ChatGPT

An Entropic Theory of Economic Value

Introduction

Energy is the lifeblood of economic activity. Every product made, service rendered, or algorithm computed ultimately derives from the transformation of energy into work or information. Classical economic growth models, however, often omit explicit thermodynamic constraints [1]. The **Entropic Theory of Economic Value** proposes that energy usage and entropy production are fundamental drivers of growth, setting physical limits on output but also enabling new forms of value creation through technological innovation. In essence, economies convert low-entropy energy and matter into high-value goods, services, and information, while expelling entropy (waste heat, emissions) to the environment [2] [3]. This perspective reframes economic growth in terms of energy *quality* (exergy) and *information*.

This report develops the entropic theory in a comprehensive, rigorous manner. We begin with a historical analysis of human energy use from agrarian times to the present, quantifying shifts in primary energy sources and efficiencies. We then introduce thermodynamic principles – Carnot efficiency, exergy, and entropy – to model economic output as energy-driven ordered work. An entropy-normalized output equation of the form $Y = \beta(E) \times E$ is derived, where E is per-capita energy use and $\beta(E)$ represents the "ordered bits" (useful cognition or work) per joule. Using this framework, we explain how modern growth is increasingly decoupling from raw labor and energy inputs: improvements in computing (CPU operations per watt) and artificial intelligence allow more GDP per unit of energy, effectively reducing entropy produced per dollar of GDP. We present time-series data for the United States on per-capita energy consumption, labor participation, productivity, and energy efficiency to illustrate these trends.

Looking ahead, the entropic perspective suggests that continued improvements in AI and **compute-per-watt** will amplify economic output even if total energy use plateaus. We argue that abundant clean energy (solar, nuclear, and potentially fusion) combined with robotics and AI cognition can usher in a new economic expansion akin to the post-WWII boom – but one rooted in **entropy-efficient growth**. Finally, we consider policy implications: expanding the electric grid for distributed renewable power, accelerating AI/robotics deployment, instituting sovereign wealth dividends to share the gains from entropy efficiency, and reforming regulations to facilitate this transition. The overarching claim is bold: **infinite** economic growth is physically plausible when growth is based on ever-greater informational content and entropy management, rather than ever-greater material throughput. The following sections ground this claim in historical evidence, physical law, and forward-looking analysis.

1. Historical Trajectory of Human Energy Use

Economic development has always been intertwined with how humans harness energy. Over time, societies have transitioned through distinct energy regimes – from reliance on the sun's biomass energy during the agrarian era, to coal in the Industrial Revolution, to petroleum in the 20th century, and onward to nuclear and modern renewables. Each transition brought orders-of-magnitude changes in energy **density** (energy per unit mass or volume) and in conversion efficiency, enabling greater economic output. This section reviews these historical shifts, quantifying primary energy sources, their energy densities, and key efficiency improvements.

1.1 Agrarian Era: Sunlight and Biomass

For most of human history prior to industrialization, the primary energy source was **sunlight**, captured indirectly through plant photosynthesis. Societies in agrarian eras met their energy needs via biomass: food for humans and draft animals, and wood for heating, cooking, and basic industries. Per-capita energy consumption in these societies was modest and relatively stable. In early 19th-century America, for example, annual energy use averaged around *100 million Btu* per person ($\approx$105 GJ) [4]. Nearly all of that came from biomass (wood and the feed for animals), meaning the average American in the 1800s burned about eight tons of wood each year [4]. Watermills and windmills contributed a small additional energy input for grinding grain or pumping water, but their impact was limited compared to biomass.

Biomass energy is diffuse and its conversion is inefficient. Photosynthesis captures only about 1–2% of incident solar energy in plant material. Human and animal muscle convert food energy to work with low efficiency, and traditional open-hearth wood burning has thermal efficiencies under 15%. Moreover, the **energy density** of dried wood is only about *16 MJ/kg* [5] – relatively low compared to later fuels. These constraints meant agrarian economies produced limited surplus output. Indeed, for centuries economic growth was slow, roughly tracking population rather than any major rise in per-capita energy use. Historical estimates suggest that from colonial times up to the late 1800s, U.S. energy use grew mainly due to population increase; per-capita use remained around that 100 million Btu level [6]. In other words, each person in an agrarian economy had available roughly the metabolic energy of food and a fireplace – an energy budget not much higher than that of preindustrial peoples centuries earlier.

Despite its low density, solar-derived biomass had one key advantage: renewability. Forests regrew and crops replenished annually. This constrained early economies to the current solar flow and land availability, imposing a kind of steady-state limit on output. Only a transformative new energy source could break the “biomass ceiling” – and that came in the form of coal.

1.2 Coal and the Industrial Revolution

The Industrial Revolution marked a fundamental break in the energy foundation of economies. **Coal** became the dominant fuel by the late 19th century, ending wood’s long reign as the primary U.S. energy source [7]. Several properties of coal enabled this shift. First, coal has significantly higher energy density than wood – roughly *24–30 MJ/kg* for hard coal [8], or about **50–80% more energy per unit mass**. Second, coal’s abundance (in Britain, Appalachia, etc.) provided a high-volume energy supply that could scale with growing industrial demand. Third, and crucially, coal powered the **steam engine**, a technology that converted heat to mechanical work and rapidly improved in efficiency and power.

Early steam engines in the late 1700s (e.g. Newcomen’s engine) were extremely inefficient, converting only ~1% of coal’s energy into work. James Watt’s innovations around 1776 improved efficiency to ~3–4%, kicking off wider adoption in mines and mills. Over the 19th century, advances in engine design (higher pressure boilers, better materials) raised thermal efficiency into the teens of percent. This was still far below theoretical limits, but it represented a many-fold improvement, meaning fewer coal pounds per horsepower-hour of work. The impact on economic productivity was dramatic. Steam engines provided abundant **mechanical labor**, freeing production from the limits of human/animal muscle or water flow. Factories, railways, and steamships proliferated, all powered by coal.

By the late 1800s, coal had decisively overtaken biomass in the U.S. energy supply [7]. In 1885, for example, U.S. coal consumption surpassed wood for the first time in history [9]. This transition fueled a sharp rise in per-capita energy use. The U.S. population not only grew, but each person on average consumed far more energy than before. Estimates suggest that during the first half of the 20th century, U.S. *per-capita* energy use roughly **doubled** – from about 100 million Btu in 1900 to 200 million Btu by mid-century [10]. Coal was a major contributor to this increase, especially in industry and rail transport, even as biomass use (wood) stagnated or declined.

The superior qualities of coal can be appreciated in terms of **energy density** and ease of use. Coal's gravimetric energy density (~24 MJ/kg) is higher than wood's, and it has a decent volumetric density since it is a solid that can be tightly packed. It enabled, for instance, locomotives and ships that could carry energy for long voyages – something impractical with bulky wood. However, coal also has drawbacks: it is labor-intensive to mine and handle, and early coal technologies produced severe urban pollution (soot, sulfur smog). Nonetheless, the net effect was an unprecedented surge in energy availability. By 1900, U.S. energy consumption was about *18 times* higher than in 1800 [11] (reflecting both population growth and per-capita rise). This surging energy input laid the foundation for exponential economic growth, ushering in the industrial age proper.

1.3 Oil, Gas, and the Rise of Petroleum

In the 20th century, a new pair of fossil fuels came to dominate: **petroleum (oil)** and **natural gas**. Petroleum's ascendancy began in the early 1900s (with the Texas oil boom and mass production of gasoline engines) and was firmly established by mid-century, when oil overtook coal as the largest energy source in the U.S. [7]. By the 1950s, cheap gasoline and diesel were powering cars, trucks, and aircraft, while fuel oil heated homes and factories. **Natural gas** use also expanded rapidly starting in the 1930s–1950s with pipeline infrastructure, providing cleaner heat and electricity generation [12].

The appeal of petroleum was rooted in even higher energy quality. Crude oil and its refined fuels carry about *42–47 MJ/kg* [13], the highest energy content per mass among common fuels (aside from natural gas which, as methane, is ~50–55 MJ/kg [14] but a gas at ambient conditions). Even more importantly, oil is a liquid at standard conditions, giving it a **high volumetric energy density** (typically 34–36 MJ per liter for gasoline/diesel). Liquids are easy to transport and store in tanks, and they can be pumped through pipelines. These attributes proved enormously advantageous: for example, motor gasoline and diesel fuel, with their combination of high mass *and* volumetric energy density, swiftly displaced coal and wood in transportation [15]. Solid fuels like coal require bulk storage and manual handling (shoveling into furnaces), whereas liquids can be handled by pumps and engines can be fed fuel continuously and automatically.

Figure 1: Energy density of various fuels by mass (horizontal axis) and volume (vertical axis) [15]. Liquid hydrocarbons such as gasoline and diesel (upper right) uniquely combine high energy per kg and *per liter, which drove their supremacy in transportation. Solid fuels like wood and coal have moderate gravimetric density but low volumetric density (lower right), making them less convenient for vehicles. Batteries (lower left) store far less energy per kg or liter than fossil fuels. Note the logarithmic scales – nuclear fission (point on far right) delivers orders of magnitude higher energy per kg of fuel (uranium), reflecting why a tiny amount of uranium can release energy equivalent to millions of kilograms of coal.*

The internal combustion engine (ICE) was the technological partner to petroleum, just as the steam engine was to coal. ICEs convert the chemical energy of fuel into mechanical work with much higher efficiency and power-to-weight than steam engines. Early gasoline engines in 1900 managed around 15% efficiency; by mid-century, car engines were ~20–25% efficient, and diesels 30–40%. The combination of high-efficiency engines and high-density fuel meant an automobile or airplane could deliver an unprecedented amount of work (miles traveled, cargo moved) per unit of fuel. This translated into greater economic output per energy input. Oil also found myriad uses in the chemical industry (plastics, fertilizers), multiplying its economic value beyond just heat or work.

By the late 1960s, U.S. **per-capita** energy consumption had surged to ~300 million Btu (≈316 GJ) per year [10], a threefold increase from the start of the century. Total U.S. energy use was nearly **ten times** higher in 2000 than in 1900 [11]. The post-WWII period (1950s–1960s) saw especially rapid growth – often 4–5% per year in energy consumption – underpinning GDP growth rates of ~4% annually. Cheap oil at about $2–$3 per barrel (in 1950s prices) fueled what economists call the post-war "golden age" of growth [16]. Even as oil prices eventually rose in the 1970s, global energy use continued its upward trajectory, only pausing briefly during recessions or oil shocks. U.S. per-capita energy use peaked around *1979 at ~360 million Btu* [10], coinciding with the all-time high in industrial activity and car travel per person.

