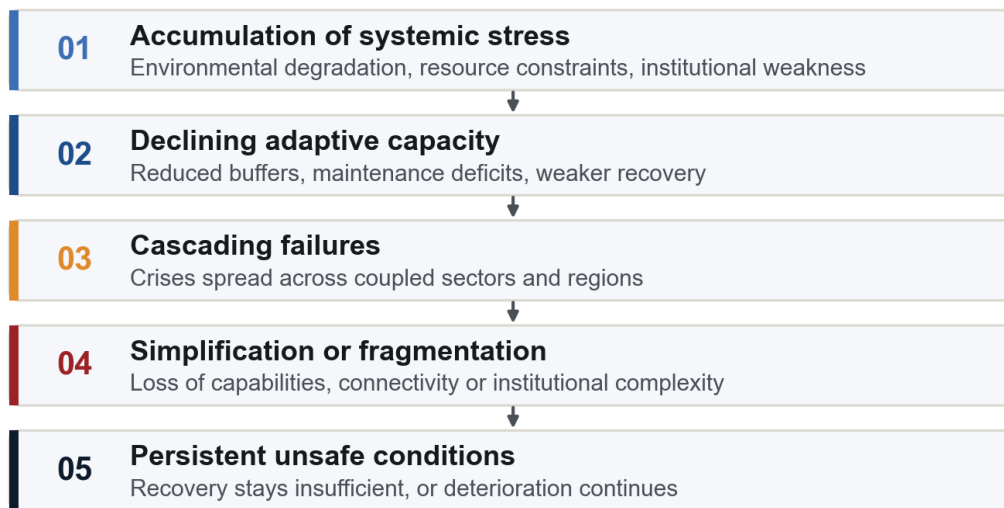


Figure 16. The proposed unraveling sequence. A scenario pathway to investigate, not an established or inevitable sequence.

Source: H Heuristics conceptual model.

Key points. The current stressors are measurable and mostly rising: seven of nine planetary boundaries are breached, carbon dioxide averages 427 ppm, and monitored wildlife has fallen 73 per cent. Resilience can fall before damage is visible; slower recovery is the early signal. Coupling and structure, not shock size alone, set cascade severity. Institutions and inequality act as the filter that decides whether stress becomes breakdown.

6. Post-Peak Systems and Long-Term Decline

6.1 Peaks, plateaus and declines

Many systems that grew for a long time are approaching a peak: some by exhaustion, some by saturation and some by choice. The best-known case in resource economics is the [Hubbert peak](#) of an oilfield. Ugo Bardi's [The Seneca Effect](#) generalises the observation, which Seneca made two thousand years ago, that growth is slow and ruin is rapid. Whether a given system shows a peak and what follows depends on the mechanism.

Human population is the largest example, and its pattern is a slowing, not a collapse. The world's population rose from about 3.0 billion in 1960 to 8.2 billion in 2025 (World Bank), while the total fertility rate fell from 4.7 births per woman in 1960, after peaking above 5, to 2.19 in 2024, close to the replacement level of about 2.1 (Figure 17). The United Nations' [World Population Prospects 2024](#) projects a peak of about 10.3 billion in the mid-2080s, gives an 80 per cent chance that the peak occurs this century, and projects that by the late 2070s there will be more people aged 65 and over than under 18 (Grade B).

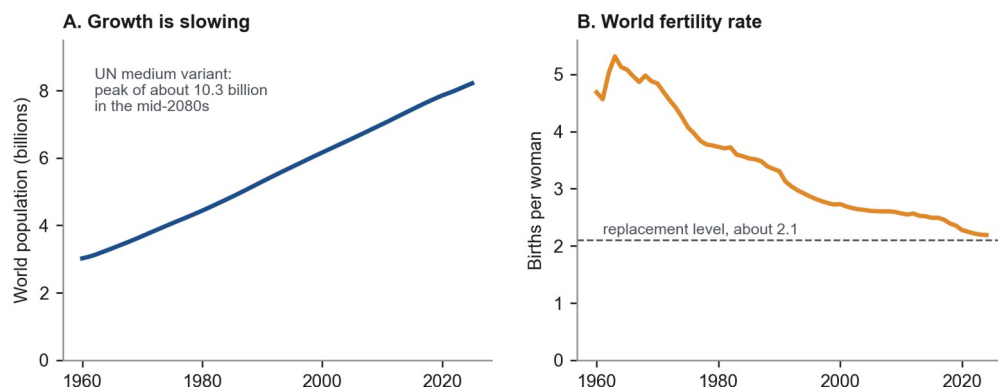


Figure 17. World population and total fertility rate, 1960 to 2025. Fertility has fallen close to replacement level and population growth is slowing.

Source: World Bank WDI (SP.POP.TOTL, SP.DYN.TFRT.IN), accessed 28 October 2026; projection from UN World Population Prospects 2024.

