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Limits to economic growth

Across the world, decisions on investment and policy are made under the assumption of continuous economic expansion. Fundamental physical limits may soon put an end to this phase of development, as foreshadowed by the 1972 report *The Limits to Growth*.

Thomas W. Murphy Jr

Quantitative economic growth, in which inflation-adjusted wealth continues to rise, has been reasonably reliable for generations and is deeply woven into modern societal structure. The promise of a tomorrow that is 'bigger' than today fuels investment, innovation and dreams. Growth is imagined to offer a solution to inequality between developed and developing nations: redistribution today is unnecessary if growth will eventually address the problem by growing the pie. Interest rates, bank loans, home mortgages and pension plans rest on the assumption of growth. The funding of social safety nets such as Social Security and Medicare in the United States is predicated upon both economic growth and growth of the labour pool. Planning at national, state, municipal and institutional levels presumes long-term stability in economic growth. When so much is staked on the assumption of growth, we owe it to ourselves to survey the foundation and expose any dangerous cracks.

The landmark report *The Limits to Growth*[1], now 50 years old, explored models for interactions between various elements of civilization, including population, agricultural output, industrial output, non-renewable resources and pollution. Alarmingly, most sets of assumptions resulted in a significant collapse before the year 2100 — often around the middle of the present century. Simultaneously doubling estimated resources, amplifying technological substitutions and efficiencies, aggressively recycling and applying strict pollution controls still resulted in a reversal of the growth paradigm. Only by imposing explicit limits to industrial output and demanding that birth rates match death rates (enabled by unspecified policies) beginning in 1975 could collapse be prevented. In no case could their model support continued growth. It is unclear whether a 50 year delay in the introduction of such measures would still be able to save their model from collapse.

While successful in raising awareness and influencing thought about limits, *The Limits to Growth* report also came under heavy and sustained attack from economists (for example, ref. [2]), such that a common perception today is that the predictions were wrong and can be safely ignored. Yet the report repeatedly clarified that it was exploring persistent dynamical modes rather than making explicit predictions, particularly highlighting the model's tendency to overshoot and collapse as a consequence of delayed negative feedback. For example, human lifetimes impose decades-long delays on resource and pollution impacts that do not restrict excessive consumption until it is too late. Comparisons of our realized trajectory over the years have yet to expose any significant departure from the runs that collapse this century, while able to rule out the report's best-case equilibrium results[3]. It is simply too early to declare the model results as being invalid.

The Limits to Growth does not address economic growth explicitly. The models tracked physical measures and not money. The discussion of equilibrium conditions towards the end of the report does imply a halt to conventional economic growth, but without elucidating why this must be so. This Comment presents an argument for how limits in the physical domain ultimately force limits on economic growth as we know it. In brief, inelastic demand for critical resources in limited supply will not permit prices for these things to become arbitrarily small, which would be necessary to maintain indefinite economic growth. The implications are profound in a society structured around growth, and the time limit is sooner than many assume.

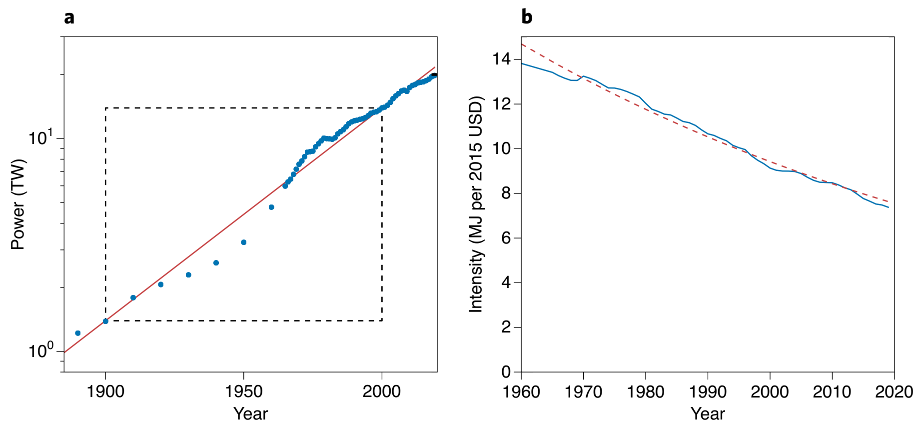

Fig. 1 | Historical energy growth and intensity decline. a, Global rate of energy expenditure on a logarithmic scale over the past century, including fossil fuel, renewable, and nuclear resources. The red line represents a 2.3% exponential growth rate, corresponding to a factor of ten per century (dotted box). The line is not a fit to the data, but is selected as a convenient and reasonable representative of global energy growth. **b**, Economic intensity for the world as a function of time (blue curve), in MJ per 2015 constant dollars. The red dashed line is a best-fit exponential function showing a decline of 1.1% per year. Data taken from refs. [10,11].