Natural gas complemented this energy story by providing cleaner and flexible energy for heating, electricity, and industrial uses. By 1950, gas was ~18% of U.S. energy consumption; by 2023, it reached ~36% [17]. The expansion of gas pipelines in the mid-20th century and the development of efficient gas turbines (for power generation) made gas a cornerstone of the energy mix. Gas has slightly lower volumetric energy density (being gaseous, unless compressed or liquefied) but burns more cleanly and in combined-cycle turbines can achieve thermal efficiencies above 50%. Thus, gas became the backbone of electricity in many regions, displacing coal in recent decades.

In summary, the 20th century's fossil fuel revolution – oil and gas on top of coal – provided a **vast increase in high-quality energy** availability. This translated into both higher output and major lifestyle changes (automobility, electrified homes, mass industrial production). Each major source had its prime sector: coal in heavy industry and rail, oil in transport and later home heating, gas in heating and electricity. By the 1970s, fossil fuels supplied over 87% of U.S. primary energy [18], a share that remains around 80% even today [19]. However, the era of exclusively fossil-powered growth began to encounter limits in the form of resource constraints, price volatility, and environmental impact – prompting exploration of new energy frontiers.

1.4 The Nuclear Era: Enormous Density, Modest Scale

Starting in the 1950s, **nuclear energy** offered a radically new energy source whose potential dwarfed that of chemical fuels. Nuclear fission of uranium releases energy on the order of *millions* of times more per mass unit than oil or coal. For example, 1 kg of natural uranium fuel (in today's typical light-water reactors) can yield about **500 GJ** of heat energy [20]. This is roughly 30,000 times the energy in 1 kg of coal [21]. In advanced breeder or fast reactors, which more completely utilize uranium, the energy yield can be up to *28,000 GJ/kg* [20] – approaching the theoretical fission energy limit. In more familiar terms, a pellet of uranium the size of a fingertip contains as much energy as a ton of coal or ~150 gallons of gasoline.

The tremendous **energy density** of nuclear fuel meant that fuel supply and storage ceased to be a limiting factor. A single large nuclear reactor (1 GW electric output) only needs on the order of 20–30 tons of fuel per year, versus millions of tons of coal for an equivalent coal plant. This has profound implications for the logistics of energy supply and the footprint of energy extraction. It also means nuclear power produces negligible CO_2 emissions during operation, an increasingly valuable trait given climate concerns.

However, the **efficiency and practicalities** of harnessing nuclear energy introduced new challenges. Nuclear plants are essentially heat engines (generating heat from fission to boil water for steam turbines) and thus still bound by Carnot efficiency limits. Typical thermal efficiencies are ~33% [22], similar to coal-fired power plants. This means ~67% of fission energy becomes waste heat. Early reactors in the 1950s–60s often had lower efficiencies and frequent outages as the technology matured. Moreover, the capital cost, safety requirements, and complexity of nuclear reactors slowed their deployment.

By the late 20th century, nuclear power provided roughly 8–10% of U.S. primary energy [23] [24] (and around 20% of U.S. electricity generation). It made an "increasingly significant contribution" after about 1970 [25], but it did not dominate the energy mix as coal and oil once did. The growth of nuclear was curtailed after the 1970s by public concerns over safety (Three Mile Island, Chernobyl) and economic factors. While nuclear energy did not revolutionize overall economic energy use to the extent fossil fuels did, it proved the concept that *energy abundance* need not rely on burning finite hydrocarbons. It also pushed engineers to new frontiers of managing high-energy flux systems and gave a glimpse of a post-fossil energy paradigm.

1.5 Modern Renewables: Solar, Wind, and the Return to Sun

In recent decades, the energy story has shifted toward **renewable sources** once again – but now leveraging advanced technology to directly harvest flows like solar radiation and wind on a vast scale. Solar photovoltaic (PV) cells and wind turbines have seen exponential growth since the 2000s, driven by improving efficiency and plummeting costs. Solar PV, in particular, represents a direct conversion of sunlight to electricity, bypassing thermal inefficiencies.

The **energy density** of sunlight is fixed by nature (~1,000 W per square meter under full sun at noon). In terms of annual energy, 1 m^2 of land in a sunny region receives on the order of 1–2 MWh of solar energy per year (equivalent to ~3.6–7.2 GJ). Photovoltaic technology converts a fraction of that to usable electricity. Early PV cells in the 1950s had efficiencies of only ~6%. Today, mainstream silicon modules reach 20% efficiency, and laboratory cells exceed 40% with multi-junction designs. Thus, the **conversion efficiency** of solar has improved by several-fold, and costs have fallen by roughly 90% in the last two decades. The result is that solar energy, once vastly more expensive than fossil energy, is now often competitive on a cost per kWh basis.

Wind energy similarly taps a diffuse source – kinetic energy in moving air – using large turbine rotors. Typical power density for modern wind farms is a few W per square meter of land (when averaging out the spacing), though the turbines themselves achieve much higher conversion within their swept area (40%+ of wind energy intercepted, approaching Betz's limit of ~59%). Like solar, wind has grown rapidly: U.S. wind generation now exceeds hydroelectric generation, becoming the largest renewable electricity source by 2019 [26] [27].

Despite their growth, **renewables remain a minority of primary energy**. As of 2021, wind and solar together still accounted for only ~13% of U.S. electricity and an even smaller fraction (~4–5%) of total primary energy use [28] [19]. However, they are the fastest-growing sources. In 2019, U.S. renewable energy consumption (including biomass, hydro, wind, solar) surpassed coal consumption for the first time since the 19th century [9] – a symbolic return to a more sustainable mix. The key difference from the agrarian era is that today's renewables are **augmented by technology**: solar panels and wind turbines achieve far higher energy capture per unit land than natural photosynthesis ever could, and they supply high-quality energy (electricity) rather than low-quality heat or labor.

Looking forward, **energy abundance** in a renewable-based economy is conceivable. The Earth receives an immense solar power influx (~174,000 TW of solar radiation), of which even a tiny fraction could power human civilization many times over. Modern estimates suggest that covering just a few percent of land area with high-efficiency PV could meet global energy needs. Similarly, known wind resources and emerging technologies like enhanced geothermal and marine energy can supplement the mix. The limiting factors are not the raw flows, but our infrastructure to convert and store this energy (and the *entropy* constraints discussed later).

Figure 2 illustrates the dramatic historical shifts in U.S. energy consumption by source over the past two centuries. It highlights the decline of biomass (wood) in the 1800s, the rise and fall of coal, the dominance of oil and gas in the late 20th century, and the recent uptick of renewables and nuclear.

Figure 2: Primary energy consumption in the United States by source, 1780–2021 (in petajoules) [11]*. This historical view shows the transitions in dominant fuels: wood (green) was primary in early America; coal (purple) surged in the 19th century; oil (teal) and gas (orange) grew explosively in the 20th century, overtaking coal by mid-century* [7]*. Nuclear (blue) appears after 1950, growing to a steady contribution. In recent years, wind (light blue) and solar (yellow, barely visible through 2010s) rise sharply, though fossil fuels (gray area collectively) still constituted over 80% of 2021 primary energy* [19]*. The total area under the curve increased ~100-fold from 1780 to 2007* [11]*, reflecting enormous growth in energy availability fueling economic expansion.*

Several quantitative observations emerge from Figure 2 and the preceding discussion:

- **Growth of energy use:** The U.S. consumed on the order of 0.3 EJ (exajoules, 10^{18} J) per year around 1780; by 2007, this reached ~100 EJ [11]. That is over a 300-fold increase. Even adjusting for population growth, per-capita energy use rose markedly (from ~100 GJ/person in 1800 to ~360 GJ in 1979, before declining to ~300 GJ today [29]).

- **Transitions in dominance:** Wood supplied over 90% of U.S. energy in 1800, but only ~10% by 1900, as coal took over. Coal itself fell from ~75% of energy around 1920 to a minor share today [12] [30]. Oil went from near-zero in 1900 to the single largest source (~45% of energy in 1970). These transitions were driven by technology (e.g. steam engine, internal combustion engine, gas turbine) that unlocked the advantages of the new fuels.

- **Energy density as a driver:** Shifts toward fuels with higher energy density (coal, oil, uranium) enabled more compact and powerful energy conversion devices, reshaping industries and warfare (as noted in Churchill's 1911 shift of the British Navy from coal to oil, which doubled ships' range and freed up cargo space [31]).

- **Efficiency improvements:** Within each fuel era, improvements in conversion efficiency multiplied the useful work obtained per unit of energy. For example, average fossil fuel power plant efficiency improved from ~10% in 1920 to ~39% by 2022 [32]. Similarly, vehicle fuel economy improved and industrial processes became more energy-efficient over time. These gains slowed the growth of energy consumption relative to economic output, a point we return to in Section 4.

In summary, human economic history can be read as a story of *energy capture*. Each era found ways to access more energy or use it in more useful ways, breaking previous constraints. But with each leap, new challenges emerged – resource depletion, environmental impact, or reaching saturation in consumption. The next sections delve into the thermodynamic principles underlying these trends, and how they impose fundamental limits but also open new pathways (especially via information technology) for achieving economic value with less energy and entropy cost.

2. Thermodynamics of Economic Production

Having surveyed how energy use underpins economic development, we now ground these insights in the laws of thermodynamics. Economies, at their core, are physical systems: they consume **exergy** (useful energy) and matter, and produce work, goods, and **entropy** (waste heat, emissions). Understanding this process requires key thermodynamic concepts:

- **First Law (Energy Conservation):** Energy cannot be created or destroyed. All output (work, heat) must come from energy inputs. This underscores why energy is a required factor of production (often underrepresented in economic models [1]).

- **Second Law (Entropy Increase):** In any energy conversion, entropy tends to increase; some energy becomes unusable (waste heat). Perfectly efficient conversion of heat to work is impossible; there is always an entropy cost. This law introduces the concept of **Carnot efficiency** – the theoretical maximum fraction of heat that can be converted to work given temperature limits.

- **Exergy vs. Energy:** *Exergy* is the portion of energy that is available to do useful work, given the system and environment. *Anergy* is the portion lost to entropy. For example, 1 MJ of high-pressure steam has a lot of exergy (can drive a turbine), whereas 1 MJ of warm water has almost none (it is low-grade heat). Economic processes are essentially about converting primary energy into exergy (work, organized energy) and dumping anergy to the environment [2].