A shrinking, ageing population does not itself cause collapse. It changes the maintenance ratio: fewer workers per unit of infrastructure and per retiree, and higher per-person upkeep for the capital stock inherited from a larger past population. It is one of the few long-term pressures that is known with high confidence, and it is therefore a good test case for planning.

6.2 Why loss is fast and recovery slow

The bistable model used in earlier sections has the form $dx/dt = r \times (1 - x/K) - c \times x^2 / (x^2 + h^2)$, in which x is the system's capacity, r its recovery rate, K its carrying limit, and c an external stress that removes capacity at a saturating rate. It is the grazing model Robert May analysed in 1977, and is the standard minimal example of a system with alternative stable states. With $r = 1$, $K = 10$ and $h = 1$, the system has a

high-capacity state for low stress, a degraded state for high stress, and between the two, a range where both are stable (Figure 18).

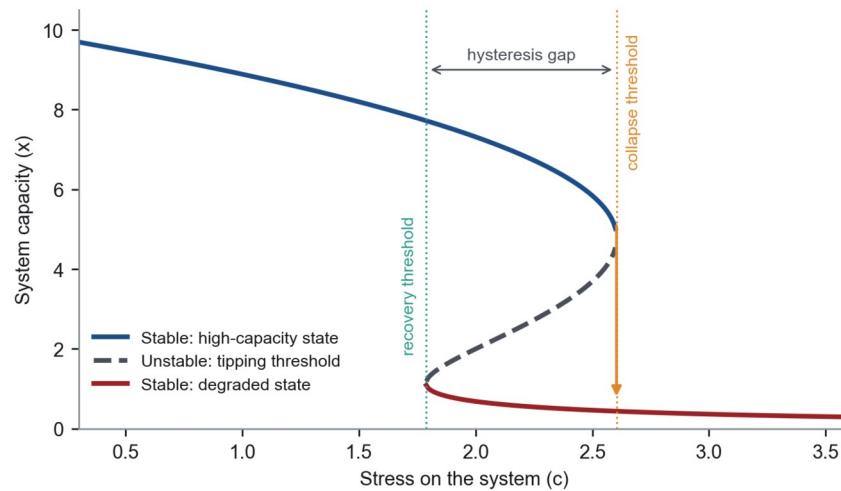


Figure 18. Equilibria of the bistable model as stress rises. The high-capacity state disappears at $c \approx 2.60$ (collapse threshold), but a system that has collapsed does not recover until stress falls below $c \approx 1.79$ (recovery threshold). The gap between the two is hysteresis.

Source: H Heuristics calculation ($r = 1$, $K = 10$, $h = 1$); model after May (1977). Illustrative; units are arbitrary.

Hysteresis is the key. Between $c = 1.79$ and $c = 2.60$, the same stress is compatible with two states, and which one the system occupies depends on its history. A system that was pushed past the collapse threshold stays collapsed even after stress falls back into this range. In the model, recovery requires cutting stress by about 31 per cent below the collapse threshold, not merely returning to it (Grade B for the principle in ecological systems; Grade D for any particular social numbers).

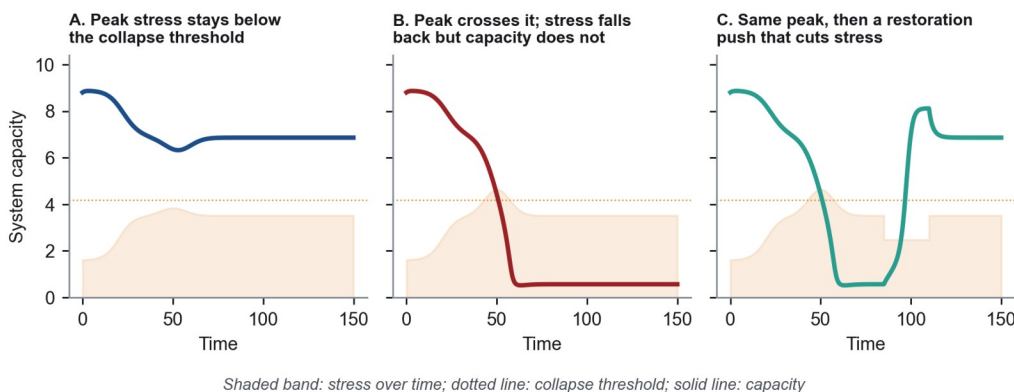


Figure 19. Three trajectories in the model. (A) Stress peaks below the collapse threshold and capacity dips but recovers to a lower stable level. (B) The peak crosses the threshold; stress then falls back to the earlier plateau but capacity stays collapsed. (C) The same peak, followed by a temporary restoration push that cuts stress below the recovery threshold; capacity recovers.

