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Galactic Scale Energy, Part 2: Can Economic Growth Last?

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This is a guest post by Tom Murphy. Tom is an associate professor of physics at the University of California, San Diego. This article is Part 2 of a two-part assessment of the implications of continued growth. Part 1 appeared here. Both articles first appeared at Do The Math.

As we saw in the previous post, the U.S. has expanded its use of energy at a typical rate of 2.9% per year since 1650. We learned that continuation of this energy growth rate in *any form of technology* leads to a thermal reckoning in just a few hundred years (not the tepid global warming, but boiling skin!). What does this say about the long-term prospects for economic growth, if anything?

Figure 1. *World economic growth for the previous century, expressed in constant 1990 dollars. For the first half of the century, the economy tracked the 2.9% energy growth rate very well (blue line), but has since increased to a 5% growth rate (red line), outstripping the energy growth rate.*

The figure above shows the rate of global economic growth over the last century, as reconstructed by J. Bradford DeLong. Initially, the economy grew at a rate consistent with that of energy growth. Since 1950, the economy has outpaced energy, growing at a 5% annual rate. This might be taken as great news: we do not necessarily require physical growth to maintain growth in the economy. But we need to understand the sources of the additional growth before we can be confident that this condition will survive the long haul. After all, fifty years does not imply everlasting permanence.

The difference between economic and energy growth can be split into efficiency gains—we extract more activity per unit of energy—and “everything else.” The latter category includes sectors of economic activity not directly tied to energy use. Loosely, this could be thought of as non-manufacturing activity: finance, real estate, innovation, and other aspects of the “service” economy. My focus, as a physicist, is to understand whether the impossibility of indefinite physical growth (i.e., in energy, food, manufacturing) means that economic growth in general is also fated to end or reverse. We’ll start with a close look at efficiency, then move on to talk about more spritely economic factors.

Exponential vs. Linear Growth

First, let’s address what I mean when I say *growth*. I mean a steady rate of fractional expansion each year. For instance, 5% economic growth means any given year will have an economy 5% larger than the year before. This leads to exponential behavior, which is what drives the conclusions. If you object that exponentials are unrealistic, then we’re in agreement. But such growth is the foundation of our current economic system, so we need to explore the consequences. If you think we could save ourselves much of the mess by transitioning to *linear* growth, this indeed dramatically shifts the timeline—but it’s also a death knell for economic growth.

Let’s say we lock in today’s 5% growth and make it linear, so that we increase by a fixed absolute amount every year—not by a fixed fraction of that year’s level. We would then double in 20 years, and in a century would be five times bigger (as opposed to 132 times bigger under exponential 5% growth). But after just 20 years, the fractional growth rate is 2.5%, and after a century, it’s 1%. So linear growth starves the economic beast, and would force us to abandon our current debt-based financial system of interest and loans. This post is all about whether we can maintain our current, exponential trajectory.

Squeezing Efficiency: Rabbits out of the Hat

It seems clear that we could, in principle, rely on efficiency alone to allow continued economic growth even given a no-growth raw energy future (as is inevitable). The idea is simple. Each year, efficiency improvements allow us to drive further, light more homes, manufacture more goods than the year before—all on a fixed energy income. Fortunately, market forces favor greater efficiency, so that we have enjoyed the fruits of a constant drum-beat toward higher efficiency over time. To the extent that we could continue this trick forever, we could maintain economic growth indefinitely, and all the institutions that are built around it: investment, loans, banks, etc.

But how many times can we pull a rabbit out of the efficiency hat? Barring perpetual motion machines (fantasy) and heat pumps (real; discussed below), we must always settle for an efficiency less than 100%. This puts a bound on how much gain we might expect to accomplish. For instance, if some device starts out at 50% efficiency, there is no way to squeeze more than a factor of two out of its performance. To get a handle on how much there is to gain, and how fast we might expect to saturate, let’s look at what we *have* accomplished historically.