Physical limits

A finite world of finite resources will not support indefinite growth in the extraction of those resources. In the case of non-renewable resources such as mined minerals and fossil fuels, whose stocks are finite, we obviously cannot continue extraction indefinitely: we simply run out of materials. But even for renewable resources such as solar power, the rate of replenishment is set by nature and cannot

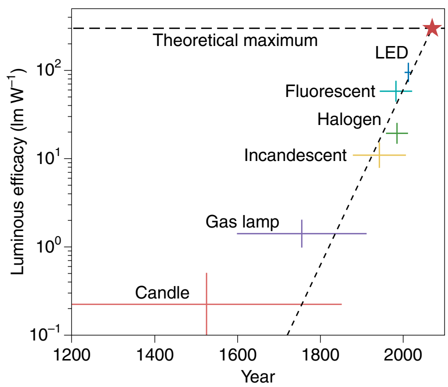

Fig. 2 | Historical lighting progression and limits. Historical progress in lighting efficiency can give the mistaken impression that a long chain of superior substitutes might continue indefinitely. But we are fast approaching the hard physical limit. The suggestive line represents a factor-of-ten improvement per century (2.3% annually), which intersects the theoretical limit at the star before the end of this century. Symbols indicate approximate ranges of use and efficiency for each technology.

grow arbitrarily large, not to mention that building the technology to harvest such flows also requires consumption of non-renewable resources.

Earth has so far seemed large enough to accommodate any withdrawal we cared to make. Sensibly, the most easily accessed resources are exploited first. This means that past experience regarding ease of extraction is not the best guide to future prospects. We drill and dig deeper in increasingly hostile and remote environments as one resource after another is depleted. Because Earth has never hosted 8 billion humans with an unprecedented and continuously growing per-capita demand, we cannot base projections for future resources on the fact that they have not yet failed us. Estimated reserves of fossil fuels, copper, cobalt, lithium, and so on do not promise centuries of worry-free resource availability. An example in the energy domain demonstrates the absurdity of indefinite growth in the physical realm. Figure 1 shows the approximately exponential evolution of global energy use over the past century. In this case, energy growth has typically been 2–3% per year.

Selecting a mathematically convenient growth rate of a factor of ten each century (corresponding to 2.3% per year; roughly commensurate with the human enterprise in recent times as shown in Fig. 1), our present-day expenditure at the level of 18 TW (18×10^{12} W) extrapolates to about 100 TW in 2100, 1,000 TW in 2200, and so on. In a continued progression, we would exceed the total solar power incident on Earth in just over 400 years, the entire output of the Sun in all directions 1,300 years from now, and that of all 100 billion stars in the Milky Way galaxy 1,100 years after that. This last jump is made impossible by the fact that even light cannot cross the galaxy in fewer than 100,000 years. Thus, physics puts a hard limit on how long our energy growth enterprise could possibly continue.

Many things are oversimplified in the previous paragraph's fantastical progression. It is in no way meant to be taken as a prediction of our future path, merely as an illustration of the absurdity of blind extrapolation of historical growth rates into the future. Those growth rates existed in the context of an increasing human population on Earth, which few would expect to continue unchecked for centuries more. The energy growth phenomenon has also been almost entirely made possible by the discovery and rapid exploitation of a one-time energy store in the form of fossil fuels. Growth in this sector is likely to cease within decades, not centuries, so that the main driver of energy growth will be removed from the table. Finally, Fig. 1 suggests that the growth rate in energy has already been weakening over the last 50 years, further reinforcing my main point that growth will not continue indefinitely, or perhaps even for much longer. Therefore, if the previous paragraph predicts anything, it is that growth of energy use on Earth will cease on a timescale that is short compared to the longevity of civilization as a whole.