Source: H Heuristics simulation (deterministic, Euler step 0.05; stress is the shaded band; final capacity 6.9, 0.6 and 6.9 in panels A, B and C). Illustrative.

Figure 19 gives the practical reading. Case A and case B experience the same final stress level, yet end in different states, because case B crossed the threshold at its peak. Case C shows that the collapsed state can be reversed by a deliberate and sufficient restoration effort. The cost of that effort, in the model, is a cut in stress larger than the one that would have been needed to avoid the collapse.

6.3 How long recovery takes

Recovery time varies by many orders of magnitude depending on what has been lost. Figure 20 gives indicative ranges. Supply chains and financial systems can be reconstituted in months to a few years. Power grids, ports and institutional trust take years to decades. Knowledge that has been lost, mature forest and topsoil take decades to centuries. Large ice sheets operate on scales of thousands of years. The ranges are H Heuristics judgement based on the literature on infrastructure, ecology and soil formation, and are offered as orders of magnitude.

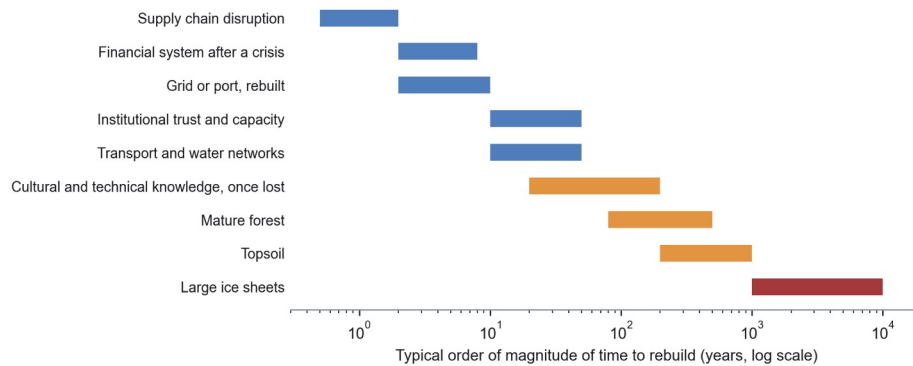


Figure 20. Indicative time to rebuild different kinds of capacity, in years on a log scale. Bars show an order-of-magnitude range.

Source: H Heuristics judgement (Grade D as precise ranges); intended to show the spread across more than three orders of magnitude.

The wide spread has a design implication. A policy that treats all losses as recoverable on a political timescale will be wrong for the slowest categories. Soil, forests, species and ice are effectively irreversible on the scale of a human lifetime, and losses there should be weighted accordingly.

6.4 The opposite outcome

The pathway in Section 5.6 is not a forecast, and the evidence against a pure-decline reading deserves equal weight. Four observations stand out.

- **Deterioration has been reversed in the past.** Under the Montreal Protocol, ozone-depleting substances were phased out, and the 2022 [UNEP and WMO assessment](#) expects the ozone layer to return to 1980 values around 2040 for the near-global average, around 2045 over the Arctic and around 2066 over the Antarctic (Grade A for the policy success). It is the clearest case of a global stressor addressed by coordinated action.
- **The energy system is changing faster than expected.** Wind and solar output in the Our World in Data series rose from about 32 terawatt-hours in 2000 to about 1,090 in 2015 and 5,525 in 2025, roughly 170 times the 2000 level. Low-carbon sources roughly doubled over the same 25 years, from 11.5 to 22.9 thousand terawatt-hours. Fossil use still rose from 94 to 144 thousand (Figure 21). [Way and colleagues](#) argued from empirical cost curves that a rapid transition would likely be cheaper than a slow one (Grade B).
- **Population growth is ending on its own.** Section 6.1 showed that fertility is near replacement level and the UN projects a peak this century, which removes one source of long-run pressure.

- **Institutions can learn.** Many deteriorations are slow enough that societies have reversed them, including lead in petrol, acid rain and urban air pollution in several cities. Learning is not guaranteed, but it is observed.

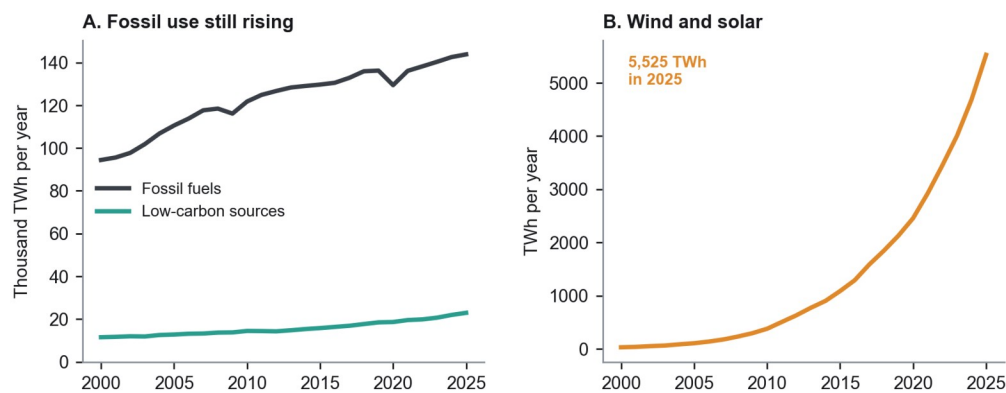


Figure 21. Energy use by source group, 2000 to 2025. (A) Fossil fuels and low-carbon sources, thousand TWh (substitution method). (B) Wind and solar output, TWh.