This section formalizes an "entropy accounting" for economic output. We model production as energy conversion to work, apply Carnot and related limits, and derive an expression for **entropy-normalized output**. In doing so, we will articulate why output Y can be expressed as $Y = \beta(E) \times E$ – effectively, GDP is proportional to energy use E, scaled by a factor $\beta(E)$ that measures how much *ordered work or information* is extracted per unit of energy. We then discuss how $\beta(E)$ has changed with technology (increasing over time) and how it encapsulates the role of human and machine intelligence in production.

2.1 Energy → Work: Carnot Efficiency and Heat Engines

The vast majority of industrial energy use involves converting heat into work or useful energy forms. Whether in a steam engine, internal combustion engine, or a gas turbine, a hot fluid expands and does work on a piston or turbine blades, then rejects waste heat to a cooler sink. Sadi Carnot's theoretical analysis (1824) of such heat engines yielded a fundamental limit: the **Carnot efficiency** $\eta_C = 1 - T_{\text{cold}}/T_{\text{hot}}$. No engine operating between a hot reservoir at temperature T_{hot} and a cold reservoir at T_{cold} can exceed this efficiency.

For example, a steam power plant taking steam at 550 K (roughly 277°C) and cooling to 300 K (room temperature) has a Carnot limit of $1 - 300/550 \approx 45\%$. Real power plants approach but do not reach this: modern combined-cycle gas turbines achieve ~60% efficiency (with $T_{\text{hot}} > 1500 K$ and multi-stage expansion), whereas typical coal plants reach ~33–40%. In 1920, average fossil power generation efficiency was only ~10% [33], meaning 90% of energy became waste heat. By 2022, the U.S. average was ~39% [32] (33% for coal and nuclear plants, ~44% for gas plants), thanks to improved materials and designs that raised operating temperatures and utilized combined cycles.

These improvements in efficiency are crucial. They effectively increase the exergy obtained from each unit of primary energy. If one Quad (quadrillion Btu) of coal produced 0.1 Quad of electricity in 1920 (at 10% efficiency) but 0.33 Quad in 2020 (33% efficiency), the latter economy can get over three times as much useful output from the same coal input. Thus, thermodynamic efficiency gains directly boost $\beta(E)$ in our formulation – more GDP per energy unit.

It's important to note that not all energy conversions involve heat engines. Electrical motors, for instance, convert electrical exergy to mechanical work at 90%+ efficiency. Lighting converts electricity to visible photons at varying efficiency (modern LEDs exceed 40% radiant efficiency). The second law still applies in these processes: for motors, the electricity itself was generated by a heat engine or hydro, etc., incurring entropy; for lighting, entropy is generated as heat for the fraction not converted to light and in the production of electricity upstream.

The **Second Law** dictates that every economic activity has an irreducible entropy cost. Whenever we create order – be it a manufactured product, an assembled car, or a string of bits in a computer memory – we must increase entropy elsewhere. Factories output waste heat; engines emit exhaust; computers warm the air. Entropy production is thus the shadow of value creation. In a very direct sense, **economic value can be seen as negentropy** (negative entropy) – creating order (structures, information) out of disorder – paid for by greater disorder emitted externally [2].

2.2 Exergy and Useful Work in the Economy

To quantify these ideas, researchers have introduced the concept of total **useful work** or exergy consumption of an economy. This is the portion of primary energy that is actually converted into mechanical work, electricity, or other *useful* forms (as opposed to simply being lost as waste heat). For the U.S., analysis by Ayres and Warr (2003) found that while primary energy consumption grew enormously throughout the 20th century, the *fraction* of that energy converted to useful work also improved due to better technology [34] [35]. In 1900, perhaps only a few percent of energy consumed ended up as useful work (the rest lost to entropy), whereas by 2000, roughly 10–15% did – reflecting the rise of high-efficiency electricity and engines.

This matters because **economic output correlates much more strongly with exergy (useful work) than with raw energy**. Neoclassical economics long assumed energy's contribution to output was proportional to its small cost share (~5% of GDP), leading to puzzles like the Solow "residual" (unexplained growth) [36]. Biophysical economists pointed out that if you factor in energy *quality* and treat useful work as a primary input, the growth accounting makes more sense [37]. Studies ignoring the restrictive cost-share assumption find that energy's output elasticity (effect on GDP) is far larger than 5% – in some cases over 50% [37]. In simple terms, energy (especially high-exergy energy) is a major driver of growth, not just a minor input.

That said, **useful work is not sufficient alone** – it needs to be directed by information and labor to produce value. This is where the concept of *ordered energy* or *cognition per joule* comes in. A certain amount of mechanical work (say 1 MJ of work) could produce a valuable product or accomplish nothing useful, depending on how it's applied. The economy's *knowledge and organizational structures* determine how effectively work is turned into GDP. We can think of this as an efficiency at the economic level: even the exergy we extract must be *used intelligently*. This efficiency has risen dramatically with advances in technology, education, and management.

2.3 Entropy-Normalized Output: Deriving $Y = β(E) \times E$

We now formalize an equation for economic output in terms of energy and entropy considerations. Let **E** be the *per-capita* primary energy consumption (in joules per person per year, for instance). Some fraction of E is converted to useful work W (joules of mechanical or electrical work) and the rest to waste heat, according to an average conversion efficiency η. We have:

$$W = \eta \, E.$$

The waste heat produced corresponds to an entropy increase of $\Delta S = \frac{E - W}{T_{\text{env}}}$ (assuming waste heat rejected at ambient temperature T_{env}). The *entropy produced per unit of useful work* is thus $(E - W)/T_{\text{env}}W$. High efficiency (large W per E) means low entropy per work output. One can define an **entropy intensity of GDP**: how much entropy (in J/K) is generated per dollar of GDP. Decoupling GDP from energy essentially means lowering this entropy per GDP.

Now, let **Y** be the per-capita economic output (e.g. real GDP per person). We propose that, to first approximation,

$$Y = \beta \times W = \beta \times \eta \, E.$$

Here, $β$ is a factor linking useful work W to economic value Y. In other words, $β$ measures how many dollars of GDP (or how much "ordered value") can be generated per joule of useful work. We can further merge $β$ and η into an overarching factor linking Y to E:

$$Y = [\, \beta \times \eta \,] \; E.$$

Call **$\alpha = β \times \eta$**, so that $Y = \alpha \, E$. This α encapsulates both the technical efficiency (η) of converting energy to work *and* the economic efficiency ($β$) of converting work to value. It is **energy productivity** in economic terms (GDP per unit energy). In the question prompt, $β(E)$ was used to denote essentially this combined factor, possibly varying with E. For clarity, we will use $β$ for the cognitive/order factor and keep η for thermodynamic efficiency, discussing $\alpha = β\eta$ as needed.

What determines $β$ (the "bits per joule" or ordered work per joule) in an economy? We can think of $β$ in terms of **information processing and intelligent control**. A joule of work applied with guidance (robots on an assembly line, or precisely timed fuel injections in an engine) can achieve far more complex and valuable outcomes than a joule expended randomly. As technology advances – with better machinery, control systems, and now digital algorithms – the *effectiveness* of each unit of work rises. In essence, $β$ is proportional to the *information content* or *negentropy* that the economy can harness per unit energy.

To illustrate with an extreme case: consider 1 kWh (= 3.6 MJ) of energy. In a primitive setting, 1 kWh in human muscle work might just dig a small hole (low value). In a modern setting, 1 kWh could run a computer that performs billions of calculations that help design a product or manage a supply chain worth millions. The energy quantity is the same; the difference in economic value arises from how information is used. That difference is captured by $β$.

Landauer's principle from information theory provides a physical limit to how many bits of information processing can be done per joule of energy. Landauer's bound states that erasing one bit of information dissipates at least $k_B T \ln 2$ energy (where k_B is Boltzmann's constant and T is temperature) [38]. At room temperature (300 K), $k_B T \ln2 \approx 2.8 \times 10^{-21}$ J. This implies **one joule** of energy could, in principle, erase or write **$\sim3.6\times10^{20}$ bits** (since $1 / 2.8\times10^{-21} \approx 3.6\times10^{20}$). This is about 3.6×10^{11} gigabits per joule. No real computer is anywhere near this efficient – modern processors use orders of magnitude more energy per operation – but it shows the astounding ceiling for $β$ in terms of computations per joule if one approaches physical limits. In other words, *the ultimate $β$ (bits per J) is extremely high*, suggesting enormous room for economic growth by increasing information utilization per energy.

How has $\alpha = β \times \eta$ (GDP per energy) changed historically? In the U.S., α has steadily increased, reflecting both thermodynamic gains (η) and better application of work ($β$). One metric of α is the **energy intensity of GDP**, the inverse of which is GDP per energy. U.S. energy intensity has dropped by more than half in the last several decades. In 1980, the U.S. economy used about 12 thousand Btu to generate one real dollar of GDP; by 2020 it used only ~5.05 thousand Btu per dollar [39]. That is, GDP per unit energy doubled (actually, $12/5 \approx 2.4\times$ increase in α). Over a longer horizon, the improvement is even greater: since 1950, U.S. real GDP (in 2012 \$) increased roughly 8-fold while energy consumption rose only ~3-fold, implying α nearly tripled.

We can incorporate both components: η improvements (e.g. power plant and engine efficiency) and $β$ improvements (better use of work via technology). For much of the industrial age, η was the primary driver (replacing low-efficiency human/animal labor and furnaces with high-efficiency machines). In the late 20th and 21st century, $β$ has taken the lead – through digitization and optimization.

Thus, **Equation (1)** $Y = β(E) \times E$ is not a static proportionality but a dynamic one. In early stages of development, $β(E)$ might rise with E as more energy allows more specialization and learning. Eventually, $β$ becomes a function of technological progress more than E itself. Some theorists have posited that beyond a certain point, energy is no longer the limiting factor – knowledge is. If E is abundant, Y grows by increasing $β$. However, E cannot drop too low either, because a minimum energy is required to sustain a given level of complexity (we cannot run an advanced economy on zero joules – organisms and machines need fuel).

Empirically, there is evidence for *decoupling* of Y and E in advanced economies, i.e. Y/E growing. For example, since around 2000 the U.S. has grown GDP significantly while total energy use has been roughly flat or even down slightly – a clear sign of rising α (we will show data in Section 3). This is consistent with $Y = \alpha E$ where α increases as $β$ (information efficiency) improves.