Another way to frame physical limitations to growth is in terms of waste heat, which is the end product of nearly all energetic utilization on Earth. Adding an exponential power output to the heat incident from the Sun and equating this to the Stefan–Boltzmann relation for power radiated to space, we find that Earth's equilibrium temperature in the absence of greenhouse gases is set by

$$P = F_\odot(1-\alpha)A_{\mathrm{proj}} + P_0 e^{r(t-t_0)} = A_{\mathrm{surf}}\sigma T^4, \quad (1)$$

where $F_\odot = 1,360$ W m^{-2} is the solar flux present at the top of the atmosphere, $\alpha \approx 0.293$ is Earth's albedo, $A_{\mathrm{proj}} = \pi R^2_\oplus$ is the projected area of Earth (radius $R_\oplus$), P_0 is civilization's power output in Watts at time t_0 (in years; for example, $P_0 = 14 \times 10^{12}$ W at $t_0 = 2,000$), and r is the growth rate, which we can set equal to (ln10)/100 ≈ 0.023 to get a factor of ten per century. On the second line is the surface area of Earth, $A_{\mathrm{surf}} = 4\pi R^2_\oplus$, the Stefan–Boltzmann constant $\sigma \approx 5.67 \times 10^{-8}$ W m^{-2} K^{-4}, and the temperature T, in kelvin. Rearranging this to get an expression of surface temperature as a function of time, and adding a greenhouse gas factor of $\Delta T_{\mathrm{GHG}} \approx 33$ K (a simple approach that will not overestimate the effect), we get

$$T = \left(\frac{F_\odot(1-\alpha) + p_0 e^{r(t-t_0)}}{4\sigma}\right)^{(1/4)} + \Delta T_{\mathrm{GHG}} \quad (2)$$

where we have divided top and bottom by $\pi R^2_\oplus$ to create a new quantity $p_0 = P_0/\pi R^2_\oplus \approx 0.1$ W m^{-2} at $t_0 = 2,000$. At present, the waste heat term is about four orders of magnitude smaller than the solar term. But at a growth factor of ten per century, they would reach parity in roughly 400 years. Indeed, the surface temperature of Earth would reach the boiling point of water (373 K) in just over 400 years under this relentless prescription. Clearly, extrapolating our recent — seemingly modest — 2.3% annual energy growth very far into the future quickly becomes ridiculous, and cannot happen.

This is not intended to suggest that waste heat is a bigger problem than, say, climate change from carbon dioxide emissions. To put the p_0 parameter in equation (2) into perspective, the current radiative imbalance associated with climate change is ~1 W m^{-2}, and thus an order of magnitude greater than waste heat. If the latter were to increase at 2.3% per year according to the historical energy growth trajectory, waste heat would rival global warming next century and quickly become dominant thereafter, shortening the period over which growth is possible even further.

Of course, it is not plausible that the world economy will grow to the point that waste heat manifests as a real concern. In the most optimistic case, we could imagine near-term continuation of our growth trajectory until reaching a long-term steady-state endpoint utilizing only renewable resources. By the arguments above, the time limit on such an expansion in the energy domain is only a few hundred years at the present growth rate. More realistically, we will experience a peak of energy use and witness a decline thereafter — possibly on a timescale of decades rather than centuries. But for the purposes of this Comment, I will assume the happier scenario of maintaining a steady post-growth usage of physical resources at a high rate of consumption. Even this is not possible in the context of non-renewable resources.

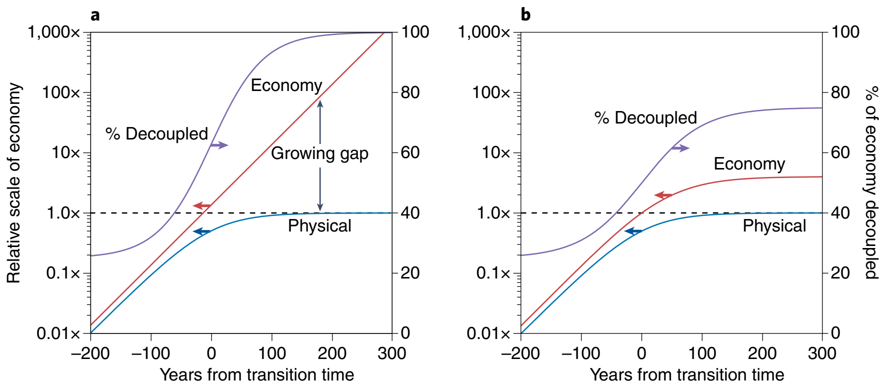

Fig. 3 | Indefinite growth versus saturated scale. a,**b**, Model scenarios for economic growth in the face of stalled or steady physical resources. In both panels, the blue line is the scale of physical activities, which reaches a saturation point due to physical constraints. The red curves represent the total economy. If demanding continued economic growth, as in panel **a**, a growing gap must open so that the fraction of economic activity in the non-physical sector (purple line; right-hand axis) approaches 100%. Panel **b** depicts a more realistic trajectory. In this case, the non-physical elements of the economy are constrained (arbitrarily) to grow no higher than 75% of the total, resulting in only a modest amount of decoupled economic growth before flattening.