Source: Our World in Data, based on the Energy Institute Statistical Review; accessed 28 October 2026. Substitution-method values overstate non-fossil primary energy.

6.5 Trajectory types

The evidence supports a range of long-term paths, not a single one. Table 4 sorts them by the relation of loss and recovery rates. The point of the table is to specify the conditions for each, so that observation can discriminate among them.

Table 4. Long-term trajectory types and the conditions they need

Trajectory	Loss vs recovery	Conditions that must hold	Signals to watch
Renewal	Recovery exceeds loss	Stress falls; maintenance is funded; coupling is reduced where it is harmful	Falling variance in key series, rising buffers, improving repair backlogs
Plateau and adaptation	Roughly equal	Stress stabilises; buffers are held constant	Stable indicators with low margin; vulnerability to shocks
Managed contraction	Loss exceeds recovery in some sectors by design	Deliberate simplification; protected core functions; social agreement	Planned decommissioning; stable provision of essentials
Stepped decline	Loss exceeds recovery after discrete shocks	Threshold crossings with partial recovery between	Repeated shocks with shrinking recovery; hysteresis in outcomes
Unmanaged collapse	Loss far exceeds recovery	Multiple threshold crossings, high coupling, institutional failure	Rapid loss of capabilities; fragmentation of networks

Key points. Many systems are near peaks, and population is the best-understood case: growth is slowing toward about 10.3 billion in the 2080s. In a bistable system, loss is fast and recovery is slow, and recovery requires pushing stress well below the point of collapse. Recovery times span from months to millennia. The evidence also shows deterioration being reversed. The right posture is conditional: the paths differ by the relation of loss to recovery, and that relation can be changed.

7. Toward a General Theory of Systemic Unraveling

7.1 What a general theory would need to do

A useful theory of unraveling should be general enough to cover a cell, a power grid, a reef and a state, and specific enough to be wrong. It should say what must be true for a structure to persist; what changes when persistence fails; and what to measure to tell the difference in advance. The proposal below assembles results from Sections 2 to 6 into five propositions. It is offered as a framework to test, and Section 8 states how.

7.2 Five propositions

P1. The persistence condition

A structure persists while its rate of capacity restoration R , meaning maintenance, replacement, repair, learning and buffer replenishment, is at least as large as its rate of capacity loss L , which is the product of stress, exposure and coupling to other failing systems. Define the *persistence margin* $M = (R - L) / L$. Positive M means capacity is maintained or grows; negative M means it declines (Figure 22). The condition is a restatement of the steady-state logic of Section 3.1 (Grade A for physical stocks; Grade C as a general social statement).

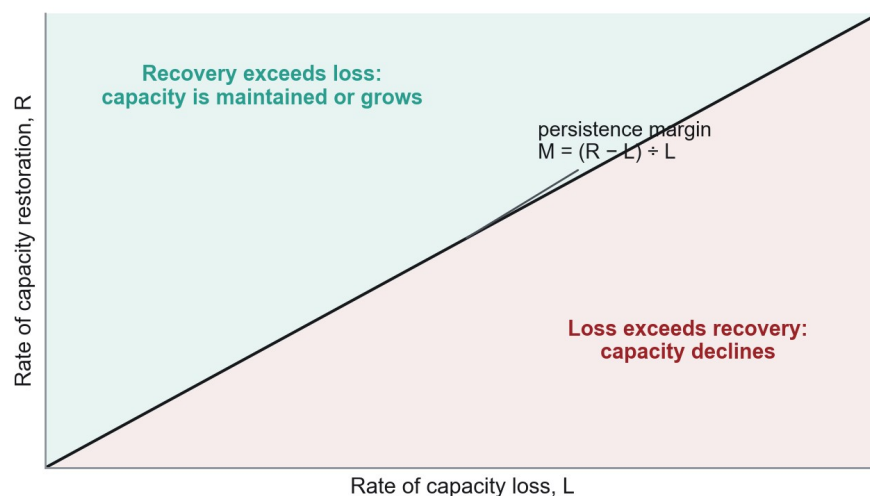


Figure 22. The persistence condition. Capacity is maintained where restoration exceeds loss, and declines where loss exceeds restoration. The margin $M = (R - L) / L$ measures distance from the boundary.