It should be noted that there are diminishing returns in some physical processes: η cannot exceed Carnot limits, and approaching those limits yields smaller incremental gains. But $β$ – tied to information – does not obviously have an easy saturation point short of fundamental physical limits like Landauer's. As long as we can find ways to create more value (more negentropy) per joule, β can keep rising. This is essentially the lever by which "infinite growth" could be made physically plausible: by driving the entropy per dollar of GDP ever lower, asymptotically toward zero (though never reaching zero). We revisit the sustainability of this vision later.

2.4 Economic Growth, Entropy, and Information

From a thermodynamic lens, the economy is a dissipative system that maintains local order (goods, infrastructure, knowledge) by **exporting entropy** to its surroundings [40]. A growing economy must either increase its energy consumption E or improve its entropy efficiency (β and η) – or both. Historically it has done both. There is a natural analogy to living organisms: we take in high-quality energy (food) and low-entropy materials, and we expel low-quality energy (heat) and higher-entropy waste, enabling us to build and move. An economy does the same on a larger scale. Physicist Edwin Schrödinger coined the term *"negative entropy"* (negentropy) to describe what life feeds on; economies too feed on negentropy.

However, unlike biological evolution, human economies can *intentionally increase* their negentropy efficiency via technological innovation. A striking trend is how much more **information and knowledge** the economy leverages now per unit of physical resource. Consider that in 1900, the dominant industries (steel, railroads, textiles) were enormously energy-intensive per dollar of output. Today's leading industries (software, electronics, finance) produce lots of value with comparatively trivial energy inputs – their main input is human and machine intelligence. The result is a declining ratio of entropy generated per unit GDP (as evidenced by declining energy and carbon intensity in many developed countries [39] [41]).

One quantitative measure of the information efficiency is the progress in **computing energy efficiency**. Koomey's law observed that computations per kWh have doubled roughly every 1.5 years [42]. Over the period 1946–2009, the number of computations per unit energy increased by a factor of about $2^{(63)} \approx 10^{19}$ – an astronomical improvement [42]. Even since 2000, despite slowing Moore's law, specialized chips and better algorithms have continued efficiency gains. This directly boosts β: more computations (which can be proxies for decisions, optimizations, designs) per joule means more cognitive output per joule. In 1985, physicist Richard Feynman estimated that computers were about 10^{11} times less energy-efficient than the theoretical limit [43]. Since then, efficiency improved ~10^4-fold [44], but we still have perhaps 10^7 times to go to reach Landauer's bound. This hints at a vast headroom for β to grow by further reducing the entropy cost of information processing.

In practical economic terms, this means we can continue growing GDP by doing things smarter, not by burning more fuels. For instance, a modern logistic system can reduce fuel use (energy) via better routing algorithms – achieving the same deliveries for less energy, effectively raising output/energy. Or consider AI-driven design: a powerful computer might simulate and find an optimal aircraft wing that uses less material and fuel, improving efficiency downstream. All of these are ways to squeeze more value (and reduce entropy generation) from a given energy budget.

However, it's essential to remember the Second Law's caution: **total entropy must still increase**. We may get extremely good at reducing entropy per dollar, but as long as GDP grows, some additional entropy is generated. The question is whether that entropy can be dealt with sustainably. Waste heat is generally not a big problem (it radiates to space as long as waste heat flux is small relative to Earth's blackbody radiation). The bigger issue is often entropy in the form of **waste and pollution**, like CO_2 (which is entropy in the sense of dispersed low-quality energy and matter). Later sections address how transitioning to cleaner energy alters the entropy calculus of growth.

In summary, the entropic theory of value sees economic output Y as proportional to energy use E, but *mediated* by a factor $\beta(E)$ that represents how effectively energy is converted into low-entropy forms (work, information, structure). Growth can come from increasing E (more energy use – historically the dominant factor) or from increasing β (more knowledge and efficiency – increasingly the case in modern economies). The next section will provide empirical evidence of how growth has been decoupling from raw energy and labor inputs, consistent with a rising β, and discuss the implications for future growth driven by AI and advanced energy sources.

3. Decoupling of Growth from Energy and Labor Inputs

A central consequence of rising energy efficiency and information intensity (α or β in our notation) is the **decoupling** of economic growth from traditional inputs like physical energy and human labor. In the mid-20th century, GDP growth in industrial economies was tightly coupled with increasing energy consumption – more factories, cars, and homes directly meant more coal, oil, and gas burned. Likewise, growth often involved employing more workers or longer working hours. That paradigm has shifted in the past few decades. Many developed countries have seen GDP continue to climb while energy use has plateaued or even declined [41]. Similarly, output has grown even as labor force participation falls and work hours stagnate, thanks to productivity gains. This section examines U.S. data to illustrate these trends.

3.1 Trends in Energy Intensity and Per-Capita Energy Use

The **energy intensity** of the U.S. economy (energy per real dollar of GDP) has been on a long downward trend. In 1983, the U.S. used about 11 thousand Btu for every $1 of GDP (in 2012 dollars). By 2020, this was down to ~5.05 thousand Btu per $ – less than half the 1983 level [39]. Figure 3 (notional, data from EIA) would show this decline as a smooth slope. The drivers include a shift from heavy industry to services, improvements in efficiency (appliances, vehicles, industrial processes), and higher energy prices at times spurring conservation. The net result is that one unit of energy yields much more GDP now than forty years ago.

At the per-capita level, U.S. primary energy consumption has actually **decreased** from its late 20th-century peak. After the 1973–79 energy crises, growth in per-capita energy use stalled. It oscillated in the range of 320–360 million Btu per person through the 1980s–90s, then peaked around 2007 and dropped. By 2019–2020, Americans were using under 300 million Btu per person [29], roughly back to late-1960s levels despite a much higher standard of living. This means the average American in 2020 was supporting a larger GDP with *less* energy than 40 years prior – a strong decoupling signal. Contributing factors are energy-efficient technologies (LED lighting, fuel-efficient cars, better insulated buildings), a decline in energy-intensive manufacturing domestically, and structural shifts to a digital economy.

To put it quantitatively: between 1979 and 2019, U.S. real GDP per capita roughly doubled, while per-capita energy use fell by ~20%. This implies an ~2.5× increase in energy productivity (GDP/E) over that period. Even from 2000 to 2018, U.S. GDP grew ~45% with essentially no increase in total primary energy. This is historically unprecedented – previous growth spurts (e.g., post-WWII) saw energy use rise in tandem with GDP. It marks the emerging dominance of the β factor (knowledge and efficiency).

Internationally, this decoupling is seen in many developed nations. The UK, Germany, Japan have all grown their economies in the 2000s while reducing total energy use. A number of studies confirm that a combination of energy efficiency and outsourcing of heavy industry has allowed GDP to rise with stable or falling energy demand in these countries [41]. For the world as a whole, total energy is still rising, but at a slower pace than GDP, causing global energy intensity to fall ~1-2% per year in recent decades [45]. In scenario terms, if efficiency improvements of ~3% per year could be sustained globally, it could offset global growth and stabilize energy demand even as GDP climbs – an outcome important for sustainability.

3.2 Labor Productivity and Workforce Trends

Simultaneous with energy decoupling, economies have been **decoupling from labor** input growth. The U.S. labor force participation rate (the share of adults either working or seeking work) rose for much of the late 20th century – from under 59% in the early 1960s to over 67% by 2000 [46] – largely due to increasing female workforce participation. Since 2000, however, this trend reversed. By 2022, labor participation had fallen to about 62% [47]. Despite a smaller fraction of people working, and an aging population, U.S. GDP in 2022 was roughly 2× what it was in 2000 (in real terms). How was this possible?

The answer lies in **labor productivity**: output per hour worked has steadily increased due to technology and better capital. Nonfarm business labor productivity in the U.S. has risen by approximately 250% since 1948 [48]. This means an average hour of work today produces 3.5× as much real output as an hour did in 1948. Even since 2000, productivity (though slower-growing) is up by perhaps 30%. Thus, even with fewer hours or fewer workers, total output can grow. In fact, from 2000 to 2019, U.S. productivity grew ~35% while median worker hours barely changed – the extra output went partly to increasing living standards and partly to other factors (there is a noted productivity-pay gap [48], but that’s another discussion).

Energy and technology are deeply intertwined with this labor decoupling. Each worker is effectively “augmented” by far more energy-driven capital and tools than in the past. A construction worker operating a modern earthmover can accomplish in one hour what would have taken weeks of manual labor – that machine is powered by energy-dense diesel fuel. An office worker today uses computers and software (powered by electricity) to leverage their intellectual effort manyfold. A single farmer with GPS-guided, AI-assisted machinery (again, fuel and electricity) can manage hundreds of acres, an impossible feat with human/animal muscle alone. In short, each worker’s output is amplified by energy and technology – hence fewer workers are needed for the same output.

This is precisely what $\beta(E)$ captures: as β rises (more cognition and tech per joule), you need less human labor per unit of GDP. We can formalize: GDP per labor-hour = (GDP/energy) × (energy per labor-hour). If energy use per labor-hour grows (each worker using more fuel and electricity) and GDP per energy grows (efficiency, info), then GDP per labor-hour soars. For example, consider manufacturing: in 1950 a factory might have had many workers doing manual assembly with modest electric tool assistance; today, the same factory might have robots (electrically powered) doing repetitive tasks and a handful of technicians overseeing. The energy consumption might be similar or even higher, but human labor input is far lower, and output higher and more consistent.

Notably, the largest productivity gains have occurred in sectors with high energy and technology use (manufacturing, agriculture). Sectors that remain labor-intensive (education, healthcare, some services) have seen slower productivity growth – often called Baumol’s cost disease. This underscores that productivity is in large part about energy and tech application: where we haven't figured out how to substitute capital/energy for labor, costs rise relative to output.

3.3 The Role of Computing and AI

A major recent driver of decoupling is the revolution in **computing and artificial intelligence**. As introduced earlier, computing efficiency (ops per joule) has improved exponentially [42] . This has enabled an explosion of digital services that add to GDP with minimal energy footprint – think of software, streaming, e-commerce, and the like. A striking example: the core operations of Google or Facebook serve billions of users but their data center energy use, while large in absolute terms, is a tiny fraction of energy use in traditional heavy industries. The "weightless economy" – bytes rather than atoms – can grow with little energy. Indeed, the ICT (information and communication technology) sector's energy use, although growing, remains on the order of a few percent of total energy consumption, even as it contributes a much larger share of economic activity and productivity across all sectors.