Unbounded implications

On the face of it, money is an artificial construct that is not bound by the laws of physics. Given this, it is unclear what might prevent economic growth from continuing apace even in the context of stalled growth in the physical domain. The idea of 'decoupling' in economics addresses exactly this point.

Not all economic activities involve intense use of physical resources. Trading fine art, counselling, professional services and gambling are examples of activities that can involve non-trivial flows of money without substantially adding to demands on physical resources. Examples abound, and the path would seem to be clear to continued economic growth unencumbered by physical limitations. Efficiency improvements can likewise result in lower energy use for the same economic benefit.

Figure 1 illustrates the hopeful trend in decoupling, whereby the energy expenditure per unit of financial activity (here 2015 constant dollars) exhibits a steady downward march. Should this be able to continue indefinitely, economic activity would not face an obvious limitation from non-growing physical sectors such as the energy industry. The global rate of decline in intensity is roughly 1% per year, which has not been enough to offset growth rates, so that the overall rate of energy use still climbs, as shown in the left panel of Fig. 1. In effect, the gross world product (GWP) grows at the rate of energy growth plus the decline rate of intensity. Energy growth at roughly 2% per year combines with the intensity rate of 1% per year for a GWP growth of approximately 3% per year.

The 1% annual improvement in energy intensity is remarkably similar to the overall trend in efficiency improvements in appliances, lighting, and transportation. Such efficiency improvements are not unbounded. Electric motors are already 80–90% efficient. Light-emitting diode performance is a factor of ten better than incandescent technology, but only a factor of three worse than theoretical limits to efficiency for white light[4]. We cannot expect efficiency to provide an eternal source of growth: much less than an order of magnitude of improvement will be achievable in most applications. Figure 2 illustrates this point for the case of lighting. Once a physical resource is saturated, we might expect some continuation of efficiency gains that can provide a modicum of additional economic growth. But it will probably be confined in both time and magnitude—the rate of improvement starting at less than 1% per year and declining from there.

One must be careful, however, about the role of financialization and debt in supporting some portion of apparent GWP growth. Debt represents a claim on future money, which therefore places some burden on future resources that nature may not provide when the bill comes due. In other words, some portion of GWP growth — and thus decoupling — may be illusory in terms of biophysical backing[5]. A careful study of the decoupling trend in Switzerland showed that much of it can be virtual rather than actual, due to outsourcing of industry[6]. As pointed out in ref. [7], the reduction in intensity seen in the right panel of Fig. 1 is more than offset by growth in population and per-capita resource demand so that the net effect is one of positive growth in resource demand (in line with the left panel of Fig. 1). Another work[8] found that efficiency gains are offset by greater use and that absolute decoupling appears to be impossible.

Setting aside these findings and entertaining the notion that decoupling could continue unbounded, let us explore the implications of continued economic growth in the context of a fixed physical scale. For the sake of argument, we will suppose that at the point growth is forced to stop in the physical domain, half of the economy is in 'decoupled' activities that bear little or no resource impact. We will further assume the same convenient 2.3% annual growth rate for the economy, yielding a factor of ten increase per century.

Continued economic growth in the face of steady-state physical resources would require all growth to be effectively in the non-physical sector, possibly assisted by modest efficiency improvements in how we use physical resources. If, for example, 50% of economic activity is tied to physical resources, 100 years later only 5% of the economy would be represented by physical activities, as the economy will have expanded by a factor of ten for the same physical footprint. In 200 years, the physical component is 0.5%. Projected forward, the physical fraction becomes arbitrarily small. Figure 3 illustrates this point, in which we see non-physical activities approaching 100% of the total economy in order to maintain growth against flat physical resources.

In other words, physical resources in this forced scenario must shrink to an ever-smaller fraction of the economy, translating to a small and diminishing fraction of an individual's annual income having to go toward physical goods. All the food, energy and material purchases would become essentially free.