Source: H Heuristics conceptual diagram.

P2. Buffers convert shocks into delays

A buffer B , such as stockpiles, reserves, spare capacity, redundancy or slack, absorbs loss at no cost to function until it is exhausted. With a constant net loss $L - R > 0$, time to functional failure is approximately $B / (L - R)$. Buffers are what make a structure look stable while M is already negative, so a measured

margin is more informative than the current level of function. Figure 14 showed the same logic at network scale: spare capacity α turned a near-total cascade into a near-zero one (Grade B).

P3. Coupling transmits loss, and its effect is non-monotonic

Coupling lets loss in one system raise L in another. Strong coupling to a failing system is the route by which local stress becomes systemic. Yet moderate coupling can also share risk and speed recovery, which is why the effect of connectivity on cascade risk is not a simple rise. Duncan Watts's [model of global cascades](#) found that large cascades occur only in an intermediate window of connectivity. The implication is that the aim is to match coupling to function, not to minimise it (Grade C).

P4. Positive feedback creates hysteresis

Where a loss of capacity raises further loss, as when degraded soil retains less water or a weakened state collects fewer taxes, the system has alternative stable states and a recovery threshold lower than its collapse threshold. In the model of Section 6, collapse happened at stress 2.60 and recovery required stress below 1.79. Hysteresis makes prevention cheaper than cure (Grade B in ecology; Grade C in social systems).

P5. Under sustained net loss, systems simplify from the top

When L exceeds R for long enough, a system sheds its most expensive layers first: long supply chains, large-scale coordination, specialised roles and discretionary functions. This is Tainter's mechanism and the pattern in the cases of Table 3. Smaller-scale structures with lower upkeep tend to persist. The loss is functional simplification, not disappearance (Grade B for the pattern; Grade C for the claim that it is a rational response).

7.3 The unraveling structure in the language of the series

The Architecture of Creation defined a creation structure as generative rules, constraints and a stability filter. The unraveling structure keeps the same three roles. The *generators* are the stressors and the entropy production that erode order. The *constraints* are the finite stocks, the physical limits on recovery speed and the coupling that binds systems together. The *filter* is adaptive capacity: the buffers, institutions and knowledge that decide what is absorbed and what is lost. A given pattern of loss can then be located in this three-part structure and tested at each part, in the way the first report located a given pattern of form.

The two structures are not rivals. They describe the same systems from the two sides of the flux. An economy that is growing complex is running a creation structure, and the same economy, if its maintenance falls behind, runs an unraveling structure. Which one dominates at a given time is determined by the sign of the persistence margin.

7.4 Indicators by stage

A framework is useful if it tells an analyst what to track. Table 5 lists candidate indicators for each stage of the sequence, with public sources. Most are level indicators; the more informative versions are rates of change, variance and recovery times, as the critical-slowness result suggests.

Table 5. Candidate indicators for each stage of the unraveling sequence

Stage	Indicator	Source
1. Stress accumulation	Planetary boundary status; atmospheric CO ₂ ; biodiversity indices; pollution burden	Planetary Health Check ; NOAA ; Living Planet Index
2. Declining adaptive capacity	Maintenance backlogs; energy return on investment; stocks-to-use ratios; recovery time and variance of key series	ASCE Report Card ; Hall et al. 2014 ; FAO food price index
3. Cascading failures	Supply-chain pressure; chokepoint transits; simultaneous multi-sector disruptions	NY Fed GSCPI ; IMF PortWatch
4. Simplification or fragmentation	Loss of connectivity or capability; institutional effectiveness; conflict incidence	World Governance Indicators ; UCDP
5. Persistent unsafe conditions	Share of population in conditions below survivability or development floors; recovery rates after shocks	World Development Indicators ; UNDP Human Development Reports

Key points. The theory reduces to five propositions: a persistence condition, buffers as delay, coupling as the transmission route, hysteresis from positive feedback, and top-down simplification under sustained loss. The persistence margin $M = (R - L) \div L$ is the organising quantity. The unraveling structure is the mirror of the creation structure, and which one dominates depends on the sign of M .

8. Testing the Thesis: Predictions, Limits and Risks

8.1 Testable predictions

A thesis that cannot fail is not worth holding. Table 6 lists eight predictions, with the evidence that would count against each. They are chosen so that independent researchers could assess them with existing or obtainable data.