AI takes this further by potentially substituting for human cognitive labor. Training a large AI model is energy-intensive (hundreds of MWh perhaps for the largest models), but once trained, using that model to perform millions of tasks may be far cheaper than human labor or older methods. The key is these tasks – translation, image recognition, decision support – can be scaled almost at the cost of electricity alone. If the electricity is renewable (low entropy cost beyond the generation), we've essentially converted photons into cognitive work. As AI improves, we foresee a scenario where a significant portion of white-collar work (accounting, drafting, basic legal work, customer service) could be handled by AI systems running on servers. This would dramatically raise output per human worker (because each worker can now supervise AI doing 10x or 100x their old workload).

One interesting metric is **GDP per kilowatt** of power consumption. While not commonly reported, one can estimate it: The U.S. GDP of $21 trillion (2019) against an average power consumption of ~3.3 TW (100 Quads/year) gives about $6.4 of GDP per watt of continuous power. If we invert that, it's about 0.16 W per dollar of GDP. Over time, this ratio has fallen – we produce more dollars per watt. If AI and automation allow a doubling of GDP without increasing power use, GDP per watt would double to ~$12.8/W.

The ultimate limit, theoretically, using Landauer's principle: one watt (1 J/sec) could perform up to 3.6×10^{20} logical operations per second (at 300K). If each operation somehow added 10^{-18} dollars of value, that watt could generate 3.6×10^{2} dollars/sec, or about $31,000 per day – from one watt! These numbers are fanciful and not directly attainable, but they highlight how *physical power is not the bottleneck* for creating economic value if intelligence is applied superbly efficiently. We are nowhere near that efficiency; thus there is enormous room to grow in output with relatively little additional energy by exploiting the information route.

In empirical terms, think of services like internet search, which deliver huge consumer surplus and advertising value for microjoules per query, or digital music and books displacing physical CDs and papers with negligible marginal energy cost. The economy's shift to digital thus shows up as less energy per unit GDP.

3.4 Evidence of Decoupling in Data

To ground this discussion, consider a few concrete U.S. data series from 1950 to 2020:

- **Primary Energy per Capita (MMBtu/person):** Rises from ~200 in 1950 to ~350–360 in the 1970s, then fluctuates and falls to ~300 by 2020 [29]. Meanwhile, real GDP per capita (2012 dollars) rose from around $20k in 1950 to $65k in 2020. Clearly, GDP/capita tripled while energy/capita only increased 50% then retreated.

- **Energy Intensity (Btu per $ GDP):** ~15,000 Btu/$ in 1950 (rough estimate), ~8,500 Btu/$ in 1980 [49], ~5,000 Btu/$ in 2020 [39]. This roughly matches a halving from 1980 to 2020. Each dollar of GDP now "contains" only one-third the energy that it did 70 years ago.

- **Labor Force Participation (%):** ~59% in 1950s, peak 67.3% in 2000 [50], ~62% in 2020 [47]. Yet unemployment in 2020 was relatively low (aside from the pandemic shock), indicating the economy doesn't require as large a fraction of people working as it did – many have retired or chosen not to work and output is still high.

- **Output per Hour (Productivity Index 2012=100):** If we index 1948 as 100, this reached about 350 by 2019 [48]. This aligns with the 246% increase (i.e. index 346) cited for 2019 over 1948 [48]. The steep rise in productivity particularly in the 1950–1970 "golden age" (over 2.5% per year [51]), a slowdown 1970–1990, then a spurt 1990s (ICT revolution) [52], and slower again post-2005.

- **Computing Efficiency (Computations per kWh):** On a log scale, this is a straight upward line with slope doubling every 1.5 years [42]. For instance, one estimate shows it went from ~5×10^{5} computations per kWh in 1950 (vacuum tubes) to ~10^{14} per kWh by 2010 (modern processors) – a nine order-of-magnitude gain, and still climbing. This single metric encapsulates how "cognitive work" cost plummeted.

The net effect visible from these data is an **uncoupling of economic value from physical throughput**. We are not fully dematerialized – the economy still uses vast energy and materials – but the correlation has weakened. Carbon emissions in the U.S. likewise peaked around 2007 and have declined since, while GDP grew, indicating decoupling of emissions (though part of that is outsourcing heavy industry and switching from coal to gas and renewables).

To be clear, global energy use is still rising in absolute terms (driven by developing countries and population growth). But even globally, energy use is rising slower than GDP: in the last decade, global GDP grew about 3% per year while energy demand grew ~2% per year, implying a 1% annual improvement in global energy intensity. In scenarios where that improvement is accelerated (through efficiency tech and structural change), it's possible to have global GDP growth with flat energy use – a form of green growth.

From an entropic theory standpoint, these trends confirm that **we have been increasing the ratio of ordered output to entropy input**. Each joule burnt in 2020 supports more complex economic structures and services than a joule burnt in 1970 did. Each human hour now coordinates far more energy and information flows than before. We are, in effect, climbing an "entropy efficiency ladder," leveraging technology (especially digital technology) to generate value in ways that minimize additional entropy.

In the next section, we will extend these trends forward. If compute efficiency and AI continue to improve β, and if we bring online new abundant energy sources (solar, wind, nuclear, possibly fusion) to ensure E is ample and clean, what does that mean for economic growth? We posit it could mean a period of rapid growth without commensurate resource strain – a true **entropy-light boom**. But to achieve this, deliberate policy choices and investments must be made, which we discuss subsequently.

4. Future Growth: The Impact of AI and Energy Abundance

Building on the evidence of decoupling, we now explore the future trajectory where artificial intelligence (AI), automation, and ultra-efficient computing combine with abundant clean energy. Could this herald a new economic expansion akin to the 1950s–60s boom, but with far less physical strain? We argue that the pieces are in place for such a scenario: **energy abundance** from solar, wind, advanced nuclear fission, and in time fusion; plus **robotic labor and AI cognition** to utilize that energy with unprecedented efficiency. In entropic terms, we can expand output while controlling entropy production, by (a) switching to high-exergy, low-emission energy sources and (b) radically increasing β – the ordered work per joule – through AI.

This section will illustrate how improvements in AI and compute-per-watt could amplify economic output without needing to increase total energy usage. We provide modeling examples and analogies to historical booms. We then discuss the physical plausibility of “infinite” growth – meaning unbounded GDP growth – in light of entropy constraints, and why knowledge-centric growth avoids the traditional limits-to-growth arguments. Finally, we consider the role of modern energy sources (solar, nuclear, fusion) in enabling this vision.

4.1 Compute-Per-Watt Trajectory and Economic Amplification

One way to project the impact of AI is to ask: how does increasing computations per joule translate into GDP? Historically, we saw that computing efficiency doubled every ~1.5 years [42]. Although further improvements might slow as CMOS technology approaches limits, even a doubling every 2–3 years means a ~10–30× improvement in a decade. This means tasks that currently consume a lot of energy could consume an order of magnitude less. For instance, a data center running AI models might today use 1 MW to handle a certain workload; if efficiency improves 10×, it could do the same with 100 kW or do 10× the work for 1 MW. Many AI researchers are also focused on algorithmic efficiency – achieving the same accuracy with smaller models or fewer operations, which multiplies the hardware gains.

When AI can perform cognitive tasks at scale for marginal energy cost, the constraint on growth shifts away from labor or even energy to some extent, and more towards **data and capital**. We can envisage, for example, an AI-driven healthcare system where diagnosis and drug discovery are largely automated. The limiting factor might be data availability or regulatory approval, not the energy to run the AI (which could be solar-powered). Similarly, fully autonomous factories – lights-out manufacturing – could operate 24/7 with robots, with energy use mainly electrical. If that electricity is cheap and clean, scaling output only means installing more robots and solar panels, not worrying about finite fuel or labor fatigue.

A simple model exercise: assume the economy can be split into a “traditional” part that scales with energy (manufacturing, transport, etc.) and an “informational” part where output scales with computations (AI, software, services). The traditional part we assume reaches a steady state of energy use (due to saturation or policy to limit emissions). The informational part, however, continues to grow by leveraging the fixed energy pool more and more efficiently (more ops per J). Then total GDP can keep rising even though energy is flat. In fact, beyond some point, the informational output likely dominates. In monetary terms, we might see a smaller share of spending on material goods and a larger share on digital goods, personalized services, entertainment, etc., which have low energy intensity. We already see trends in that direction in advanced economies (consumption shifting to health, education, entertainment, all less energy-intensive than, say, steel or automobiles).

We can run a hypothetical numerical projection: Suppose total U.S. primary energy stays around 100 Quads/year (≈105 EJ/year) through 2050, but GDP doubles from 2020 to 2050. This requires a halving of energy intensity (not far from current trajectory). That doubling could come from increments like: 20% from more energy (some increase), 80% from higher $β$. Now imagine beyond 2050, energy usage even declines (due to efficiency and population stabilization or decline), yet GDP keeps rising through the 2060s and 2070s by continued improvements in $β$ (AI, quantum computing, etc.). We could eventually reach a state where per-capita energy consumption is back to mid-20th century levels, but the standard of living (GDP per cap) is 10 or 20 times higher. The "physical footprint" of the economy would thus be greatly reduced relative to output – a very sustainable scenario if managed well.

One should ask: does increasing $β$ face diminishing returns or physical limits? We discussed Landauer's principle as a physical limit to information processing efficiency. There is also a practical limit that human needs and desires might saturate: there are only so many digital services or AI outputs one can consume. However, historically we've seen new forms of consumption arise (who in 1950 could foresee people paying for virtual goods or online subscriptions?). If value is defined by what people are willing to pay, seemingly intangible improvements (like better AI medical diagnoses that extend life, or more immersive entertainment) can drive GDP. And these often don't demand proportional energy.

There is an additional effect: as AI and automation handle more production, **marginal costs** of many goods and services may drop, potentially lowering prices or shifting value to new areas. Some economists fear a scenario of technological unemployment or deflation. But one could also get a virtuous cycle: with cheap abundant outputs, people may pursue new creative endeavors, new industries arise (e.g., space tourism, virtual reality experiences) – each of which can create new forms of value (again, possibly not heavily energy-intensive if optimized).