The Good, the Bad, and the Average

A few shining examples stand out. Refrigerators use half the energy that they did about 35 years ago. The family car that today gets 40 miles per gallon achieved half this value in the 1970’s. Both cases point to a 2% per year improvement (doubling time of 35 years).

Not everything has seen such impressive improvements. The Boeing 747 established a standard for air travel efficiency in 1970 that has hardly budged since. Electric motors, pumps, battery charging, hydroelectric power, electricity transmission—among many other things—operate at near perfect efficiency (often around 90%). Power plants that run on coal, natural gas, or nuclear reactions have seen only marginal gains in efficiency in the last 35 years: well less than 1% per year.

Taken as a whole, we might then loosely guess that overall efficiency has improved by about 1% per year over the past few decades—being bounded by 0% and 2%. This corresponds to a doubling time of 70 years. How many more doublings might we expect?

Potential Gains and Limits

Many of our large-scale applications of energy use *heat engines* to extract useful energy out of combustion or other source of heat. These include fossil-fuel and nuclear power plants operating at 30–40% efficiency, and automobiles operating at 15–25% efficiency. Heat engines therefore account for about *two-thirds* of the total energy use in the U.S. (27% in transportation, 36% in electricity production, a bit in industry). The requirement that the entropy of a closed system may never decrease sets a hard limit on how much efficiency one might physically achieve in any heat engine. The maximum theoretical efficiency, in percent, is given by $100\times(T_h-T_c)/T_h$, where T_h and T_c denote absolute temperatures (in Kelvin) of the hot part of the heat engine and the "cold" environment, respectively. Engineering limitations prevent realization of the theoretical maximum. But in any case, a heat engine operating between 1500 K (hot for a power plant) and room temperature could at most achieve 80% efficiency. So a factor of two improvement is probably impractical in this dominant domain.

The reverse of a heat engine is a *heat pump*, which uses a little bit of energy to move a lot. Air conditioners, refrigerators, and some home heating systems use this technique. Somewhat magically, moving a certain quantity of heat energy can require less than that amount of energy to accomplish. For cooling applications, the thermodynamic limit to efficiency is given by $100\times T_c/(T_h-T_c)$, again expressing temperatures on an absolute scale. A refrigerator (usually a freezer with a piggybacked refrigerator) operating at room temperature can theoretically achieve 1100% efficiency. The Energy Efficiency Ratio (EER), which is displayed for most new cooling devices, is theoretically bounded by $3.4\times T_c/(T_h-T_c)$, which in this example is 36. Today's refrigerators achieve EER values of about 12, so that only a factor of three remains. The same can be said for the Coefficient of Performance (COP) for heat pumps, which is bounded by $T_h/(T_h-T_c)$. Like refrigerators, these are performing within a factor of 2–3 of theoretical limits.

Lighting has seen dramatic improvements in recent decades, going from incandescent performances of 14 lumens per Watt to compact fluorescent efficacies that are four times better, at 50–60 lumens per Watt. LED lighting currently achieves 60–80 lumens per Watt. An ideal light source emitting a spectrum we would call white (sharing the exact spectrum of daylight) but contrived to have no emission outside our visible range would have a luminous efficacy of 251 lm/W. The best LEDs are now within a factor of three of this hard limit.

The efficiency of gasoline-powered cars can not easily improve by any large factor (see heat engines, above), but the *effective* efficiency can be improved significantly by transitioning to electric drive trains. While a car getting 40 m.p.g. may have a 20% efficient gasoline engine, a battery-powered drive train might achieve something like 70% efficiency (85% efficiency in charging batteries, 85% in driving the electric motor). The factor of 3.5 improvement in efficiency suggests effective mileage performance of 140 m.p.g. One caution, however: if the input electricity comes from a fossil-fuel power plant operating at 40% efficiency and 90% transmission efficiency, the effective fossil-to-locomotion efficiency is reduced to 25%, and is not such a significant step.