Table 6. Eight predictions and what would count against them

#	Prediction	Would count against it	Current status
1	Variance and lag-1 autocorrelation rise before abrupt transitions in systems with positive feedback	Large samples of real transitions with no change, or with false-positive rates too high to be useful	Supported in models and some ecological data; contested in climate subsystems (Grade B/C)
2	Cascade severity depends more on buffers and network structure than on the size of the initiating shock	Empirical cascades whose severity tracks shock size and not structure	Supported in models and case studies (Grade B)
3	Systems whose maintenance spending falls below depreciation show rising failure rates	Long-run infrastructure data with falling maintenance and stable failure	Supported for physical infrastructure (Grade A/B)
4	Intermediate coupling carries the highest systemic cascade risk	Monotonic increase or decrease of risk with coupling in realistic networks	Supported in stylised models (Grade C)
5	Falling net energy surplus precedes simplification of complex societies	Societies that simplify with rising surplus, or complexify with falling surplus, repeatedly	Plausible; evidence mixed (Grade C)
6	Recovery takes longer than loss, and hysteresis is common where feedbacks are positive	Systems in which recovery matches loss time symmetrically after threshold crossing	Supported in ecology (Grade B)
7	Concurrent stressors produce super-additive damage	Additivity or sub-additivity in joint-exposure studies across sectors	Some evidence for compound events; incomplete (Grade C)
8	Restoring buffers early costs less than rebuilding after a threshold is crossed	Cases where late rebuilding costs less than early maintenance	Consistent with hysteresis; cost data scarce (Grade C)

8.2 Limits of the analogy

The thermodynamic argument bounds the energy and material budget of a society. It does not determine how a society uses it. Between the budget and the outcome sit politics, culture, technology and chance. Technologies can shift constraints, as when a new energy source changes the surplus, and institutions can raise or lower the cost of coordination. A model that treats a society as a stock with a decay rate leaves these out, and the Tainter literature has been criticised for the same reason.

There is a second limit of method. The simulations in this report are minimal models, chosen because their behaviour is understood. They show that a mechanism can produce a pattern; they do not show that it does so in any particular real system. The bistable model's thresholds (2.60 and 1.79) are properties of its parameters and have no direct social interpretation.

8.3 Alternative explanations

The same evidence can be read differently. Declines in complexity might reflect political decisions and elite behaviour, not entropy-like drift. Resource constraints might be relaxed by innovation, as in the historical case of oil and, increasingly, solar power. Resilience might be higher than the model suggests because societies adapt in ways models omit. The framework's response is to specify what would distinguish the readings (Table 6) and to hold conclusions loosely until the discriminating data exist.

8.4 Risks of misreading

Entropy language invites two failures. One is fatalism: if decline is written into physics, why act? The thermodynamic argument says no such thing, since open systems can persist indefinitely, and the central lesson of Section 6 is that loss can be reversed. The other is false precision: assigning numerical probabilities or dates to collapse on the basis of illustrative models. This report gives none. A third and subtler risk is the use of 'natural decline' arguments to excuse neglect of maintenance or of vulnerable populations. Where a loss is preventable, the physics is not an excuse.

8.5 Open questions

- Can a defensible metric of societal persistence margin be built from public data, and does it predict transitions out of sample?
- How much do real social systems exhibit critical slowing down, and over what time horizon?
- What is the system-level net energy of a high-renewable economy including storage, grids and materials?
- How should coupling be designed, between full interdependence and isolation, for the functions societies most need?
- Which losses are effectively irreversible on human timescales, and how should policy weight them?

Key points. The thesis makes eight predictions that can fail, and each has a stated disconfirming result. The thermodynamic argument bounds budgets but does not determine outcomes. The models illustrate mechanisms and do not forecast. The main interpretive risks are fatalism, false precision and the use of decline as an excuse.

9. Applications and Heuristics

9.1 Ten working heuristics

The framework condenses into ten heuristics for anyone responsible for a complex system. They are working rules, not laws, and they are listed in the order in which they are most often useful.

1. **Track the margin, not the level.** A system's current performance says little about whether restoration keeps pace with loss. Ask what the maintenance and renewal rate is relative to the wear rate.
2. **Treat maintenance as the primary budget line.** Deferred maintenance is borrowing against future entropy. The ASCE gap of \$3.7 trillion is a debt in this sense.
3. **Size buffers to the hub.** In a hub-and-spoke system, failure at the most connected nodes dominates. In Figure 14 even full spare capacity did not save a network from the loss of several hubs.
4. **Watch recovery speed.** Slower return from small shocks is among the earliest signs of lost resilience. Measure it.
5. **Match coupling to function.** Remove coupling that carries no benefit; build modularity and circuit-breakers where it does. Do not mistake connectivity for resilience, or isolation for safety.
6. **Plan for hysteresis.** Do not assume that removing the cause restores the state. Estimate the gap between the collapse and recovery thresholds, and act before the first.
7. **Weight irreversible losses more.** Losses of soil, species, ice and institutional memory take far longer to rebuild than finance or supply chains (Figure 20).
8. **Protect the filter.** Institutions, trust and equity decide how much stress becomes breakdown (Figure 15). They are infrastructure, and they need upkeep.
9. **Simplify deliberately before simplification is forced.** When complexity costs more than it returns, a planned reduction of the most expensive layers preserves core functions. Forced simplification is indiscriminate.
10. **Keep analogy honest.** Use entropy as a physical constraint when a measurable energy, material or information quantity is involved, and as a metaphor only when labelled as such.