In essence, advanced AI and robotics increase the **productive capacity** of the economy without necessarily increasing energy input. This is analogous to how electrification and mechanization massively boosted capacity in the 20th century. For example, the 1950s U.S. saw a boom partly because previously unused productive capacity (from wartime industry and new tech) was turned to civilian use, and cheap energy (oil at ~$2/barrel) was abundant [16]. Today, one could argue we have underutilized productive capacity in the form of computing power and algorithms that are not yet widely applied. Once deployed (say self-driving vehicles, automated warehouses, AI assistants in every field), they could spark a new productivity surge.

4.2 Energy Abundance: Solar, Nuclear, and Fusion

Now consider the **energy side** of the equation. Even if total primary energy does not need to grow as fast as GDP, having *cheap, clean, abundant energy* removes potential brakes on growth and helps in substituting away from resource-constrained or polluting inputs. We are entering an era where such abundance is plausible:

- **Solar PV** is on track to become the cheapest source of electricity in most of the world. Solar capacity doubles roughly every 3–4 years globally. The solar resource is effectively limitless at human scales – the challenge is land use and storage. With cheap battery storage (costs also falling), solar can provide a majority of electricity in many regions. We already see periods in some countries where solar (and wind) produce >50% of power. If the cost of solar plus storage falls below, say, 2 cents per kWh, it becomes economically attractive to electrify almost everything (EVs, heat pumps, industrial heat via electric resistance or heat pumps, etc.). Abundant electricity would also enable energy-intensive carbon capture or water desalination if needed, addressing environmental issues.

- **Wind power** complements solar in many regions (often blowing at different times). Offshore wind, in particular, has huge potential with high capacity factors and now larger turbines (15 MW and up). A combination of wind, solar, hydro, and some nuclear could yield nearly 100% carbon-free power without shortage. The U.S. has enough technical renewable potential (in solar/wind) to supply many times its current usage; the bottlenecks are grid infrastructure and storage.

- **Nuclear fission** technology, if advanced (e.g. small modular reactors, molten salt reactors), can provide reliable baseload power with zero carbon. Next-generation reactors promise lower cost and improved safety. If regulatory and economic barriers are overcome, a wave of new nuclear build could ensure around-the-clock abundant power. Uranium supplies are sufficient for many decades at higher usage, and with breeder reactors or uranium from seawater extraction, fission could supply millennia of energy (though that may not be needed if renewables dominate).

- **Fusion energy**, long the stuff of sci-fi, has recently seen breakthroughs (e.g., net gain at NIF in 2022, and many private startups pursuing magnetically confined fusion). It's not guaranteed, but if fusion becomes practical by mid-century, it would truly be a game-changer: essentially limitless energy from hydrogen isotopes, with negligible pollution. Fusion could provide high process heat for industry and electricity with no long-lived waste. Even before full powerplant fusion, intermediate technologies like high-temperature geothermal (drilling deep with new techniques) or advanced concentrated solar can fill niches.

The key point for entropic growth is that these sources dramatically *lower the entropy cost per unit of energy delivered*. Burning coal or oil not only wastes a lot of heat (entropy) but also dumps CO_2, which increases environmental entropy (climate disorder). Solar and wind take already high-entropy incoming solar flux and convert a portion to electricity – they don't *add* net entropy to Earth beyond what sunlight does naturally; in fact, by converting some to work and then heat, they just shift where entropy is produced (ultimately, solar panels actually heat the Earth slightly less than if the sunlight hit dark ground, since some energy is converted to electrical work and eventually radiated as heat elsewhere). Nuclear fission does produce waste heat (entropy) but no CO_2; and its energy density is so high that the material entropy footprint (mining, waste) per joule is extremely low when managed.

With abundant clean energy, we can afford to run energy-intensive processes that mitigate entropy elsewhere: e.g., direct air capture of CO_2 (an entropy-reducing process globally, requiring energy input to create order by removing dispersed CO_2), recycling and pollution cleanup technologies, and perhaps even geoengineering if necessary. These would address some of the external entropy burdens of growth.

In a scenario where solar and nuclear energy are plentiful, and assuming human society invests in the infrastructure (expanded grids, transmission, energy storage like batteries or hydrogen), we remove the classical Malthusian concern of energy scarcity. The cost of energy could drop precipitously in real terms, much like the cost of computation has. We already see electricity costs from new solar/wind farms at <\$0.03/kWh in best cases, and some foresee <\$0.01 by 2030s in high-sun regions. At that point, running data centers, factories, or charging vehicles becomes very cheap. Cheap energy also means we could synthesize fuels (like green hydrogen or ammonia) for uses that are hard to electrify directly (aviation, long-haul shipping), closing the loop on decarbonization.

In such an environment, increasing GDP is not constrained by needing more fossil fuel. We can increase production (whether it's desalinating more water for a megacity or producing more fertilizers for food) without hitting a hard energy wall or emitting commensurate carbon. The limiting factor shifts to how well we manage materials and pollution – which again can be helped by energy (recycling aluminum, for example, takes energy but avoids needing to mine more, etc.).

Thus, energy abundance ensures that as β allows more output per joule, we are not forced to restrict joules for fear of scarcity or climate impact. We could even allow E to grow modestly if needed, but coming from clean sources, the extra entropy (waste heat) can be dissipated by Earth's radiation to space, and it wouldn't be enough to materially heat the planet (for perspective, even if world energy consumption were 5x current, ~3000 GW, that's 0.003% of solar energy absorbed by Earth; climate change from GHG is a bigger issue than direct waste heat).

4.3 A New 1950s-Style Economic Expansion?

The 1950s and 1960s were a time of rapid economic growth, rising median incomes, and broad optimism in many Western countries (and some other parts of the world). The foundations of that boom included: plentiful cheap energy (the U.S. was the Saudi Arabia of oil then), pent-up technological advancements (radar, jets, computing proto-tech from wartime), a young growing workforce, and high investment in infrastructure (highways, power grids, schools). The result was annual GDP growth often 4–5%, unemployment low, and a sense that technology (nuclear power, space travel, etc.) would solve many problems.

Our current situation has some analogies. We have a trove of revolutionary technologies hitting maturity: artificial intelligence algorithms, robotics, biotech, nanotech. We have a need to rebuild infrastructure – this time, green infrastructure (renewables, EV charging networks, updated grids). Energy, while facing a transition, is on the verge of being ultra-cheap and clean, as described. Unemployment in many advanced countries is fairly low, but labor shortages in certain areas (skilled trades, care work) suggest a role for automation to fill gaps. There's also a demographic difference: populations are aging and not expanding like in the 1950s, which could dampen growth. But that is precisely why productivity through AI/automation is critical – to counteract a shrinking workforce.

If we harness AI and abundant energy right, we could see **productivity growth** rates climb back to 3% or more (they have been ~1–2% in recent decades in the U.S.). Combined with even modest labor force growth, that could yield 3–4% GDP growth consistently. Over a generation, that compounds significantly (a 3.5% growth for 20 years would almost double GDP). More importantly, it could improve *real wages* and quality of life by making goods and services cheaper and more available. Imagine a scenario where personalized AI tutors make education more effective (human capital boost), home robots handle domestic chores (time savings, quality of life boost), and medical AI plus biotech cures or manages chronic diseases better (health and productivity boost). These are qualitative improvements that don't necessarily reflect as exponential energy use – they reflect using intelligence to solve problems.

This optimistic scenario does require the right policies and social adaptation (discussed in Section 5). But it is physically plausible and even likely if no major global disruptions occur. Some economists refer to general-purpose technologies (GPTs) like steam power or electricity that unlock eras of growth. AI is being hailed as such a GPT now. Combined with the energy GPT (renewables/fusion), the synergy can be powerful.

One can also draw a parallel to the **1990s IT boom**: productivity jumped as businesses adopted computers and the internet. Initially, it required complementary investments (skills, reorganizing firms, etc.), but once it clicked, we got a decade of solid growth with low inflation (the so-called ICT productivity paradox resolved). Similarly, AI might currently not show big effects yet because it's just emerging, but by 2030 we may see its full impact, especially as it is integrated with physical automation (the robots in warehouses, trucks, etc. guided by AI brains).

An entropic lens on such an expansion would note: growth is achieved by *reducing the entropy per output*, not by massive increases in energy or raw resource inputs. It is "clean growth." For example, the marginal cost of an AI-written software or AI-generated design is almost just the electricity for the computer – which could be solar-derived. The cost and entropy footprint of duplicating software is negligible compared to building a physical product. So scaling those outputs to everyone (e.g. giving every person a personalized AI doctor on their phone) yields huge utility with minimal physical strain.

This is not to say there are no challenges. Transitions can be disruptive: jobs in some sectors will vanish, new skills required in others. There could be increased inequality if the gains are not broadly distributed (we'll discuss sovereign wealth dividends and such in next section). There are also security considerations – an AI-driven world might have new risks. And even with abundant clean energy, other resources (like certain minerals for batteries or rare earths for motors) might become limiting unless recycling and alternatives are developed (which again is an engineering solvable problem, given energy).

In sum, the elements for a modern "long boom" exist: technology, energy, and presumably the human desire for improved living standards. An *Entropic Theory* perspective encourages us that there is no physical law forbidding continued growth – no imminent "running out of energy" as some fear, nor a necessary stagnation due to saturation of ideas (because new knowledge creates new desires). The main constraints may be political or societal, not thermodynamic. As long as we can keep lowering the entropy per unit of value, we can grow *value* indefinitely. This ties into the final part of the entropic theory: the idea of **infinite growth** in a finite world is not a contradiction if growth comes from intangibles (information, experiences, knowledge) whose physical footprint can be very small. We will elaborate on policy needed to realize this and measure progress via an Entropic Value Index (EVI).

5. Policy Implications and the Entropic Value Index (EVI)

The entropic perspective on economic value has concrete implications for policy and how we measure progress. If energy and entropy efficiency are keys to growth, then policies should facilitate transitions to high-efficiency, low-entropy systems. In this section, we outline strategic policy areas: expanding and modernizing the electric grid, accelerating AI and robotics adoption while managing workforce transitions, capturing the gains from entropy efficiency in public wealth, and reforming regulations that slow down clean energy and tech deployment. We also propose an **Entropic Value Index (EVI)** as a metric to track how effectively an economy converts energy into ordered economic value over time. This index could guide policymakers in balancing growth and sustainability.

5.1 Grid Expansion and Clean Energy Infrastructure

A top priority is upgrading infrastructure to accommodate **abundant clean energy**. The electric grid is the central conduit for high-exergy energy (electricity) that will replace many direct fossil fuel uses. However, many countries face bottlenecks: insufficient transmission lines to connect windy plains or sunny deserts to cities, aging local grids that struggle with distributed solar or EV charging loads, and slow interconnection queues for new renewable projects.