As mentioned above, a broad swath of common devices already operate at close to perfect efficiency. Electrical devices in particular can be quite impressively frugal with energy. That which isn't used constructively appears as waste heat, which is one way to quickly assess efficiency for devices that do not have heat generation as a goal: power plants are hot; car engines are hot; incandescent lights are hot. On the flip side, hydroelectric plants stay cool, LED lights are cool, and a car battery being charged stays cool.

Summing it Up

Given that two-thirds of our energy resource is burned in heat engines, and that these cannot improve much more than a factor of two, more significant gains elsewhere are diminished in value. For instance, replacing the 10% of our energy budget spent on direct heat (e.g., in furnaces and hot water heaters) with heat pumps operating at their maximum theoretical efficiency effectively replaces a 10% expenditure with a 1% expenditure. A factor of ten sounds like a fantastic improvement, but the overall efficiency improvement in society is only 9%. Likewise with light bulb replacement: large gains in a small sector. We should still pursue these efficiency improvements with vigor, but we should not expect this gift to provide a form of unlimited growth.

On balance, the most we might expect to achieve is a factor of two net efficiency increase before theoretical limits and engineering realities clamp down. At the present 1% overall rate, this means we might expect to run out of gain this century. Some might quibble about whether the factor of two is too pessimistic, and might prefer a factor of 3 or even 4 efficiency gain. Such modifications may change the timescale of saturation, but not the ultimate result.

Faith in Technology

We have developed an unshakable faith in technology to address our problems. Its track record is most impressive. I myself can sit at my dining room table in California and direct a laser in New Mexico to launch pulses at the astronaut-placed reflectors on the moon and measure the distance to one millimeter. I built much of the system, so I am no stranger to technology, and embrace the possibilities it offers. And we've *seen* the future in our movies—it's almost palpably real. But we have to be careful about faith, and periodically reexamine its validity or possible limits. Following are a few key examples.

What About Substitutions?

The previous discussion is rooted in the technologies of today: coal-fired power plants, for goodness sake! Any self-respecting analysis of the long term future should recognize the near-certainty that tomorrow's solutions will look different than today's. We may not even have a *name* yet for the energy source of the future!

First, I refer you to the previous post: the continued growth of *any* energy technology—if consumed on the planet—will bring us to a boil. Beyond that, we hit astrophysically nonsensical limits within centuries. So energy scale *must* cease growth. Likewise, efficiency limits will prevent us from increasing our effective energy available without bound.

Second, you might wonder: can't we consider solar, wind and other renewables to be more efficient than fossil fuel power, since the energy has free delivery? It's true that unlike the business model for the printer (cheap printer, expensive ink cartridges that ruin you in the end), the substantial cost for renewables is in the initial investment, with little in the way of consumables. But fossil fuels—although a limited-time offer—are also a free gift of nature. We do have to put effort into retrieving them (delivery not free), although far less than the benefit they deliver. The important metric on the energy/efficiency front is energy return on energy invested (EROEI). Fossil fuels have enjoyed EROEI values typically in the range of 20:1 to 100:1, meaning that less than 5% of the eventual benefit must be invested up front. Solar and wind are less, at 10:1 and 18:1, respectively. These technologies would avoid wasting a majority of the energy in heat engines, but the lower EROEI means it's less of a freebee than the current juice. And yes, the 15% efficiency of many solar panels does mean that 85% goes to heating the dark panel.

What About Accomplishing the Same Tasks with Less?

One route to coping with a fixed energy income is to invent new devices or techniques that accomplish the same tasks using less energy, rather than incrementally improve on the efficiency of current devices. This works marvelously in some areas (e.g., generational changes in computers, cell phones, shift to online banking/news).