9.2 Where the heuristics apply

- **Infrastructure and utilities.** Maintenance backlogs, redundancy at critical nodes and stress-testing for compound events. The sibling report [The Heat Trap](#) traces how population is moving into the most climate-exposed regions, where infrastructure will have to be built and maintained under rising heat.
- **Public finance and development.** Treat preventive investment in buffers as cheaper than post-crisis recovery, as in [Convergence Before Crisis](#), which makes a timing argument: several slow stresses peak together between 2040 and 2060, and development cuts vulnerability faster than mitigation cuts hazard.

- **Supply chains and firms.** Map hubs, hold slack where a single node dominates, and track recovery time from disruptions, as set out in [The Cascading Risk Atlas](#).
- **Natural-resource management.** Use early-warning indicators for fisheries, rangelands and water systems, and set targets with the hysteresis gap in mind.
- **Long-range planning.** Use the five trajectory types of Table 4 as scenarios, and link each to indicators in Table 5.

9.3 Research agenda

Five projects would test and sharpen the framework. First, build a persistence-margin indicator for a few well-documented systems, such as national road networks, power grids and river basins, and test whether it predicts failure. Second, assemble a panel of historical transitions with enough resolution to test critical slowing down in social data. Third, estimate system-level net energy for scenarios with high renewable shares. Fourth, calibrate cascade models on real interdependency data for energy, food and finance. Fifth, run joint-exposure studies to test super-additivity of compound stressors. Each project can be done with public data.

Key points. Ten heuristics follow from the framework: track the margin; fund maintenance; size buffers to hubs; watch recovery speed; match coupling to function; plan for hysteresis; weight irreversible losses; protect institutions; simplify on purpose; keep analogy honest. They apply to infrastructure, public finance, supply chains, resource management and long-range planning.

10. Conclusion

Entropy is not a prophecy. It is a bill. The second law says that order must be paid for, and the history of life, cities and civilisations is a history of paying it: with energy from the Sun, with materials from the ground, with labour, with maintenance and with the continuing renewal of information in the form of institutions, knowledge and trust. When payment keeps pace with loss, structure persists and can grow. When it does not, structure thins, couples more tightly to what remains and fails in ways that look sudden from the outside.

The contemporary polycrisis is a test of that arithmetic at planetary scale. Seven of nine planetary boundaries are breached, energy use is some fifteen times what it was in 1900 and still largely fossil, material flows exceed 100 billion tonnes a year with a small circular share, and maintenance backlogs grow in the best-documented infrastructure systems. The same evidence shows that stress has been reduced before, that clean energy is growing at a rate few forecast, and that population growth is slowing by itself. The pathway of unraveling is a scenario to test and avoid, and the tools to avoid it are the ones set out here.

The framework offers a single organising question for any system: is restoration keeping pace with loss? If yes, measure the margin and protect it. If no, find which of the three parts of the unraveling structure (generators, constraints, filter) can be changed soonest, and change it before a threshold is crossed. The period before a threshold is the cheap one. That is what the physics, the models and the history have in common.

Key points. Order must be paid for, and civilisations are no exception. Unraveling is a process with a mechanism, a sequence, early warnings and, above all, a window in which it can be interrupted. The task is to keep restoration ahead of loss.

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Glossary

Adaptive capacity	The ability of a system to absorb, adjust to or recover from stress without losing its essential functions.
Basin of attraction	The set of states from which a system returns to a given stable state. Its size is a measure of resilience.
Buffer	Slack in a system, such as stock, spare capacity or redundancy, that absorbs loss without immediate loss of function.
Cascade	A sequence in which failure of one component raises the load on others, causing further failures.
Coupling	The degree to which the state of one component or system depends on another.
Creation structure	A combination of generative rules, constraints and a stability filter that explains why forms recur (Architecture of Creation).
Critical slowing down	The slower recovery from small perturbations, visible as rising variance and autocorrelation, as a system nears a threshold.
Dissipative structure	An ordered pattern maintained by a continuing flow of energy or matter through a system far from equilibrium.
Energy rate density	Power flowing through a system per unit mass, in erg per second per gram; proposed by Chaisson as a complexity metric.
Entropy	A measure of the number of microscopic states compatible with a macroscopic description; in an isolated system it does not decrease.
EROI	Energy return on energy invested: the ratio of usable energy delivered to energy used to obtain it.
Hysteresis	A path-dependent response: the threshold at which a system recovers differs from the threshold at which it collapsed.
Persistence margin	$M = (R - L) \div L$, the relative excess of capacity restoration over capacity loss.
Polycrisis	A causally entangled set of crises across systems whose combined effect exceeds the sum of their separate effects.
Regime shift	A large, persistent change in the structure and function of a system, often when a threshold is crossed.
Resilience	The magnitude of disturbance a system can absorb before moving to a different state or regime.
Unraveling structure	The combination of stressors, constraints and filters that governs how a system loses organisation (this report).