This result makes little sense in the context of supply and demand. Food, energy and materials are non-negotiable requirements for basic life and functioning. It seems ludicrous to imagine that these vital resources incapable of further expansion would become essentially free of charge. Under such circumstances, one person could afford to buy them all and then raise prices. A different way to put it is that a limited supply coupled with mandatory demand will find an equilibrium price that saturates at a finite value. Once this happens, growth in the non-physical sectors will no longer be possible. Finite physical resources ultimately act as an anchor to the entire economy. Arguably, we might expect such a saturation to occur well within a century of the end of physical growth, lest the scarce resources shrink to a dubiously small fraction of the total economy.

The red curve in the right panel of Fig. 3 shows a more realistic trajectory for the economy in the face of a steady physical scale. In this example, non-physical activities are allowed to comprise 75% of the economy before saturating. Although this upper limit is arbitrary, its exact value does not change the resulting saturation of the overall economy. Any limit on the fraction of an economy that is decoupled from physical resources will act to limit economic growth in the context of saturated physical growth.

Lessons

An end to quantitative economic growth need not translate to an end to innovation or other forms of qualitative development and improvement. But growth as we have known it will no longer be able to drive the way civilization operates. The entire financial, economic, political and social system will be forced to undergo radical change, leaving something bearing little resemblance to today's world.

Given that assumptions of quantitative growth are pervasive in our society and have been present for many generations, it is perhaps not surprising that growth is not widely understood to be a transient phenomenon. Early thinkers on the physical economy, such as Adam Smith, Thomas Malthus, David Ricardo and John Stuart Mill saw the growth phase as just that: a phase[9]. For these pioneers, land was the ultimate resource, and they did not foresee the one-time bonanza that would be unleashed by fossil fuels. It is tempting to think that we, too, may not appreciate revolutionary substitutions in our future. But bear in mind that no new sources of energy have been identified in the last 50 years despite substantial attention and awareness about fossil fuel depletion. Just because a game-changing transformation like the discovery of fossil fuels happens once does not guarantee a repeat performance. Even if amazing substitutions are to arise going forward, it is still not possible to grow our use of physical resources on this planet indefinitely, and the overall economy will struggle to grow once growth in the physical sector is capped. The thermodynamic limits explored above, for instance, apply to any energy technology we care to imagine.

More realistically, it is not clear whether we could even maintain a steady flow of resources indefinitely into the future. Far more likely is an overtaxed overshoot of sustainable practices, only apparent and demonstrable in hindsight. Even if growth stopped today, the pressures on ecosystems at the present scale may be enough to drive the system into collapse. Any delay in negative feedback generically leads to overshoot, as stressed in *The Limits to Growth*[1]. The fact that ecological damage is still accumulating at today's scale of activity is an indication that we have already passed the mark of a sustainable footprint on the planet. If that is so, we can expect to experience a decline in the scale of physical resource exploitation that will not only precipitate a halt to economic growth, but will drag it downward as well, in a sort of permanent recession or depression. Since growth to some extent depends on faith in future growth in order to spur investment, this nonlinear feature could translate into a fairly rapid evaporation of capitalist ambitions. We must therefore be careful to understand the phenomenon and its implications so that we do not to allow a panicked departure from growth that may result in unnecessary suffering or ill-intentioned opportunists exploiting the chaos.

The pervasiveness of growth can be understood in the context that we prefer it to the alternative. Growth side-steps the contentious issue of dividing up the pie by conjuring an expansion of the pie. As long as resources are present to support it, one can expand the monetary scale as a claim on future resources: a statement that tomorrow will be bigger than today. This frontier attitude is only valid as long as growth in the physical scale is still possible. But an increasing population with an increasing per-capita demand on resources will eventually surpass the physical system's ability to support arbitrary demands, if it has not done so already. While this scenario more obviously applies to a limitation in the physical domain, economic activity cannot be entirely divorced from this reality, and will likewise experience limits.

The Limits to Growth ends by saying:

> "...short-term concerns will generate the exponential growth that drives the world system toward the limits of the Earth and ultimate collapse. With [an equilibrium goal and human will to achieve it], mankind would be ready now to begin a controlled, orderly transition from growth to global equilibrium."

We would be wise to plan for a post-growth world. Academics have a special societal responsibility to recognize long-term threats and help humanity steer clear. In this case, economic growth is impossible to sustain, and a deliberate transition away from it will take time. Our academic institutions could be put to good use by helping to define a future world that respects planetary limits. Academics have an opportunity to help define an enduring partnership with the planet whose value could be appreciated for millennia to come. Clinging to growth at this point would seem to be a foolish strategy that is destined to fail. Prudence would suggest a departure from growth as soon as is possible, because we are unable to judge when the damage is too great to repair. ❐

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Competing interests

The author declares no competing interests.