But some things are hard to shave down substantially. Global transportation means pushing through air or water over vast distances that will not shrink. Cooking means heating meal-sized portions of food and water. Heating a home against the winter cold involves a certain amount of thermal energy for a fixed-size home. A hot shower requires a certain amount of energy to heat a sufficient volume of water. Can all of these things be done more efficiently with better aero/hydrodynamics or traveling more slowly; foods requiring less heat to cook; insulation and heat pumps in homes; and taking showers using less water? Absolutely. Can this go on forever to maintain growth? No. As long as these physically-bounded activities comprise a finite portion of our portfolio, no amount of gadget refinement will allow indefinite economic growth. If it did, eventually economic activity would be wholly dominated by us "servicing" each other, and not the physical "stuff."

What About Paying More to Use Less?

Owners of solar panels or Prius cars have elected to plunk down a significant amount of money to consume fewer resources. Sometimes these decisions are based on more than straight dollars and cents calculations, in that the payback can be very long term and may not be competitive against opportunity cost. Could social conscientiousness become fashionable enough to drive overall economic growth? I suppose it's *possible*, but generally most people are only interested in this when the cost of energy is high to start with. Below, we'll see that if the economy continues its growth trend after energy use flattens, the cost of energy becomes negligibly small—deflating the incentive to pay more for less.

The Unphysical Economy

In a future world where energy growth has ceased, and efficiency has been squeezed to a practical limit, can we still expect to grow our economy through innovation, technology, and services? One way to approach the problem is to demand that we maintain 5% economic growth over the long term, and see what fraction of economic activity has to come from the non-energy-demanding sector. Of course all economic activity requires *some* energy, so by "non-energy" or "unphysical," I mean those activities that require minimal energy inputs and approach the economist's dream of "decoupling."

We start by setting energy to flatten out as a logistic function (standard S-curve in population studies), with an inflection point at the year 2000 (halfway along). We then let efficiency boost our effective energy at the present rate of 1% gain per year, ultimately saturating at a factor of two. The figure below provides a toy example of how this might look.

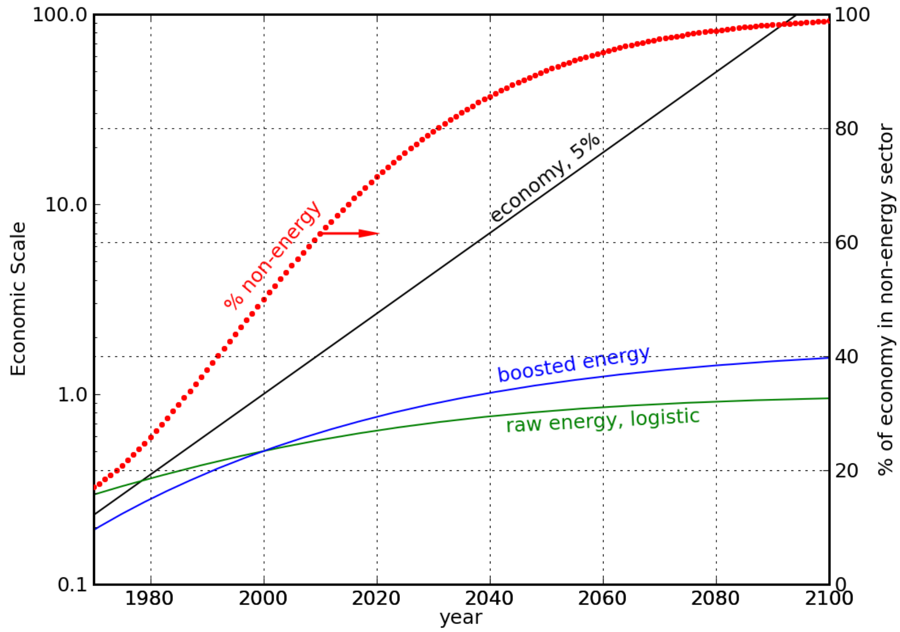

Figure 2. *Projected contribution to a steadily growing economy from non-energy-related activities in the face of flattening raw energy available and efficiency saturation. The green curve represents the scale of raw energy available each year, while the blue curve is the effective energy available through gains in efficiency. Regardless of timescale, the key feature is that the fraction of the economy that is independent of energy availability must grow to dominate all other activities in order to keep growth alive, here reaching 98% by the end of the century. This is an untested—and possibly physically untenable—economic state. Note that the vertical axis for the economic scale curves is logarithmic.*