Appendix A: Key Quantities

Table A1. Key quantities used in this report

Quantity	Value	Source
Boltzmann constant, k	1.380649×10^{-23} J/K	SI definition
Minimum erasure heat, $k T \ln 2$ (300 K)	$\approx 2.9 \times 10^{-21}$ J per bit	Landauer (1961); calculation
Solar surface temperature / Earth effective temperature	5,772 K / ≈ 255 K	Standard reference values
Entropy export ratio (Earth)	≈ 23	H Heuristics calculation
World primary energy, 2025	≈ 600 EJ ($\approx 167,000$ TWh); 177,900 TWh on substitution series	Energy Institute 2026; Our World in Data
World primary energy, 1900	$\approx 12,100$ TWh	Our World in Data
Fossil share of primary energy, 2025	$\approx 86\%$ (direct); 81% (substitution)	Energy Institute; Our World in Data
Atmospheric CO ₂ , 2025 annual mean	427.35 ppm	NOAA Mauna Loa
Global temperature anomaly, 2024 (1951–1980)	+1.28 °C (NASA); ≈ 1.55 °C above 1850–1900 (WMO)	NASA GISS; WMO
Planetary boundaries breached	7 of 9	Planetary Health Check 2025
Wildlife population decline, 1970–2020	73% (average, monitored)	Living Planet Report 2024
Pollution-attributed deaths, 2019	≈ 9 million	Lancet Commission update, 2022
Material use / circular share	>100 Gt a year / 6.9%	Circularity Gap Report 2025
Human-made mass, 2020	≈ 1.1 Tt ($\geq$ living biomass)	Elhacham et al. (2020)
US infrastructure investment gap	\$3.7 trillion (of \$9.1 trillion need)	ASCE 2025
World population, 2025 / projected peak	8.2 billion / ≈ 10.3 billion, mid-2080s	World Bank; UN WPP 2024
Total fertility rate, 1960 / 2024	4.69 / 2.19 births per woman	World Bank WDI
Energy–income elasticity, 2022	0.82 ($R^2 = 0.77$; 142 countries)	H Heuristics calculation, World Bank WDI

Appendix B: Model Notes

Every simulation in this report is a minimal model written for illustration. Parameters are listed so results can be reproduced.

Table B1. Simulation parameters

Figure	Model	Parameters and method
2	Ehrenfest urn	$N = 50$ and 500 particles; one random particle moves per step; entropy computed as the binary entropy of the fraction on the left; seed 11. Return time analytic, 2^N steps.
3	Radiation spectra	Planck's law for $5,772$ K and 255 K, each normalised to unit area; entropy ratio taken as the temperature ratio.
9	Complexity cost–benefit	Benefit $B(c) = 4.2 \sqrt{c}$; cost $C(c) = 1.1 c$; marginal ratio $B'(c)/C'(c)$.
13	Critical slowing down	$dx = [x(1 - x/10) - c(t) x^2/(x^2 + 1)] dt + 0.18 dW$; stress c rising linearly from 1.0 to $1.12 \times$ the fold (2.60); 300 runs, step 0.1 ; series sampled each time unit; Gaussian detrending ($\sigma = 25$); window 100 ; aligned to the first crossing of $x < 3$.
14	Load-redistribution cascade	$N = 220$; random: $G(n, m)$ with $m = 2n$; hub-and-spoke: Barabási–Albert, $m = 2$; load = betweenness; capacity = $(1 + \alpha) \times$ initial load; the highest-load node(s) removed; cascade run to completion; metric is the share of nodes outside the largest connected component; mean of 2 – 3 seeds.
18	Bistable stress model	$dx/dt = r x (1 - x/K) - c x^2/(x^2 + h^2)$, $r = 1$, $K = 10$, $h = 1$; equilibria by root-finding; collapse threshold $c = 2.60$; recovery threshold $c = 1.79$.
19	Trajectories	Same model; stress $c(t) = 1 + 1.2 s((t - 20)/4) + \text{peak} \times \exp(-(t - 50)/10)^2$, with s the logistic function, and peak 0.2 (A) or 0.7 (B, C); in C stress is reduced by 0.65 for $85 \leq t < 110$; Euler step 0.05 .

The data series (Figures 6, 7, 12, 17 and 21) were downloaded on 28 October 2026.