Policy response should include large-scale investments in transmission (akin to the interstate highway buildout, but for power lines) and a streamlining of permitting for these lines [53]. Expanding grid capacity increases the *entropy-handling capability* of the economy – it allows more energy to flow where it's needed with minimal losses (modern HVDC lines have low resistive losses). A robust grid also enhances resilience, reducing chaotic outages that cause economic losses (and entropy spikes in the form of emergency fuel use when power is out).

In addition, storage infrastructure (utility-scale batteries, pumped hydro, etc.) needs scaling to smooth the variability of renewables. Policy can incentivize storage deployment (through subsidies, market designs that reward grid services, etc.). Energy storage effectively shifts entropy production in time (charging uses extra energy when supply is high, discharging prevents inefficient peaker plants later). It thus optimizes the overall entropy production per delivered kWh.

On the generation side, governments should continue to support R&D and demonstration of advanced nuclear and potentially fusion. While solar and wind will do heavy lifting in the near term, having dispatchable clean power like modular reactors or eventually fusion reactors can ensure we meet demand peaks and have energy for high-heat industrial processes. Removing regulatory hurdles that are not justified by safety (for nuclear) and providing funding for first-of-a-kind plants would accelerate these options.

Crucially, fossil fuel externalities (CO_2 emissions) need to be priced or regulated to push the transition. A carbon price or cap-and-trade system internalizes the entropy cost of greenhouse gas emissions (which are an entropy dump into the atmospheric commons). This steers investment toward low-entropy (low emissions) energy sources. Even without explicit carbon taxes, strong emission standards and clean energy standards can achieve similar outcomes.

Finally, electrifying transportation (EVs), buildings (heat pumps), and industry will increase electricity demand even as fossil fuel demand falls. Policy should support this electrification (EV charging networks, incentives for heat pump adoption, RD&D for electric industrial heaters or electrolysis for hydrogen, etc.). Electrification improves efficiency (an EV uses energy more efficiently than an ICE vehicle; a heat pump 3-4x more than a furnace) – so it directly raises $β$ by requiring less primary energy for the same service.

In summary, enabling **energy abundance** means building the hardware to use solar, wind, nuclear at scale. It is akin to building the aqueducts and roads of ancient times – foundational investments that unlock commerce and growth. The difference is these are *entropy-conscious* investments: they aim for a high-exergy, low-waste energy system, which is the backbone of entropic value creation.

5.2 AI, Robotics, and the Future of Work

The rise of AI and robotics calls for proactive policies to maximize benefits and mitigate disruptions. On one hand, we want to accelerate **adoption of productivity-enhancing AI** across industries to boost $β$ (the ordered output per joule). This could involve government incentives or programs to help small and mid-sized businesses implement AI solutions, similar to how extension services helped farmers adopt mechanization. Workforce development programs are needed to reskill workers for tasks that complement AI (since AI will handle routine parts, humans can focus on creative, complex, or interpersonal tasks).

Education policy in particular should emphasize digital literacy and adaptability, to produce workers who can work alongside AI or in fields that AI cannot (yet) fully automate. For instance, training more data analysts, engineers, healthcare technicians etc., while also teaching soft skills that remain a human advantage. An agile workforce ensures that AI amplifies human labor rather than replaces it outright in a harmful way.

However, we should prepare for potential **labor displacement** in certain sectors. Truck drivers, assembly line workers, and even some professional services could see AI/automation reduce demand for human labor. Here, social safety nets and transition support are crucial: unemployment benefits, possibly a form of *universal basic income (UBI)* or *sovereign wealth dividends* (discussed below) to share productivity gains, and public sector job creation in areas where human touch will always be valued (education, elder care, infrastructure projects). Historically, productivity leaps eventually create new jobs (who imagined app developers as a career in 2000?), but in the short-term, targeted support matters for equity.

Policymakers should also encourage **competition and dissemination** of AI technology, rather than allowing a few firms to monopolize the gains. If AI's benefits are widely spread, it contributes more to overall economic value. Open-source AI and government-funded research can ensure more players have access to advanced algorithms, not just tech giants.

From an entropic view, society should steer AI to problems that reduce entropy and waste: smart grids optimizing energy use, AI in material science finding low-energy pathways to synthesize chemicals, AI in agriculture reducing water and fertilizer waste, etc. Government grants and prizes can incentivize AI developers to focus on these public-good applications.

There is also a regulatory dimension: ensuring AI is used safely and ethically. This includes data privacy, algorithmic bias correction, and possibly slowing deployment in sensitive areas until proven (like fully autonomous vehicles needing safety thresholds). However, overregulation that unduly slows AI progress could hamper the $β$ growth we need for the entropic expansion. A balanced approach is necessary – agile governance where regulations update as the technology evolves (sandboxes, pilot programs).

5.3 Sovereign Wealth Dividends from Entropy Efficiency

As $β$ rises and the economy becomes more productive per unit input, a question arises: who captures the gains? In recent decades, a significant share of productivity gains accrued to capital owners rather than labor, contributing to inequality [48]. The entropic theory suggests that much of growth will come from technology (AI, automation) and natural capital (sunlight, etc.) rather than human toil. Therefore, there is a case for society at large to benefit from these “automation dividends” or “resource dividends.”

One mechanism is through a **sovereign wealth fund** or public ownership stakes in the new wealth generators. For example, a government could levy a micro-tax on AI-driven corporate profits or productivity gains and channel that into a fund. Alaska’s Permanent Fund, which pays dividends to residents from oil revenues, is an analogy – it treated oil (a natural resource) as a commonwealth asset. Similarly, one could treat the gains from national data or public AI research as partly belonging to citizens. The fund’s returns could then pay an annual **universal basic dividend** to all citizens, representing their share of the high-entropy to low-entropy conversion gains.

Such a policy ensures that as entropy efficiency improves (and maybe displaces some jobs or compresses wages in some sectors), everyone still gets a slice of the bigger pie. This can maintain aggregate demand and social stability, fueling further growth in a virtuous circle. It also politically legitimizes the push toward automation: people will support innovations that they know they will benefit from.

Another approach is to encourage profit-sharing and cooperative models in companies adopting heavy automation – essentially aligning the interests of workers and owners in the transition. Tax incentives could favor firms that retrain and share productivity gains with employees versus those that simply cut staff.

Tax policy in general might shift from taxing labor (income/payroll taxes) to taxing resource use or high-level rents. For instance, a carbon tax (which prices entropy cost) can replace some payroll tax, encouraging employment while discouraging pollution. Land value taxes or data usage taxes could tap into unearned incomes that tech monopolies or resource owners accumulate, redistributing some to the public.

In short, **policy should seek to socialize the benefits of entropy reduction** without stifling the entrepreneurial drive. A populace that feels vested in AI/robotics success (through dividends or guaranteed basic income) will be more receptive to change and experimentation.

5.4 Regulatory Reform for Innovation

One often-overlooked aspect is the need to reform or remove regulations that slow down **innovative projects** in energy and infrastructure. For example, in the U.S., big projects can be bogged down by years of environmental reviews and local opposition (NIMBYism). While careful review is important, the current processes often consider narrow local impacts and not the broader benefit of, say, a transmission line that could reduce fossil fuel use (a net environmental gain). Streamlining permitting – with clear timelines, one-stop federal coordination, and perhaps “strategic infrastructure” status for key grid and renewable projects – is needed to accelerate the entropic transition.

Similarly, nuclear regulations currently make building new reactors extremely costly and time-consuming. If next-gen reactors are inherently safer (many designs are passively safe), regulators could adapt a more risk-informed approach, allowing deployment and learning-by-doing. The entropic view would weigh the *opportunity cost* of not having that clean high-exergy source sooner (which is continued fossil use and more entropy dumping).

In the realm of transportation and cities, zoning and other regulations often prevent densification or new efficient builds. Relaxing restrictive zoning can allow more energy-efficient living patterns (e.g., multi-family housing, shorter commutes, integrated public transit). It also can reduce material use per capita (apartments share walls, saving heating/cooling energy).

Liability and legal frameworks for AI and autonomous vehicles need updating too – to provide clarity and confidence for companies to deploy, while protecting the public. For instance, establishing how insurance or fault works for an AI-driven car encourages adoption by reducing uncertainty.

Because the economy is dynamic, **regulatory agility** is vital. Policymakers might institute periodic reviews of major regulations under a lens of “does this hinder or help the low-entropy growth transition?”. Sunsetting outdated rules can remove friction. Also, enabling more experimentation (regulatory sandboxes for, say, drone delivery or AI diagnostics in healthcare) allows learning and proof-of-concept, after which successful models can be scaled with appropriate rules.

5.5 Entropic Value Index (EVI) – A New Metric for Progress

Traditional metrics like GDP are good at capturing overall output but not the efficiency or sustainability of that output. We propose an **Entropic Value Index (EVI)** to track how much economic value is created per unit of energy and entropy expended. One simple version of EVI could be the ratio of GDP (in real terms) to primary energy use. This essentially measures $α = GDP/E$. An indexed value (e.g., EVI = 100 in year 2000) would then show improvements over time (if EVI = 150 by 2020, that’s a 50% increase in GDP per energy). We might refine this by considering *exergy* rather than raw energy (accounting for the quality of energy used), but exergy data are harder to get – however, one could approximate by counting only the useful portion of energy (like electricity, mechanical work) in the denominator.

Another refinement is incorporating an entropy term for emissions or waste. For example, one might divide GDP by a composite of energy use and CO_2 emissions (since emissions represent future entropy cost via climate change). If the economy reduces CO_2 per GDP, that should reflect as an improved EVI. Essentially, EVI could be multi-dimensional: capturing energy intensity and carbon intensity improvements together.

The purpose of EVI is to quantify how well we are doing in the **decoupling** process. A rapidly rising EVI indicates that technology and efficiency are outpacing any growth in raw energy usage – a hallmark of sustainable growth. It’s akin to an energy-specific productivity metric. Policymakers could set EVI targets (like improving EVI by X% per year) and align incentives accordingly (through R&D support, standards, etc.).