The timescale is not the important feature of the figure. The important result is that trying to maintain a growth economy in a world of tapering raw energy growth (perhaps accompanied by leveling population) and diminishing gains from efficiency improvements would require the "other" category of activity to eventually dominate the economy. This would mean that an increasingly small fraction of economic activity would depend heavily on energy, so that food production, manufacturing, transportation, etc. would be relegated to economic insignificance. Activities like selling and buying existing houses, financial transactions, innovations (including new ways to move money around), fashion, and psychotherapy will be effectively all that's left. Consequently, the price of food, energy, and manufacturing would drop to negligible levels relative to the fluffy stuff. And is this realistic—that a vital resource at its physical limit gets arbitrarily cheap? Bizarre.

This scenario has many problems. For instance, if food production shrinks to 1% of our economy, while staying at a comparable absolute scale as it is today (we must eat, after all), then food is effectively very cheap relative to the paychecks that let us enjoy the fruits of the broader economy. This would mean that farmers' wages would sink far lower than they are today relative to other members of society, so they could not enjoy the innovations and improvements the rest of us can pay for. Subsidies, donations, or any other mechanism to compensate farmers more handsomely would simply undercut the "other" economy, preventing it from swelling to arbitrary size—and thus limiting growth.

Another way to put it is that since we all must eat, and a certain, finite fraction of our population must be engaged in the production of food, the price of food cannot sink to arbitrarily low levels. The economy is rooted in a physical world that has historically been joined at the hip to energy use (through food production, manufacturing, transport of goods in the global economy). It is fantastical to think that an economy can unmoor itself from its physical underpinnings and become dominated by activities unrelated to energy, food, and manufacturing constraints.

I'm not claiming that certain industries will not grow: there will *always* be growth in some sector. But *net* growth will be constrained. Winners will not outpace the losers. Nor am I claiming that some economic activities cannot exist virtually independent of energy. We can point to plenty of examples of this today. But these things can't grow to 90%, then 99%, then 99.9%, etc. of the total economic activity—as would be mandated if economic growth is to continue apace.

Where Does this Leave Us?

Together with the [last post](), I have used physical analysis to argue that sustained economic growth in the long term is fantastical. Maybe for some, this is stating the obvious. After all, Adam Smith imagined a 200-year phase of economic growth followed by a steady state. But our mentality is currently centered on growth. Our economic systems rely on growth for investment, loans, and interest to make any sense. If we don't deliberately put ourselves onto a steady state trajectory, we risk a complete and unchoreographed collapse of our economic institutions.

Admittedly, the argument that economic growth will stop is not as direct a result of physics as is the argument that physical growth will stop, and as such represents a stretch outside my usual comfort zone. But besides physical limits, I think we must also apply notions of common sense and human psychology. The artificial world that must be envisioned to keep economic growth alive in the face of physical limits strikes me as preposterous and untenable. It would be an existence far removed from demonstrated modes of human economic activity. Not everyone would want to participate in this whimsical society, preferring instead to spend their puffy paychecks on constrained physical goods and energy (which is now dirt cheap, by the way, so a few individuals could easily afford to own *all* of it!).

Recognizing the need to ultimately transition to a non-growth economy, I am personally disconcerted by the fact that we lack a *tested* economic system based on steady-state conditions. I would like to take a conservative, low-risk approach to the future and smartly place ourselves on a sustainable trajectory. There *are* well-developed steady-state economic models, pioneered by Herman Daly and others. There are even stepwise plans to transition our economy into a steady-state. But *not one* of those steps will be taken if people (who elect politicians) do not crave this result. The only way people will crave this result is if they understand (or experience) the impossibility of continued growth and the consequences of not acting soon enough. I hope we can collectively be smart enough to make this transition.

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