Looking historically, the U.S. EVI (GDP per energy) has roughly tripled since 1950. We would expect it to perhaps double again in the next few decades if AI and clean energy deploy widely. EVI could also be used to compare countries: often GDP per energy is much higher in advanced economies than developing ones. Rather than that implying developing countries should not grow energy use (they will need to), it points to an opportunity for leapfrogging – adopting more efficient tech from the start to grow their EVI faster. International support could focus on giving developing nations access to high $β$ technologies (renewables, efficient appliances, industrial processes, etc.) so they can get more GDP bang per energy buck and not follow the old path of “grow now, clean up later.”

One can also invert EVI to get energy (or emissions) per GDP – which climate analysts already track (declining energy intensity trends). EVI just flips it to frame it positively as an index of value per entropy.

Additionally, we could broaden the concept to an "Entropic Well-being Index" by incorporating not just GDP but measures of human development achieved per unit entropy. For instance, how many quality-adjusted life years, or how much education, etc., per joule used. This would align with UN sustainability metrics.

In conclusion, EVI provides a focused way to monitor our progress toward the entropic ideal: infinite growth in value with finite, manageable growth in entropy. It can guide policy (similar to how energy intensity and carbon intensity already do, but giving it a cohesive theoretical framing).

5.6 Summary of Policy Directions

To summarize the policy discussion:

- **Invest in energy infrastructure:** Build the grid and energy storage for a high-renewables, high-electrification future. Support advanced nuclear and possibly fusion R&D. Price carbon to internalize entropy costs of emissions.

- **Facilitate AI & automation:** Educate and adapt the workforce, use incentives for adoption in beneficial areas, provide social safety nets for transitions, and ensure broad sharing of the gains (through dividends or labor policies).

- **Reform regulations:** Speed up permitting for clean energy and infrastructure projects, update rules to enable new tech (autonomy, etc.), and continuously prune regulations that hinder entropy-efficient innovation.

- **Use new metrics:** Track Entropic Value Index or similar to ensure we are on course. If EVI stagnates, that's a warning sign that we're not improving efficiency or that rebound effects (more usage from efficiency gains) are negating progress – which may need policy response like efficiency standards or usage taxes.

The overarching aim of these policies is to create an economy where **physical constraints are not binding** on growth because we operate near physical optimal efficiency. Growth then is a matter of ideas, creativity, and making sure everyone benefits – areas where human ingenuity is the limiting factor, not joules or atoms.

Conclusion

The Entropic Theory of Economic Value reframes economic growth as fundamentally an interplay between energy, entropy, and information. By viewing wealth creation through the lens of thermodynamics, we reconcile how "infinite" GDP growth can occur on a finite planet: it is achieved by relentlessly increasing the ordered work and information extracted per unit of energy, while minimizing entropy wasted per unit of output. Humanity's historical energy transitions – from sun-fed biomass to coal, oil, and the modern advent of solar and nuclear – all highlight the pursuit of higher exergy and efficiency, enabling leaps in living standards. Thermodynamic laws, once seen as potential limits to growth, become guiding principles for sustainable expansion when paired with technological ingenuity.

We developed an equation $Y = \beta(E) \times E$ as a simple but profound descriptor: output is proportional to energy use times the "cognitive efficiency" β. Traditional growth models that ignored energy and entropy ended up with mysterious residuals and unsustainable assumptions [54]. In contrast, an entropic approach recognizes that the dramatic growth of the past two centuries was driven by orders-of-magnitude increases in both energy availability and β (through technology and knowledge). It also recognizes that there are physical ceilings – Carnot limits, Landauer's limit – but that we operate far below those ceilings at present. Thus, the room for growth by improving β is enormous, more than enough to support many doublings of GDP without proportional increases in energy or emissions.

We demonstrated with U.S. data how economic growth has been decoupling from raw inputs: energy intensity is half of what it was in 1980 [39], and per-capita energy use is below 1970s levels [29] even as GDP per capita reaches new highs. Labor, too, is being augmented by energy-driven automation, such that a smaller workforce can produce more output than a larger one did decades ago [46] [48]. These trends are not a sign of "growth ending," but rather a sign of *growth changing its nature* – from extensive growth (more inputs) to intensive growth (more efficiency and knowledge). This is precisely the kind of growth that can continue indefinitely, bounded only by our creativity and the ultimate physical limits which are astronomically high.

Looking ahead, the convergence of AI and cheap clean energy provides a realistic path to sustain high growth in an environmentally viable way. AI increases β by leveraging every joule for more complex tasks, while solar, wind, and nuclear provide the joules without depleting or polluting. We painted a scenario of a new economic boom, where productivity surges and prosperity extends widely, so long as we manage the transition with wise policies. That includes investing in infrastructure, retraining workers, and perhaps distributing some of the automation gains via mechanisms like a universal basic dividend. These steps would ensure that the entropic efficiency gains translate into human welfare broadly, not just concentrated profits.

Crucially, embracing an entropic perspective adds optimism to the often doom-and-gloom narrative around limits. Yes, the planet has finite resources and a limited ability to absorb waste, but by sharply increasing our efficiency (doing more with less) we effectively "expand" the carrying capacity in terms of value. For instance, delivering education or healthcare digitally to billions has negligible marginal environmental cost compared to trying to give each person a car and a big house, yet it tremendously improves quality of life. As more of our consumption turns to these low-entropy forms – experiences, information, personalized services – we can keep growing GDP and well-being with a light footprint.

We must also remain vigilant that *entropy doesn't bite back*. Climate change is essentially an entropy problem (excess heat trapped). We have a window to solve it by transitioning energy now – a test of whether our technological β can outpace the negatives of past growth. Likewise, biodiversity loss and other ecological issues are signs of entropy accumulating in unwanted places (disorder in ecosystems). The same ingenuity that drives economic growth must be applied to restore balance (e.g., using clean energy for direct air capture, precision agriculture to spare land for nature, etc.). The entropic theory doesn't dismiss these concerns – it provides the framework to address them without halting growth.

In final thought, infinite growth is only physically plausible if it's *growth in knowledge and organization*, not unbounded growth in material throughput. But knowledge has no known limits – each idea can spark another, and each improvement in β opens doors to even greater improvements (AI designing better AI, for example). With the right orientation, our economy can become an ever more sophisticated engine that turns raw energy into the twin outputs of prosperity and progress, all while respecting the laws of thermodynamics. Achieving this vision calls for aligning our policies, metrics, and innovations with the goal of maximizing **entropic value** – maximizing the economic bang for each thermodynamic buck. The Entropic Value Index will tell the tale: if it keeps rising, we will know we are on the path where growth and sustainability march hand in hand into the future.

Sources:

- Historical shifts in U.S. energy usage [7] [11]
- Energy density of fuels (wood: 16 MJ/kg; coal: ~25 MJ/kg; oil: ~45 MJ/kg; uranium: 500 GJ/kg in LWR) [8] [20]
- Carnot efficiency and power plant improvements [32]
- Economic importance of energy and exergy in growth [37] [34]
- Decline in U.S. energy intensity 1980–2020 [39]
- Changes in per-capita energy use in U.S. (peak 1979, decline to 2020) [29]
- Rise and fall of labor force participation and rise of productivity [46] [47] [48]
- Computing efficiency doubling ~every 1.5 years (Koomey's law) [42] and far from physical limits [43]
- Landauer's principle: min kT ln2 energy per bit [38]

---

[1] [2] [3] [16] [34] [35] [36] [37] [40] [54] Energy, Entropy, Constraints, and Creativity in Economic Growth and Crises
https://www.mdpi.com/1099-4300/22/10/1156

[4] [6] [10] [26] [27] [28] [29] Energy in the United States - Wikipedia
https://en.wikipedia.org/wiki/Energy_in_the_United_States

[5] [8] [13] [14] [20] [21] Heat Values of Various Fuels - World Nuclear Association
https://world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels

[7] [18] [25] History of energy consumption in the United States, 1775–2009 - U.S. Energy Information Administration (EIA)
https://www.eia.gov/todayinenergy/detail.php?id=10

[9] U.S. renewable energy consumption surpasses coal for the first time ...
https://www.eia.gov/todayinenergy/detail.php?id=43895

[11] [12] [19] [30] [53] United States energy history in two charts - Visualizing Energy
https://visualizingenergy.org/americas-energy-history-in-two-charts/

[15] [31] Fuel energy density: What is it and why is it important? - Visualizing Energy
https://visualizingenergy.org/fuel-energy-density-what-is-it-and-why-is-it-important/

[17] [23] [24] U.S. energy facts explained - consumption and production - EIA
https://www.eia.gov/energyexplained/us-energy-facts/

[22] [32] [33] US Historical Energy Use
https://physics.weber.edu/schroeder/energy/USEnergyHistory.html

[38] The Landauer Principle: Re-Formulation of the Second Thermodynamics Law or a Step to Great Unification? - PMC
https://pmc.ncbi.nlm.nih.gov/articles/PMC7514250/

[39] U.S. energy intensity has dropped by half since 1983, varying greatly by state - U.S. Energy Information Administration (EIA)
https://www.eia.gov/todayinenergy/detail.php?id=48976

[41] Energy use is declining in some countries, despite economic growth.
https://ourworldindata.org/energy-gdp-decoupling

[42] [43] [44] Computations per kilowatt-hour over time for personal computers alone.... | Download Scientific Diagram
https://www.researchgate.net/figure/Computations-per-kilowatt-hour-over-time-for-personal-computers-alone-Efficiency-doubled_fig4_224128141

[45] Global Economy Becoming Less Energy Intense | Climate Central
https://www.climatecentral.org/news/global-economy-using-energy-more-efficiently-20542

[46] Women staging a labor force comeback - The Hamilton Project
https://www.hamiltonproject.org/publication/post/women-staging-a-labor-force-comeback/

[47] Labor Force Participation in California
https://www.ppic.org/publication/labor-force-participation-in-california/

48 Decades of rising economic inequality in the U.S.: Testimony before ...
https://www.epi.org/publication/decades-of-rising-economic-inequality-in-the-u-s-testimony-before-the-u-s-house-of-representatives-ways-and-means-committee/

49 [PDF] Energy Efficiency in the United States: 35 Years and Counting
https://www.aceee.org/sites/default/files/publications/researchreports/e1502.pdf

50 United States Labor Force Participation Rate - Trading Economics
https://tradingeconomics.com/united-states/labor-force-participation-rate

51 In Brief: The Recent Rise in US Labor Productivity
https://www.economicstrategygroup.org/publication/in-brief-us-labor-productivity/

52 Measuring Productivity and Growth Rates - Lumen Learning
https://courses.lumenlearning.com/oldwestbury-wm-macroeconomics/chapter/reading-the-new-economy-controversy/